

A Cup of the Sea

The Immanent Metaphysics
for Readers of Jorge Cham and Daniel Whiteson

Forrest Landry

UVSM PUBLICATIONS
Wytheville, Virginia

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Published by UVSM Publications LLC
965 Reed Creek Mill Rd
Wytheville, VA 24382-8287
USA

uvsmpublications.com
contact@uvsmpublications.com

ISBN 979-8-90710-442-6

DOI: https://doi.org/10.67291/XSJQ8270

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A Frequently Asked Preface

In Which Two Guides to the Universe Are Set on the Table, and a Cup Beside Them

Why would I read another book about the same universe, when I have read the books of Jorge Cham and Daniel Whiteson?

Four Words

Open *We Have No Idea*, the first book of Jorge Cham and Daniel Whiteson, at its thirteenth chapter. The thirteenth chapter has a title: "What Happened to Chapter 13?" The whole text of the chapter is four words: "We have no idea" (*We Have No Idea*, ch. 13).

Cham and Whiteson published *We Have No Idea* in 2017. Cham is a cartoonist, the creator of the online comic *PHD Comics*. He earned his doctorate in robotics at Stanford. Whiteson is a professor of experimental particle physics (the study of the smallest pieces of matter by experiment) at the University of California, Irvine. Whiteson does his research with the Large Hadron Collider at CERN, the European laboratory for particle physics near Geneva. The Large Hadron Collider is a great ring in which particles are smashed together so that physicists can see what comes out.

The thirteenth chapter of *We Have No Idea* is a joke on the old superstition that thirteen is an unlucky number. The chapter is also a joke on the book's own refrain, the line the authors come back to again and again. The authors answer question after question across the seventeen chapters of the book with the same four words, "We have no idea", and those four words give the book its title.

In the first chapter of *We Have No Idea*, the authors draw a pie chart of everything in the universe, matter and energy together. About five percent of the pie is the stuff we know: stars, planets, and everything on them.

About twenty-seven percent is what physicists call *dark matter*. Physicists take dark matter to be a kind of matter, known only by its pull on the matter we can see. About sixty-eight percent is what physicists call *dark energy*. The authors write that physicists think dark energy is causing the universe to expand. The authors put their question in one line: "What is the other 95 percent of the universe made of? We don't know" (*We Have No Idea*, ch. 1).

Four years later, Cham and Whiteson published a second book, *Frequently Asked Questions About the Universe*. In the introduction to the second book, the first three words are "Everyone has questions". A few lines later the authors say what the book offers: "Fortunately, we have answers" (*Frequently Asked Questions About the Universe*, Introduction). The second book grew out of the questions that listeners sent in to the authors' podcast, *Daniel and Jorge Explain the Universe*, and the authors say that those listeners run in age from nine to ninety-nine.

Set the two books side by side, and the two books do two jobs for the same curious reader. The first book, *We Have No Idea*, is a guide to what physics has not yet found out. In the second book, *Frequently Asked Questions About the Universe*, the authors answer the questions that everyone asks as far as physics can answer them today. In this book I take up the same questions and answer them from a second ground: what every act of knowing must contain.

What Jorge Cham and Daniel Whiteson Showed

In the first pages of *We Have No Idea*, Cham and Whiteson say what the book is about: "Instead, this book is about all the things we don't know about the universe" (*We Have No Idea*, Introduction). Their purpose is to fill their reader with excitement about what is still unknown. The authors call what is still unknown "uncharted territory left to explore", and they write that "the first step in discovery is to know what is unknown" (*We Have No Idea*, Introduction). They hold that the grand mysteries have answers that exist, whether or not anyone has found the answers yet: "The

exciting thing is that the grand scientific mysteries have real, hard answers" (*We Have No Idea*, ch. 1). In each chapter, the authors take a question a reader might ask, tell what has been measured, set what has been measured apart from what is not yet known, and say what an answer could mean for humans.

The authors end *We Have No Idea* on the deepest question they can ask: why the universe exists, and why the universe is the way it is. They think the deepest question may lie beyond what science can test. They take their hope from the growth of science itself: "Like the observable universe, the testable universe is expanding" (*We Have No Idea*, "A Conclusion of Sorts", "The Testable Universe"). Astronomers call everything whose light has reached us the *observable universe*. The observable universe grows as light from farther away arrives. The authors answer their last question with their refrain, "We have no idea", and then they close on one more line: "But it will certainly be an exciting ride" (*We Have No Idea*, "A Conclusion of Sorts", "The Testable Universe").

In *Frequently Asked Questions About the Universe*, Cham and Whiteson answer as a physicist answers. They state the standard they use in the book's first chapter: "A physicist will say something is possible if they don't know of a law of physics that prevents it" (*Frequently Asked Questions About the Universe*, ch. 1, "Practical Versus Possible Versus Not Impossible"). By the physicist's standard, three chapters end with the answer yes: the chapter on teleportation, the chapter on travel to the stars, and the chapter on whether we live inside a computer simulation. The authors leave the practical work to engineers: "We trust that once the physicists declare it possible, the engineers will eventually figure out a way to make it practical" (*Frequently Asked Questions About the Universe*, ch. 1, "Practical Versus Possible Versus Not Impossible"). The authors also say where their answers stop. They warn that some answers will be "agonizingly incomplete", because each of those answers stops where what humans know stops (*Frequently Asked Questions About the Universe*, Introduction). They hold that asking is itself a hopeful act: "You see, asking ques-

tions supposes that it's possible to find the answers, which we believe is an act of hope" (*Frequently Asked Questions About the Universe*, Introduction).

In the last chapter of the second book, the authors take up what they call probably the most frequent question they get. Listeners usually add the most frequent question at the end of another question: "What does that even mean?" (*Frequently Asked Questions About the Universe*, ch. 20). The authors say that the meaning of an answer is the context the answer gives a life. They say that each of us finds that meaning for ourselves. They close the book by asking their reader a question: "So what are your frequently asked questions?" (*Frequently Asked Questions About the Universe*, ch. 20).

Both books are warm and funny. Both books say what physics has measured and what physics has not yet measured. The questions of Cham and Whiteson are good questions, and I take each question as the authors ask it.

Where This Book Stands

The subtitle of this book names the ground from which I answer: an account called the *Immanent Metaphysics*. In this book, metaphysics means the study of what must be so for anything at all to be known. Immanent means within. In the Immanent Metaphysics I reason from inside the act of knowing, here and now, as the act happens, and from no place outside the world. The question of the Immanent Metaphysics is what every act of finding out must contain, whatever is found and whoever or whatever does the finding. The question has an answer, and the answer turns out to be exact, and rich, and the same everywhere. "Exact" means that each thing every act of finding out must contain is fixed precisely. "Rich" means that the answer contains a great deal. "The same everywhere" means that the answer applies to every act of finding out, by anyone or anything, at any place and any time. The only ground of the Immanent Metaphysics is the act of knowing. The Immanent Metaphysics uses noth-

ing from physics: no measurement, no law, no result of any experiment. I work out the physics from the act of knowing alone, and then I set the physics beside what has been measured. Where I take something from established physics or from measurement, I say so in plain words in the chapter: in Chapter 10 I take the form of the bending of space and time from general relativity, and one number, Newton's constant, from measurement; in Chapter 5 I take six numbers from measurement for the working account of the masses, and one, the electron's mass, for the closure account; and in the appendix "For the Specialist" I give, for every claim, whether I work it out from the act of knowing, take it from established physics, or read it from measurement. The Immanent Metaphysics is my own work: I first set it out in my book *An Immanent Metaphysics* (2001), and I work out its physics, from the act of knowing, in a series of later books, every one of them mine, which Appendix B, For the Specialist, names chapter by chapter, with the place in each book that every step draws on. In this book "I" means me, the writer of those books, except in a question asked in the reader's words (as the chapter titles are).

Cham and Whiteson's questions come from the side of the telescope and the collider, the side of what instruments have measured. I answer the same questions from the side of the act of finding out. Where my answer agrees with the answer of Cham and Whiteson, I say so, and I say from what separate ground I reach my answer. Where the two answers differ, I give the reason for the difference. I quote the authors' refrain, "We have no idea", as their words. In my own voice, I say what has been measured and what has not yet been measured, as plain facts. I answer each question from the Immanent Metaphysics.

A finding is the result of one act of finding out, such as one reading of a thermometer. Every finding is made at some place, at some moment, and as one of the things that could have been found. The world has three *settings* in which anything is measured: *space*, the place of a finding; *time*, the moment of a finding; and *possibility*, the range of what could have been found instead. Each setting has a plain shape, the same throughout. Each setting can also be *bent*: made uneven, so that one part of the setting

differs from another part. Three things in nature do the bending. Gravitation (the pull we call gravity) bends space. What Cham and Whiteson call dark energy bends time. What Cham and Whiteson call dark matter bends possibility. Dark energy and dark matter together make up the other ninety-five percent of the authors' pie, so that ninety-five percent is two of the three bendings: the bending of time and the bending of possibility. Chapter 1 begins with the authors' pie, and shows what the three settings are and why each setting is bent. The book's chapters are arranged in seven Parts. The chapters after Chapter 1 follow the rest of the road, one question after another. The road runs from the pie to the pieces of matter, and then to the space and time in which the pieces are found. Then the road runs to the clock, to the stars, to the beginning of the universe, to you, and to the far future.

Who This Book Is For

This book is for you if you have read *We Have No Idea*, or *Frequently Asked Questions About the Universe*, or both, and closed the book with a question still turning in your head. This book is also for you if you have read neither, because in each chapter I tell what Cham and Whiteson showed before I give my own answer. You can read this book without knowing any physics or any mathematics. In this book I quote, briefly, everything you need from the books of Cham and Whiteson, with the chapter where you will find each quotation, and the section where the chapter has sections. If you want to read the books side by side, use the table at the back of this book, "Reading Beside Cham and Whiteson". The table shows, beside each chapter of this book, the chapters and sections of Cham and Whiteson's books that are about the same question.

How to Read It

Each chapter of this book is about one question, asked in the words a reader of Cham and Whiteson would use, and many of the questions are titles of chapters in their books. Near the start of each chapter, I tell a scene from the published record, in which a named person is at work at a known date and the idea of the chapter appears in that person's work.

I show you every idea before I name the idea, in a picture, a scene, or something you can try at your own table. I explain every new word in plain words where you first meet the word. At the back of the book, the list "Terms" contains each explanation again, as a reminder.

The chapters need no mathematics. Where a relation between two quantities matters, I state the relation in words, in one sentence. In the chapters, I write the numbers you need in words, such as "about ninety-five percent". At the back of the book, the appendix "For the Specialist" contains all the mathematics and the exact values with all their digits. For every claim that I take into a chapter from my physics books, the appendix also names the book, chapter and section that contain the full argument for the claim. For every measurement in a chapter, the appendix lists the measured value and the primary paper, the paper in which the measurement was first reported.

Measurements appear in two places in this book. I describe each measurement already made in the chapter where the measurement matters: what was done, what was found, and what we now know. I gather the measurements still to come in the appendix "What the Coming Measurements Will Find". For each coming measurement, the appendix says what will be measured and what my account, the Immanent Metaphysics, says will be found.

You may skip both appendices and lose nothing. The answer in each chapter is complete in the words of the chapter itself. The appendices are there for you if you want the exact values, or want to know what to watch for in the coming years.

Every chapter ends with the same three parts. The first part is the chapter's answer in one sentence you can keep, set off as "The short answer". The second part is a sentence or two on why the short answer matters. In every chapter but the last, the third part is the question that the next chapter is about. The last chapter ends instead with a few closing lines about the cup of coffee that you will set on your table at the end of this Preface. You can read the book straight through, as one walk, or stop at any short answer and still have something to tell a friend.

A Cup of the Sea

The title *A Cup of the Sea* names a position: the position of a measurement made from inside the world it measures, by an instrument that is part of that world. My book *The View from Inside* draws that position as a picture. At its outset, *The View from Inside* states a plain fact: every finding in science is made from inside the world it finds, by instruments and observers that are part of that world. *The View from Inside* adds that, for most measurements, being inside changes almost nothing. A thermometer is a tiny part of the room whose warmth the thermometer measures. In the tenth chapter of *The View from Inside*, I ask you to imagine learning about the sea by dipping a cup into the sea. The cup holds real sea water, and from that water you can learn a great deal, but no cup ever holds the whole sea. A measurement of the energy of empty space is in the cup's position, and further inside than the cup, because the instrument that makes the measurement is itself made of the very things that hold the energy the instrument measures. An instrument that measures the energy of empty space is not a cup dipped into the sea from a boat; it is a cupful of the sea, trying to know the rest of the sea. In Chapter 3 I name the things that hold the energy of empty space, and I show how much of that energy a cupful of the sea holds: a share, never the whole.

Before Chapter 1, pour yourself a cup of coffee (or picture a cup of coffee) and set the cup on the table beside this book. If you have read *Frequently Asked Questions About the Universe*, you have met a cup of coffee be-

fore: in the first chapter of that book, coffee spilled on your pants is the small mistake that a trip back in time would undo. Leave your own cup on the table, unspilled. Your cup will come back in many chapters, and each time I will ask you to notice one thing about the cup.

Here, in brief, is what this book holds that Cham and Whiteson's books do not: the ninety-five percent as the bending of time by the cosmological constant and of possibility by the dark matter (Chapters 1 to 3); a closed list of kinds of particle, with no fourth generation and no smaller piece waiting below, and charges forced as the one solution that keeps the forces consistent (Chapters 4 and 5); gravity as the arena on which the three forces act, joined side by side with the quantum, with neither given up or quantized (Chapters 7 to 9); ten dimensions, one of time, three of space and six of possibility (Chapter 11); time going forward because every comparison goes one way, from what could be found, to the finding, to its record (Chapter 13); the speed of light as the outer edge of comparison itself (Chapter 15); the Big Bang as the turn, in a cycle of epochs with no first turn (Chapters 20 and 22); an open future, in which one outcome that nothing fixed is chance seen from outside and choice seen from inside (Chapter 26); a world that is no computer program (Chapter 27); a far future in which the emptying ends in a turn that begins the next epoch (Chapter 29); and questions that never run out, because no investigation moves the edge of the unknowable (Chapter 32). If you have read another of my books written for the readers of another author, you know the ground already: comparison, its content and its context, the three settings and the Incommensuration Theorem, which I teach again here in Chapter 1 with a ramp and a staircase. Everything else in this book is set beside Cham and Whiteson's own pictures, beginning with their pie in Chapter 1. Read the chapters in order, because each chapter builds on the ones before it. Where a chapter uses a word or a result that an earlier chapter teaches, a short box at the head of the chapter lists the word or result, with the chapter that teaches it. Where a chapter retells what Cham and

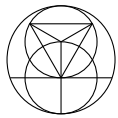
Whiteson showed, the retelling stands in a shaded box headed "From Cham and Whiteson's pages": a reader who knows their books can pass over the boxes, and a reader new to their books can read the boxes first.

The question of this book is what the universe is made of when every answer is found from inside the universe. Cham and Whiteson begin their first book, *We Have No Idea*, with the question of what the universe is made of, and I begin this book with the same question.

What is the universe made of, and how can anyone give exact percentages for the parts nobody understands?

PART ONE

FROM THE PIE TO THE PIECES



Chapter One

What Is the Universe Made Of?

In which the pie of the universe is cut again, and most of it turns out to be the bending of the settings in which everything is found

What is the universe made of, and how can anyone give exact percentages for the parts nobody understands?

On the morning of 21 March 2013, the European Space Agency held a media briefing at its headquarters in Paris on the first results of its Planck satellite. Jean-Jacques Dordain was the agency's Director General. Dordain spoke at the briefing beside George Efstathiou, director of the Kavli Institute for Cosmology at the University of Cambridge. Dordain and Efstathiou spoke about a picture of the whole sky. The Planck satellite had made the picture from its first fifteen and a half months of looking. The picture showed the oldest light in the universe, set free when the universe was about three hundred and eighty thousand years old. The oldest light has been stretched since its release into a faint glow of microwaves. The glow is about two and seven tenths degrees above the coldest cold there is (absolute zero). The picture was a mottle of slightly warmer and slightly cooler spots. Each spot was a patch of sky that the satellite found a little warmer, or a little cooler, than the whole sky's average. The agency announced how the universe is divided, and the agency's figures came from the pattern of warm and cool spots. Normal matter, the stuff of stars and galaxies, came to four and nine tenths percent of everything. Dark matter, known only by its pull, came to twenty-six and eight tenths per-

cent. The rest was dark energy. The agency's announcement also gave the age of the universe: about 13.8 billion years, where a billion is a thousand million. Dordain said in the agency's release on the day of the briefing that "our blueprint of the cosmos is far from complete".

So a picture of the sky gave the shares of the universe to a tenth of a percent, yet nearly all of what the picture weighed (the matter and energy whose amounts the picture measured) was something no one could name. Every one of the shares came from comparing warmth with warmth. The instrument that made the comparisons was inside the universe that the instrument was weighing.

From Cham and Whiteson's pages

The Pie, as the Authors Draw It

Jorge Cham is a cartoonist, and Daniel Whiteson is a particle physicist. Cham and Whiteson open their book *We Have No Idea* with the same numbers as the Planck announcement, rounded. Cham and Whiteson say everything you have ever seen or touched is built from three particles: the up quark, the down quark and the electron. The *quarks* are particles of matter that, bound together, build the tiny core at the center of every atom. The electrons surround the core of the atom. Cham and Whiteson count the discovery of the three building blocks (the up quark, the down quark and the electron) as a great achievement. Then they add a catch: everything built from the three particles is about five percent of the universe. Cham and Whiteson ask the question and answer it in two short lines: "What is the other 95 percent of the universe made of? We don't know" (*We Have No Idea*, ch. 1). Cham and Whiteson draw the universe as a pie: five percent normal matter, twenty-seven percent dark matter, sixty-eight percent dark energy.

In their third chapter, Cham and Whiteson take up the second half of your question, how anyone can give exact percentages for the parts nobody understands, and they ask it in their own words: how do

physicists know how much dark matter and dark energy there is? Cham and Whiteson answer in three parts. The most precise measurement comes from the oldest light, which Cham and Whiteson call the universe's baby picture. If the shares were different, the pattern of spots in the oldest light would come out differently. So physicists can read the shares from the pattern. A second measurement comes from the speed at which the universe expands, which astronomers read from exploding stars. A third measurement comes from computer models of how galaxies grew. The models come out wrong when physicists give them the wrong amounts of dark matter and dark energy. The three measurements, from the oldest light, from the speed at which the universe expands and from the computer models of how galaxies grew, agree. Because the three measurements agree, Cham and Whiteson can say how much dark matter and dark energy there is, while Cham and Whiteson also say that they do not know what dark matter and dark energy are: "Welcome to the era of precision ignorance" (*We Have No Idea*, ch. 3, "The Pie Chart").

Cham and Whiteson write that the amounts are known "with fairly good confidence", because separate kinds of measurement agree (*We Have No Idea*, ch. 3, "The Pie Chart"). The great question of *We Have No Idea* is what the dark parts of the pie are. Cham and Whiteson hold that the question has an answer: "The exciting thing is that the grand scientific mysteries have real, hard answers" (*We Have No Idea*, ch. 1).

To give the answer, we need one picture and a few plain words. The picture is a cup of coffee on your own table.

I take Cham and Whiteson's message as they give it. I give an answer to what the slices of the pie are.

A Cup on the Table

There is a cup of coffee on your table. You put your hand around the cup and notice that the cup is still warm.

When your hand touched the cup, you set the warmth of the cup against the warmth of your hand, and you found a difference. I call the act of setting one thing against another, as you set your hand against the cup, a comparison. A *comparison* is the act of finding whether two things are the same or different in some respect, and every measurement is a comparison. Three ordinary instruments show the act: a thermometer compares the warmth of a room with the thermometer's column of liquid, a ruler compares the edge of a table with the ruler's marks, and a satellite compares the warmth of one patch of sky with the warmth of another patch. Whatever makes a comparison is a *comparer*: a person, an instrument, a detector, an atom, anything that registers one thing against another, whether or not the comparer has a mind. A comparison leaves behind a *finding*: the outcome of one comparison, laid down as a record. Your noticing that the coffee is warm is a finding, and so is each spot on the Planck map.

Now look again at your finding that the coffee is warm. Three things are present in the finding: first, there is your noticing, and second, there is what you found, the warmth. Third, there is where you found the warmth: on this table, at this moment, in this cup that could have been cold, or spilled, or a cup of tea.

The *content* of a finding is what the finding finds: in your finding, the warmth of the coffee. The *context* of a finding is where the content is found. The context has three sides, and the cup shows all three. I call each side of the context a *setting*. One setting is *space*: the warmth is here, on this table, and not across the room. One setting is *time*: the warmth is now, at this moment, and not an hour ago. One setting is *possibility*, the range of what could have been found instead: the coffee is warm, among all the ways the cup could have been, cold, spilled or tea. Space, time and possibility are *the three settings* of every finding.

Every finding has a content and a context, from your hand on the cup to a satellite's map of the sky, and the context always has the three settings. Three ordinary findings, and each of the three shows one of the set-

tings. A map lays a pattern out in space. A push is a force acting over a time. When a forecast gives a seventy percent chance of rain, the forecast is a probability spread over what could happen.

The Ramp and the Staircase

The content and the context of a finding behave differently, and the reason is one fact that holds of every comparison.

Picture two ways up a hill. One way is a ramp. The ramp is smooth: every small step forward is a small step up, with nothing sudden anywhere. The ramp is also uneven: its slope follows the hill, steeper here and gentler there, so no stretch of the ramp is quite like another. The other way is a staircase. Every step of the staircase is exactly like every other step, so the staircase is the same all along. The staircase also comes in steps: between one step and the next there is nothing to stand on.

I use two plain words for what the ramp has and what the staircase has. When nothing in a thing is sudden, the thing is *continuous*: a small move in a setting brings only a small change of what is found, as a small step along the ramp brings only a small rise. When what is found stays the same across a change of setting, the thing is *symmetric*, as the staircase's steps are all alike. The opposite of continuous is *discontinuous* (something sudden, as at the edge of a step). The opposite of symmetric is *asymmetric* (something different everywhere, as along the ramp).

Now try to build a third way up the hill. The third way is to be perfectly smooth, and also perfectly the same at every point, the height of the path included. If a path has the same height at every point, the path is flat, and a flat path never rises. The reasoning about the flat path holds for every comparison. Perfect continuity means that the small change shrinks to none: where the setting does not change, what is found does not change. Perfect symmetry means that where the setting does change, what is found still does not change. If continuity and symmetry are both perfect together, the comparer finds "same" whatever the setting, and a comparer who can only ever find "same" has stopped comparing, as the flat path

has stopped rising. The reasoning about continuity and symmetry, turned over, shows that perfect asymmetry and perfect discontinuity cannot go together either, because a comparer with both would find "different" whatever the setting, and so would have stopped comparing too.

The *Incommensuration Theorem* states the result of the reasoning about the third way up the hill: at the foundation of any event (anything that happens) or comparison, symmetry and continuity cannot both be perfect together, and neither can asymmetry and discontinuity. When no common measure fits two things, the two things are incommensurable. Perfect symmetry and perfect continuity are incommensurable, since no comparison can have both. The Incommensuration Theorem is a structural fact about the nature of knowing. Symmetry and continuity cannot both be applied, simultaneously and fundamentally, to any event or comparison; and neither can asymmetry and discontinuity. The Incommensuration Theorem holds of every event and every comparison there is, whoever or whatever makes the comparison, because the proof of the theorem uses nothing except what a comparison is. When a comparison is perfected at its foundation, the comparison is one of two kinds, like the ramp or like the staircase: smooth and uneven, or the same everywhere and in steps.

Physicists find both kinds, and they find each kind in its own place. What is found comes in steps and is the same for everyone: light arrives one particle at a time, and an electron measured in one laboratory is the same as an electron measured in any other laboratory. So content, what is found, is like the staircase. The context, where content is found, is smooth. Space and time have no steps, and a small move in space or in time brings a small change. So the context is like the ramp, and the Incommensuration Theorem says what the smoothness costs the context: a setting that is perfectly smooth cannot also be perfectly even, the same throughout.

Three Settings, Three Bends

Picture a sheet of rubber, ruled in equal squares and pulled flat. Every square is like every other square, and the sameness of the squares throughout is the plain shape of the sheet. If you set a heavy ball on the sheet, the squares near the ball stretch, while the squares far from the ball stay as they were. When a setting is uneven in the way the stretched sheet is uneven, the setting is *bent*: one part of the setting differs from another part, where the plain shape of the setting would be the same throughout. The Incommensuration Theorem shows that a setting that is perfectly smooth cannot also be perfectly even, so every perfectly smooth setting is bent.

The Incommensuration Theorem applies to each of the three settings, since comparison happens in each of them. Each setting is a side of the context, so each setting is like the ramp: perfectly smooth. So, by the Incommensuration Theorem, none of the three settings (space, time and possibility) is perfectly even. Three further facts about the settings show that each setting has a bend of its own. First, the settings are *inseparable*: every finding has all three settings, so no setting can be left plain while another setting is bent. Second, the settings are *not interchangeable*: no setting can stand in for another, so the bend of one setting cannot do the job of the bend of another setting, and each setting needs a bend of its own. Third, the settings are *distinct*: each is a different setting, so each bend is a different thing, and there are three bends. My account has three axioms, which are the basic statements of the account, and the third axiom has three clauses: the three facts that the settings are inseparable, not interchangeable and distinct. The third axiom, like each axiom, holds of every comparison whatever, as I say in Chapter 13, and in this book I use it for the three settings, here, and for content and context, in Chapters 22, 28 and 29. I call one setting, together with the content found in that setting, a column. I also call a bend a distortion. I name the three bends in one line: "Each column therefore carries a distortion that is not zero: in space, gravitation; in time, the cosmological constant; in possibility, the dark matter".

The line contains three familiar names: gravitation, the cosmological constant and the dark matter. Gravitation bends space. Space curves around a star or a planet, as the rubber sheet curves around the ball. Bound things such as planets and galaxies form in the curve of space, and light follows the curve.

The cosmological constant bends time. Picture two galaxies far apart. As time runs on, the distance between the two galaxies grows. The cosmological constant makes the growth of the distance speed up, the same at every place. The cosmological constant is the physicists' name for what Cham and Whiteson call dark energy. The cosmological constant is the one constant term in Einstein's equations of gravity, the equations that say how energy shapes space and time. The cosmological constant is the same at every place, and at every time of the present era of the world, the era that began with the Big Bang. Chapter 3 shows what the cosmological constant is: the share of the energy of empty space that a measurement made from inside the universe takes in. The cosmological constant bends how the whole universe runs from one time to the next.

The dark matter bends possibility. Picture a galaxy turning so fast that the pull of all the galaxy's visible stars and gas could not hold the galaxy together. The galaxy holds together all the same, and the dark matter is what holds the galaxy together. The dark matter is a bend of possibility, the setting of what could be found, and the dark matter has no content of its own, which is why the dark matter has never been found doing anything but pulling. Chapter 2 shows how a bend of possibility with no content of its own does nothing but pull.

Now return to Cham and Whiteson's pie. The pie divides the energy of the universe into slices. The dark energy slice is the bend of time. The dark matter slice is the bend of possibility. Gravitation, the bend of space, has no slice of its own. Gravitation is the response of space to matter, and it is not an item in the budget of the universe at all.

So the dark ninety-five percent of the pie is the bending of two of the settings in which everything is found: time and possibility. So most of the energy of the universe is a distortion of the setting, not things in it.

The three bends behave as the three clauses of the third axiom say: the bends are distinct, inseparable and not interchangeable. The bends are distinct, because each bend behaves in its own way: the cosmological constant is even everywhere and never clumps, gravitation follows matter, and the dark matter clumps. The bends are inseparable, because all three bends appear together in the one equation that governs the expansion of the universe. The bends are not interchangeable, because no bend does the job of another bend. No amount of the cosmological constant gathers dark matter into a *halo*, the great cloud of dark matter in which each galaxy sits. And no amount of dark matter speeds up the expansion of the universe.

Each dark slice is a bend of one of the settings, and the Incommensuration Theorem and the three clauses of the third axiom require a bend of each setting. Cham and Whiteson count the two dark slices, the ninety-five percent, as stuff whose nature is not yet known. The two answers differ for one reason: my starting point is what every measurement contains, and every measurement contains the three settings, each of them bent.

What is the five percent of Cham and Whiteson's pie, the slice that is stuff? The five percent is content: everything made of atoms, stars and gas and planets and people. Cham and Whiteson ask how many other kinds of particle there are. I argue that the list of kinds of particle is complete. The structure of comparison is what every comparison must contain, and each kind of particle answers to one part of the structure of comparison. You have met some parts of the structure of comparison already: content and context, and the Incommensuration Theorem, which governs content and context. Every part of the structure of comparison now has its particle, and no part is left without a particle. So the five percent slice is made from a closed list of kinds of particle. In Chapter 4 I walk through why the list is closed.

How a Picture Weighs What It Cannot See

We can now answer the second half of your question: how can a picture of the sky give exact shares of things no one has seen?

Go back to the spots on the Planck map. In the early universe, before the first atoms formed, ordinary matter and light were mixed together in one hot glowing gas. Sound ran through the gas. The ordinary matter took part in the sound and rang with the light. The dark matter only pulled, and took no part in the sound. The spots of the oldest light come in favored sizes, as a drum sounds favored notes. Each favored size shows more or less strongly in the map, depending on how much of each kind of matter there was. The ordinary matter shows in the map in one way, because the ordinary matter rang, and the dark matter shows in the map in another way, because the dark matter only pulled. So the oldest light lets physicists weigh the ordinary matter and the dark matter separately.

Weighing by the oldest light works on a thing nobody can see, because the two kinds of matter leave two different marks. The weighing uses only two properties that the dark matter has always shown: the dark matter has weight and takes part in nothing else. Cham and Whiteson are right that physicists can measure the amounts without knowing what the dark matter is. I also state the reason for the two properties: light, detectors and every instrument register content, and the dark matter is a bend of a setting, so the dark matter shows itself only by its weight.

Cham and Whiteson put their trust in agreement among separate methods, and my account has the same view of method. Physicists guard against an error of method by making a second kind of measurement, in a separate way. An error of method is a mistake built into one way of measuring, which that way's own stated margin of error does not show.

Most astronomers use an account of the universe called the standard picture of cosmology. Astronomers who use the standard picture fit the shares to the sky: they choose the values of the shares that make the sky calculated from the standard picture match the measured sky. I set the share of matter, ordinary and dark together, at about thirty-one percent.

The figure of thirty-one percent comes from one relation about the measurement we make now, from inside the universe. I walk through the relation behind the figure of thirty-one percent in Chapter 3. I set the split between dark matter and ordinary matter at one number, six less two divided by pi: a little more than five and a third kilograms of dark matter for every kilogram of ordinary matter. The number six less two divided by pi is a count of what a measurement made today takes in: six for the dark matter against one for the ordinary matter, less a small share, two divided by pi. The measurement counts kinds of shape, where a kind of shape means one of the basic pieces from which a shape can be built. The surface of a ball, for example, is built from two kinds of shape: a single point, and a disk whose whole rim is drawn together to that point, like a drawstring bag pulled shut. The shape of the setting of possibility has six kinds of shape, and the dark matter ranges over the whole of that shape, so the dark matter is counted by all six kinds. The ordinary matter is counted in the space we can see, and the part of that space from which light has reached us is a solid ball, which has one kind of shape alone. The six kinds of shape of possibility are a different count from the six small dimensions of possibility that Chapter 2 introduces, although both counts come to six. The small share, two divided by pi, is taken from the six by the bending of the shape of possibility, and the appendix "For the Specialist" sets out the count in full. In my own figures, the universe is about thirty-one percent matter and about sixty-nine percent the cosmological constant, and the dark matter is about five and a third times the ordinary matter. My figures come to about five percent ordinary matter, about twenty-six percent dark matter and about sixty-nine percent dark energy in Cham and Whiteson's terms: Cham and Whiteson's pie, with a reason beside each slice.

The Planck team released its final analysis of the oldest light in 2018, and published it in 2020. In the 2018 analysis, the Planck team found the share of matter at thirty-one and a half percent, with a margin running from a little under thirty-one to a little over thirty-two percent. The Planck team's margin includes my share of a little over thirty-one percent. The

2018 analysis also found amounts of dark matter and of ordinary matter whose ratio is within about a hundredth of a percent of my six less two divided by pi. Later, astronomers combined Planck's map with maps of the oldest light made from the ground by the South Pole Telescope and the Atacama Cosmology Telescope. The combined maps give a ratio about a tenth of a percent above my number, well inside the margin of the combined maps, a little under one percent either way.

Astronomers also have a second kind of measurement of the matter in the universe, one that does not use the oldest light. In the second kind of measurement, astronomers measure what share of all the matter is ordinary matter. The share of ordinary matter is my split seen from the other side: one kilogram of ordinary matter in every six and a third or so kilograms of matter. One kilogram in six and a third is a little above fifteen and a half percent. On one route, astronomers take the amount of ordinary matter from the lightest elements, which were made in the first minutes of the universe, together with the spacing of galaxies across the sky. On another route, astronomers weigh the hot gas held inside clusters of galaxies. The result from the lightest elements is a little below sixteen percent, and the result from the cluster gas is fifteen and six tenths percent, so each result agrees with my value. Each result was found without the oldest light.

We now know three things. First, the shares of the pie are known with fairly good confidence, as Cham and Whiteson say, because separate kinds of measurement agree. Second, I set the share of matter from one relation about the measurement made now, from inside the universe, and the separate measurements show the same share. Third, I fix the ratio of dark matter to ordinary matter by what the measurement made now takes in, and the separate measurements show the same ratio.

The Cup Again

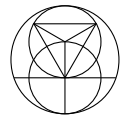
Put your hand around the cup once more. The warmth you find is the content. The context is the table, the moment and the cup that could have been cold: the three settings of space, time and possibility. None of the three settings is a thing in the cup. Each setting is part of where the warmth is found.

When a satellite measures the energy of the whole universe from inside the universe, the satellite's measurement has the same parts as your finding. The five percent that is stuff is content, made of a closed list of kinds of particle. The rest of what the satellite weighs is the shape of the settings in which everything is found. The bend of time is about sixty-nine percent of the energy, and the bend of possibility is about twenty-six percent. The bend of space, gravitation, is the response of space to matter, and gravitation has no share of its own.

> **The short answer**
>
> Most of the universe's energy, about ninety-five percent, is the bending of time by the cosmological constant and of possibility by the dark matter, and the five percent that is stuff comes from a closed list of kinds of particle.

Once the short answer is given, the book's question turns from "what is the ninety-five percent made of?" into "what is each bend, and what do the settings do?", and I answer part of the new question in every later chapter. The short answer also shows why the bends could be measured at all from our place inside the universe: a measurement made from inside the universe finds the bend of possibility by the pull of that bend and the bend of time by the push of that bend on the expansion.

If a quarter of everything is a bend of possibility, what is that bend, and why does nothing but its weight ever show it?



Chapter Two

What Is Dark Matter?

In which the unseen weight of the galaxies turns out to be a vibration of possibility, found by its pull and by nothing else

What is dark matter, and why can't we see it?

What this chapter uses

A *comparison* is the act of finding whether two things are the same or different in some respect, and every measurement is a comparison; a *finding* is the outcome of one comparison, laid down as a record; a *comparer* is whatever makes a comparison, whether or not the comparer has a mind (Chapter 1).

The *content* of a finding is what the finding finds, as the warmth of your coffee; the *context* is where the content is found, and the context has three sides, the three settings of space, time and possibility (Chapter 1).

The three *settings* in which anything is measured are space, the place of a finding; time, the moment of a finding; and possibility, the range of what could have been found instead; a setting is *bent* when one part of the setting differs from another part (Chapter 1).

Continuous: nothing is sudden, as along a ramp; *discontinuous*: something is sudden, as at the edge of a step; *symmetric*: what is found stays the same across a change of setting, as each step of a staircase is like every other; *asymmetric*: different everywhere, as the height along a ramp is (Chapter 1).

The *Incommensuration Theorem*: at the foundation of any event or comparison, symmetry and continuity cannot both be perfect together, and neither can asymmetry and discontinuity. The Incommensuration Theorem is a structural fact about the nature of knowing (Chapter 1).

Three things in nature do the bending: gravitation bends space, the cosmological constant bends time, and the dark matter bends possibility (Chapter 1).

In the late 1960s, two astronomers set out to measure how the Andromeda galaxy turns. Andromeda is the large galaxy nearest to our own. The two astronomers were Vera Rubin and Kent Ford, of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington. Ford

had built a new instrument for measuring the turning of Andromeda. The instrument was a *spectrograph*, a device that spreads the light of a source into its colors, the way a prism spreads sunlight into a rainbow. The spectrograph carried an image tube, which strengthened faint light before the light reached the photographic plate. Rubin and Ford used the spectrograph on the 72-inch telescope at Lowell Observatory and on the 84-inch telescope at Kitt Peak. Rubin and Ford aimed the spectrograph at sixty-seven clouds of glowing hydrogen gas scattered through Andromeda's disk, from about ten thousand to nearly eighty thousand light-years from the center of Andromeda (a light-year is the distance light travels in a year). A typical exposure of one cloud took an hour to an hour and a half.

Glowing hydrogen gives off light of one exact shade of red. A cloud moving away from us shows the red shade shifted a little toward longer waves, and a cloud moving toward us shows the red shade shifted a little toward shorter waves. The size of the shift therefore measures the speed of the cloud along our line of sight. Andromeda turns, so the clouds on one side of its center move toward us and the clouds on the other side move away. From the shifts, Rubin and Ford found how fast each cloud travels around the center.

Picture the planets around the Sun. Almost all the mass of the solar system sits in the Sun, so the far planets travel slowly and the near planets travel fast. If the mass of a galaxy sat where the light of the galaxy is brightest, near its center, the galaxy would turn the way the solar system turns: slowly at its edge. Andromeda turns differently. Rubin and Ford found the speeds of the outer clouds falling off only slowly, out to the farthest cloud they measured. The speeds of the clouds showed Rubin and Ford that the mass inside each distance from the center keeps growing, roughly in step with the distance, out to about forty-five thousand light-years, and grows more slowly beyond. Far from the center, where the starlight thins, the pull on the clouds does not thin with the starlight. Rubin and Ford published the measurement in February 1970 (Rubin and Ford,

Astrophysical Journal, 1970). Rubin and Ford's measurement showed a pull where almost nothing shines: something unseen holds Andromeda's outer clouds in their orbits.

From Cham and Whiteson's pages

What Cham and Whiteson Showed

Jorge Cham and Daniel Whiteson open their second chapter by telling you that you live among the unseen stuff: "Dark matter is everywhere. In fact, you're probably swimming in it" (*We Have No Idea*, ch. 2, opening). Cham and Whiteson give three lines of evidence for dark matter, each with a picture. First, galaxies spin so fast that the pull of their visible stars could not hold the galaxies together: the stars would fly off, as Ping-Pong balls would fly off a spinning merry-go-round. Second, heavy, invisible matter bends the light of more distant galaxies, so that one galaxy can appear twice in the sky. Astronomers call the bending of light by unseen mass *gravitational lensing*, because the unseen mass bends the light as a glass lens does. Third, two clusters of galaxies crashed into each other. The crash left the gas and dust of the two clusters in a tangled heap, while the dark matter of the clusters, mapped by the bending of light, kept going as if nothing had happened. Of the crash, Cham and Whiteson write: "The most convincing single piece of evidence for dark matter came when we observed a giant galactic collision in space" (*We Have No Idea*, ch. 2, "Ways We Know Dark Matter Is There").

Then Cham and Whiteson list what is known about dark matter. Dark matter has mass, is invisible and gathers around galaxies. Neither ordinary matter nor other dark matter seems to touch dark matter. Cham and Whiteson also list four forces, the four ways in which matter is known to act on matter. The first force is gravity. The second force is electromagnetism, the force between electric charges, which also makes light. The third force is the weak nuclear force, a feeble force behind one kind of radioactivity. The fourth is the strong nuclear

force, which holds together the core of every atom. The core of an atom is called its *nucleus* (in the plural, *nuclei*). A nucleus is made of protons and neutrons. A *proton* is the particle that forms, alone, the nucleus of the simplest atom, hydrogen. A *neutron* is a particle of almost the same mass as the proton, with no electric charge. Of the four forces, Cham and Whiteson write, "the only one that we know for sure applies to dark matter is gravity" (*We Have No Idea*, ch. 2, "How Dark Matter Interacts").

Cham and Whiteson write that, on the simplest idea, dark matter is one new kind of particle that touches ordinary matter very weakly through a new force. Physicists try to catch a particle of that kind by filling a container with a cold compressed gas and surrounding the container with detectors that go off when dark matter bumps one atom of the gas. Other physicists look in particle colliders for collisions that make dark matter. In a later chapter Cham and Whiteson add that dark matter lacks "the same kind of pressure that resists gravity", and so dark matter keeps clumping together (*We Have No Idea*, ch. 15, "Gravity Versus Pressure"). Cham and Whiteson answer the question of what dark matter is in one sentence: "The short answer is that we still have very little idea what dark matter is" (*We Have No Idea*, ch. 2, "How Can We Study Dark Matter?"). In the same passage Cham and Whiteson write that they know dark matter is there, how much dark matter there is and roughly where, but not what kind of particles dark matter is made of, or even whether dark matter is made of particles.

On whether dark matter exists, the account I give in this book agrees with Cham and Whiteson, and I reach that answer from a separate ground: what every act of knowing must contain. On what dark matter is, the account has a definite answer, and the answer explains why dark matter shows itself by its weight alone.

Real Energy, Where It Pulls

Cham and Whiteson and I agree that the universe contains matter that has never been seen to do anything except pull by its weight. The dark matter is real energy, located where it pulls. The dark matter pulls by the ordinary law of gravity, the law Einstein gave.

The evidence for the unseen pull is older than Rubin and Ford's measurement. In 1933 the astronomer Fritz Zwicky measured the speeds of the galaxies in the Coma cluster, a great swarm of galaxies, and found the galaxies moving far too fast for the visible galaxies to hold together. Rubin and Ford found the same unseen pull inside a single galaxy. Astronomers can also weigh the unseen matter by the bending of light, with no assumption about how the unseen matter moves, and the bending of light shows the same extra weight.

Some physicists have asked whether the extra pull comes from a changed law of gravity at the edges of galaxies, not from unseen matter. The measurements show that the unseen matter is there. With a changed law of gravity, clusters of galaxies still fall short of the mass that their motions need. The oldest light is the faint glow set free when the universe was about three hundred and eighty thousand years old, and the oldest light still reaches us from every direction. The oldest light carries a pattern of warmer and cooler spots. Astronomers call the strength with which each favored size shows a *peak* of the pattern. Astronomers have measured the third peak. The third peak is higher than a changed law of gravity predicts for a universe without dark matter. In 2024 the astronomer Indranil Banik and his colleagues used measurements from the Gaia satellite, which maps the positions and motions of stars, to examine pairs of stars that orbit each other far apart. If the law of gravity were changed, the change would show itself most plainly in pairs of stars that far apart. The pairs of stars move by Newton's law. Banik and his colleagues ruled out the changed law by a wide margin. We now know that the extra pull is the pull of something that is there.

I add a reason why the dark matter must be there at all. Chapter 1 showed that every finding has a content, what is found, and a context, where the content is found, and that the context has three sides, the three settings: space, time and possibility. Chapter 1 also showed the Incommensuration Theorem. The Incommensuration Theorem applies to each of the three settings, so no setting can be perfectly even. The three settings are also distinct, inseparable and not interchangeable, and these three facts are the three clauses of the third axiom. So each setting carries a bend of its own, and the bend of one setting cannot stand in for the bend of another. Gravitation bends space. The cosmological constant bends time. The dark matter bends possibility. So two things together require the dark matter: the Incommensuration Theorem and the three clauses of the third axiom. That is, in any world where findings can be made at all, the setting of possibility has a bend.

What It Is: A Vibration of Possibility

Think of a crystal, a grain of salt or a quartz pebble. The atoms of a crystal are held in a lattice, a regular grid in which each atom is held at its own place by the pull of the neighboring atoms. The lattice can vibrate. Physicists find that the vibrations of a held lattice come in small units of definite energy, called *phonons*: each phonon is a vibration of the crystal itself, with no extra thing added to the crystal. A vibrating crystal rings, and the crystal carries energy in its ringing, but the ringing crystal holds no new stuff.

The world has a part that is held in the same way as the lattice of a crystal. To see that part, start with the word *dimension*: a dimension is one independent direction in which a thing can be placed. A point on a map needs two numbers, how far east and how far north, so a map has two dimensions. A point in a room needs three numbers, so space has three dimensions, and time adds one more. Beyond the three dimensions of space and the one of time, the world has six further dimensions, held at a size

about a hundred billion billion times smaller than a proton, far too small to see. With the three of space and the one of time, the world has ten dimensions in all.

The six further dimensions have a shape, and the shape is the shape of a range of possibilities. Picture first a choice between two answers, yes and no. Every possible state of a choice between yes and no is one point on a globe: the north pole is wholly yes, the south pole is wholly no, and every point between is one blend of the two answers. The latitude of the point says how much of each answer the blend holds. The longitude of the point is a position on a circle, like the position of the hand of a clock. The longitude says how the two answers are combined. So a choice between two answers has a range of possible states with a shape: the surface of a globe, with two dimensions. A choice among three answers has a range of possible states too, and that range has a shape of the same kind, with four dimensions. Two numbers say how much of each answer the blend holds, and two positions of clock hands say how the three answers are combined. Four of the six further dimensions have exactly the shape of the range of states of a choice among three answers, while the other two have exactly the shape of the globe of a choice between two answers. So the six further dimensions have exactly the shape of a range of possibilities. I take the six further dimensions to be the setting that Chapter 1 called possibility: the range of what could have been found instead, as the coffee in your cup could have been cold, or tea. I call the six further dimensions the *six small dimensions of possibility*.

The six small dimensions of possibility are held at one size and one shape at every place in space, as a crystal keeps one spacing of its atoms throughout. The limit of comparison is the scale that bounds how sharply any comparison made from a place can locate anything. The limit of comparison fixes the size and shape of the six small dimensions. Each direction of the six small dimensions has the size of that scale. The limit of comparison is the same at every place. The vibrations of the six small dimensions come in units of definite energy, because the six small dimensions are held, as a lattice is held.

I identify the dark matter with the lasting vibrations of the six small dimensions. I call one unit of that lasting vibration a *gyration*: a lasting vibration of the six small dimensions of possibility, and the unit of which the dark matter is made. A gyration is to the setting of possibility what a phonon is to a crystal: a ringing of the setting itself. A gyration has energy, so it has weight, and it pulls. A gyration belongs to the setting of possibility itself, while content is what is found in a setting. So a gyration is no item of content.

The gyrations were made once, at the beginning of our *epoch*: one era of the world, in which stars, galaxies and *black holes* form. A black hole is a region in which matter is packed so densely that nothing that falls in, not even light, comes back out. If a thing, once made, gives its energy to nothing and takes energy from nothing, the thing can have been made only where conditions were extreme enough for the thing to exchange energy with the rest of the world. The beginning of our epoch had conditions that extreme: at the beginning of our epoch, and only there, the six small dimensions and the large dimensions of space and time took their shape together. So the beginning of our epoch is the one place where gyrations are made. Since then the gyrations have kept their energy wherever they moved.

Each gyration is heavy. The mass of one gyration is about ten billion billion times the mass of a proton, so very few gyrations carry all the dark matter. Near the Sun there is about one gyration in every few tens of thousands of cubic kilometers. Cham and Whiteson are right that you are swimming in dark matter: the weight of dark matter is all around you. I add that the weight comes in few, very heavy units, spread thin.

Why Nothing but Its Weight Shows It

Look at the cup of coffee on your table. You know the cup is there in three ways: you see it, you feel its warmth with your hand near it, and you feel its weight when you lift it. Each of the three ways is one channel of finding, one way in which a thing can be found. Now close your eyes,

hold your hand away from the steam, and lift the cup. The weight alone tells you that the cup is there, and how much the cup holds. A thing can be found through one channel only, and a finding through that one channel is a finding all the same.

The dark matter is found through one channel only, its weight. Light, detectors and every other instrument register content, the things found in the context. The dark matter is a vibration of the setting of possibility, so no instrument registers the dark matter as a thing found. Instruments register the dark matter's pull on the things they do find: the bent light of far galaxies, and the speeds of Andromeda's clouds. The dark matter shows itself in the one way a bend of possibility can show itself in space: by pulling. Cham and Whiteson call dark matter "invisible" (*We Have No Idea*, ch. 2, "What We Know about Dark Matter"), and their word is exactly right. I give the reason: the dark matter is dark because of what the dark matter is, a vibration of the setting of possibility.

The dark matter acts on ordinary matter and on itself only by its weight, so the dark matter collides with nothing. Astronomers call the colliding pair of clusters that Cham and Whiteson describe the Bullet Cluster. In 2006 the astronomer Douglas Clowe and his colleagues mapped the mass of the Bullet Cluster by the bending of light. Clowe and his colleagues found the mass lying with the galaxies, apart from the hot gas that holds most of the ordinary matter. In 2004 the astronomer Maxim Markevitch and his colleagues had used the collision of the Bullet Cluster to set an upper limit, at a small value, on how strongly the dark matter scatters off itself. Gyrations scatter off one another only by their weight. So gyrations scatter far more weakly still: at least forty-five powers of ten below the limit of Markevitch and his colleagues. Forty-five powers of ten is a factor of a one followed by forty-five zeros.

The dark matter also lasts. A state lasts when every way out of the state is closed. A gyration has three possible ways out: into ordinary matter, into ripples of space, and into evaporation. All three ways out are closed.

The first way out, into ordinary matter, is closed because a vibration of the setting of possibility and an item of content are different kinds. The setting of possibility takes its shape only at the beginning of an epoch, so within an epoch nothing turns a vibration of that setting into an item of content.

The second way out leads into *ripples of space*: waves in the shape of space itself, which physicists call gravitational waves. To *decay* is to turn into lighter things and give them one's energy. A vibration of the six small dimensions could decay by passing its energy into ripples of space. Picture the surface of a balloon, and pair each point with the point directly opposite it, through the center. A balloon squeezed in at both poles looks the same after each point is swapped with its opposite: the pattern of squeezing at both poles keeps its sign under the swap. Now push a balloon in at the north pole and out at the south pole. After the swap, the balloon is out at the north and in at the south: the balloon has become its own reverse. The pattern of pushing in at one pole and out at the other changes its sign under the swap. Two of the six small dimensions have the shape of the globe of a choice between two answers. The laws of the six small dimensions are unchanged when each point of that globe is swapped with its opposite point. So every vibration of the six small dimensions either keeps its sign under the swap or changes its sign. Because the laws are unchanged by the swap, a single vibration that changes its sign cannot pass its energy to vibrations that keep their sign. Ripples of ordinary space keep their sign. The dark matter is the lightest vibration of the six small dimensions that changes its sign. So the dark matter has no lighter vibration that changes its sign to fall to, and nothing to decay into.

The third way out is *evaporation*: to shed mass a little at a time, as a puddle dries, until a lower level of the same kind is reached. A gyration sits at the floor of the six small dimensions, the lowest level of its kind. So a gyration has no lower level to evaporate into.

The measurements agree that the dark matter lasts. In 2016 the physicists Vivian Poulin, Pasquale Serpico and Julien Lesgourgues showed, from the history of the expansion of the universe, that the amount of dark

matter has not changed since the oldest light was released. Poulin, Serpico and Lesgourgues ruled out any decay of the dark matter with a *lifetime* (the average time a thing lasts before it decays) shorter than about a hundred and sixty billion years.

Now turn to the searches for a particle of dark matter. For decades physicists have built tanks of liquid xenon, a heavy gas cooled until it is liquid, to catch a particle of dark matter bumping into one atom of xenon. The tanks hold several metric tons of xenon and are set deep underground. The LZ experiment has the largest of the tanks. The LZ team published its results in 2025, after watching the equivalent of more than four metric tons of xenon for a whole year, and the team found no particle of dark matter. At the Large Hadron Collider, the largest particle collider, physicists have found no particle of dark matter either. The physicists in every search of this kind find nothing, because detectors register content and the dark matter is no content. For the same reason, physicists will find nothing in any future search through any channel but weight.

One gyration holds far more energy than any collider brings together. In its present run, which began in 2022, the Large Hadron Collider brings two protons together with about fourteen thousand times the energy held in the mass of one proton. Even when the collider smashes two heavy nuclei of lead head on, the collider brings together only about a million times the energy of a proton's mass. One gyration holds the energy of the mass of about ten billion billion protons, about ten trillion times more than the collision of two nuclei of lead (a trillion is a million million). So no collider makes even one gyration. Cham and Whiteson imagine that dark matter might one day be made and harnessed in colliders (*We Have No Idea*, ch. 2, "Why This Matters"). I answer that nothing within our epoch turns ordinary matter into dark matter: no process in a collider, in a star or anywhere else.

The List of Kinds Is Full

Cham and Whiteson leave open whether dark matter is made of one new kind of particle, of several kinds with a dark chemistry of their own, or of particles at all. In a separate line of argument, I start from the particles and not from the dark matter, and I reach an answer: the dark matter is no kind of particle.

Picture a hall in which every seat is numbered and every seat is taken. If a newcomer's ticket names a seat, and the newcomer differs in nothing at all from the person already in that seat, then the newcomer is no second person, because nothing could tell the newcomer apart from the person already in the seat. Chapter 1 said that the small part of the universe that is stuff is made of a closed list of kinds of particle. The closed list is like the hall: each place on the list is a numbered seat, and each kind of particle fills one seat. I derive every place on the list from what every comparison requires. Every place on the list is filled by a kind of particle already found. Chapter 4 shows why the list is closed: every comparison has three positions, every kind of matter comes three times, and a kind is told from every other kind by three things. The three things that tell the kinds apart leave no place for a new kind. Physicists ask a dark-matter particle to have mass, with no link to light and no link to the strong or the weak nuclear force. One place on the list has exactly those features, and a part of the *neutrino* already fills that place. The neutrino is the very light particle that passes through almost everything. A neutrino spins as it travels. A neutrino has two parts, which spin in opposite senses about the direction of travel, as a screw turns one way or the other. Physicists call one of the two parts right-handed. The right-handed part is the part that fills the place on the list. The neutrino's measured mass is the sign of its right-handed part, since, as I show in Chapter 6, a mass is the joining of a particle's left-handed part to its right-handed part; the right-handed part feels none of the three forces, so it is found through that mass alone. A second occupant of that place would differ in nothing from the right-handed part of the neutrino, so, like the newcomer in the hall, the second

occupant would be no second kind. So the list of kinds holds no dark-matter particle. Physicists search for a new kind of particle to account for the dark matter, but they find none.

The neutrino itself is not the dark matter. The dark matter is no content, and the neutrino is content. The measured masses of the neutrinos also show, on separate ground, that the neutrinos are not the dark matter. No two neutrinos of one kind can share one state of motion, so a small galaxy can hold only so much of a particle as light as the neutrino. The known neutrinos fall short of the mass that the faintest small galaxies would need, by a factor of at least about three hundred.

Between gyrations, as between gyrations and us, the one force that acts across ordinary space is weight. A *charge* is the property that a force takes hold of, as electric force takes hold of electric charge. The gyrations carry a charge of their own. The charge of the gyrations is taken hold of by forces that belong to the turnings of the small globe: the two of the six small dimensions that have the shape of a globe. At the strength I compute for those forces, the forces are bound tight at the size of the six small dimensions. So the forces never act across ordinary space, and therefore the gyrations build no dark atoms, no dark chemistry and no dark life.

The Scaffolding of the Galaxies

In their later chapter, Cham and Whiteson write that "it's currently believed that dark matter is responsible for galaxies forming early in the history of the universe" (*We Have No Idea*, ch. 15, "Gravity Versus Pressure"). In their words, the first galaxies came early "thanks to the invisible hand of dark matter's gravity" (*We Have No Idea*, ch. 15, "Gravity Versus Pressure"). Cham and Whiteson write that in a universe without dark matter, the first galaxies would have taken many more billions of years to form. I agree that dark matter made the first galaxies form early. For a universe without dark matter, I give a different answer: in such a universe no galaxy would have formed at all, because small excesses of density in ordinary matter alone grow too slowly.

When the oldest light went free, the ordinary matter was spread almost evenly, with differences of density of about three parts in a hundred thousand. Until then the ordinary matter had been part of the hot, glowing gas of the early universe, a *plasma* (a gas so hot that its atoms are broken into charged pieces). In the plasma, the pressure of light kept the ordinary matter ringing like sound and kept the ordinary matter from gathering. Since the oldest light went free, the distances between things have grown about a thousand and ninety times. Once matter, and no longer light, sets the pace of the expansion, a small excess of density grows in step with the distances between things. Three parts in a hundred thousand, grown a thousand and ninety times, comes to about three parts in a hundred at most, because the growth slows once the push of the cosmological constant comes to set the pace of the expansion. A region draws together into a galaxy only when its excess of density reaches about one, far above three parts in a hundred, so ordinary matter alone would have formed no galaxy.

The dark matter took no part in the ringing of the plasma and only pulled, so in the dark matter the small differences of density began to grow before the oldest light went free. The dark matter gathered into *wells*, places a little denser than their surroundings, whose extra pull draws more matter in, as water runs into a dip in the ground. Once the ordinary matter was free of the light, the ordinary matter fell into the wells of dark matter. In the wells the ordinary matter radiated away its energy, sank, and broke up into stars, while the dark matter, which radiates nothing, kept its motion and stayed spread out. So every galaxy is a bright core of stars and gas inside a larger cloud of dark matter, the galaxy's halo, and the halos gather into ever larger groups. The dark matter built the scaffolding on which the galaxies formed: the wells and halos into which the ordinary matter fell.

The gyrations build the scaffolding of the galaxies because the gyrations are perfectly *cold*, in the astronomers' sense of the word: they move so slowly that they clump on every scale, down to the smallest. Each gyration is so heavy that its own motion fades as the universe expands. If a

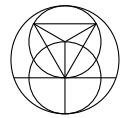
gyration set out at the beginning of our epoch at nearly the speed of light, even that gyration has moved less than a meter on its own in the whole history of the universe. So the gyrations clump, on every scale, exactly as cold dark matter clumps in the standard picture of cosmology, the account of the universe that most astronomers use. I give a new answer to what the dark matter is. But the dark matter behaves exactly as astronomers have measured, in everything astronomers can see.

The halo of Andromeda is also the reason for what Rubin and Ford saw. The clouds at the edge of Andromeda move fast because the halo of gyrations around Andromeda reaches far beyond the stars of Andromeda, and the weight of the halo holds the clouds in their orbits.

> **The short answer**
>
> The dark matter is real energy located where it pulls, made of lasting vibrations of the six small dimensions of possibility, and so no instrument will ever find it except by its weight.

The short answer names one of the two bends that Chapter 1 found in place of the unknown ninety-five percent of Cham and Whiteson: the bend of possibility. The short answer also shows that a setting can carry energy, and weigh, without being stuff in the setting. Cham and Whiteson close their chapter with "Just because it's dark doesn't mean it doesn't matter" (*We Have No Idea*, ch. 2, "Why This Matters"). I agree, and I add that the dark matter acts on everything else by its weight and in no other way.

If the dark matter is the bend of possibility, what is the bend of time, the dark energy that speeds up the expansion?



Chapter Three

What Is Dark Energy?

In which a cup dipped in the sea holds a cupful, and the largest part of the universe is found to be a share

What is dark energy, the thing pushing the universe apart?

What this chapter uses

A *comparison* is the act of finding whether two things are the same or different in some respect, and every measurement is a comparison; a *finding* is the outcome of one comparison, laid down as a record; a *comparer* is whatever makes a comparison, whether or not the comparer has a mind (Chapter 1).

The *content* of a finding is what the finding finds, as the warmth of your coffee; the *context* is where the content is found, and the context has three sides, the three settings of space, time and possibility (Chapter 1).

The three *settings* in which anything is measured are space, the place of a finding; time, the moment of a finding; and possibility, the range of what could have been found instead; a setting is *bent* when one part of the setting differs from another part (Chapter 1).

Continuous: nothing is sudden, as along a ramp; *discontinuous*: something is sudden, as at the edge of a step; *symmetric*: what is found stays the same across a change of setting, as each step of a staircase is like every other; *asymmetric*: different everywhere, as the height along a ramp is (Chapter 1).

Three things in nature do the bending: gravitation bends space, the cosmological constant bends time, and the dark matter bends possibility (Chapter 1).

On 8 February 1917, a paper by the physicist Albert Einstein was read to the Prussian Academy of Sciences in Berlin. The paper's title was "Cosmological Considerations in the General Theory of Relativity". Einstein had completed his theory of gravity two years before, and in the 1917 paper he applied the theory to the universe as a whole. Einstein held, as most scientists of his day held, that the universe stands still, neither growing nor shrinking. But Einstein's equations allowed no universe that stands still. The reason is gravity: acting alone, gravity draws any still ar-

rangement of matter together. So Einstein added one more term to his equations. The new term was a constant, the same at every place and at every time. The constant term could balance the pull of gravity and hold Einstein's universe still. Four days before the paper was read, Einstein wrote to the physicist Paul Ehrenfest in Leiden that he had done something in the theory of gravitation which "exposes me a bit to the danger of being committed to a madhouse".

When astronomers found that the universe is growing, Einstein set the constant term aside, and for about sixty years most physicists took the value of the constant term to be zero. In 1998 physicists brought the constant term back, as the simplest explanation of the largest part of the universe. Chapter 1 showed that each of the three settings in which everything is found (space, time and possibility) is bent: made uneven, so that one part of the setting differs from another. Chapter 2 showed that the dark matter is the bend of possibility. This chapter is about the bend of time, which is carried by the term Einstein wrote into his equations in the winter of 1917.

From Cham and Whiteson's pages

What Cham and Whiteson Showed

In *We Have No Idea*, the cartoonist Jorge Cham and the physicist Daniel Whiteson picture the universe as an apartment building of one hundred floors. Everything we know occupies the bottom five floors, twenty-seven floors belong to the dark matter, and sixty-eight floors belong to what physicists call dark energy. Of the sixty-eight floors of dark energy, Cham and Whiteson write: "It's the biggest chunk of reality, and we have almost no idea what it is" (*We Have No Idea*, ch. 3, opening).

Cham and Whiteson tell how dark energy was found, "quite by accident" (*We Have No Idea*, ch. 3, opening). Two teams of astronomers set out to measure how fast the expansion of the universe was slowing down. To the astronomers' surprise, the two teams found that the expansion is speeding up.

Cham and Whiteson then ask what dark energy could be. One currently popular idea, they write, is that dark energy comes from the energy of empty space. *Quantum mechanics*, also called quantum theory, is the physics of the very small: of atoms, of light, and of the particles that matter is made of. Cham and Whiteson call the idea of the energy of empty space "a surprisingly reasonable explanation", because in quantum mechanics it is quite natural for empty space to have an energy of its own (*We Have No Idea*, ch. 3, "What Could Dark Energy Be?"). Cham and Whiteson name one problem with the idea: the size of the energy. When scientists calculate from quantum mechanics how much energy empty space should have, the answer is too big, by a factor that Cham and Whiteson put between ten to the sixty and ten to the hundred.

A *field*, in physics, is something spread through all of space whose smallest ripples are the particles. Light, for example, is the ripple of one field. Cham and Whiteson tell of other ideas for dark energy: new forces, or new fields that fill space, and in some of these ideas the new fields change with time. Cham and Whiteson find all of the new forces and new fields difficult to test. Cham and Whiteson conclude: "Dark energy could almost literally be anything" (*We Have No Idea*, ch. 3, "What Could Dark Energy Be?"). Cham and Whiteson put the conclusion more plainly still in their second book, *Frequently Asked Questions About the Universe*: "'dark energy' is simply the term we use to describe the increasing expansion of the universe" (*Frequently Asked Questions About the Universe*, ch. 18, "Space-Bending Warp Drives").

Cham and Whiteson give a message in three parts, in their own terms. The speeding up is a measured fact. "Dark energy" is the name of the cause of the speeding up, and Cham and Whiteson have almost no idea what the cause is. And when scientists calculate the popular candidate for the cause, the energy of empty space, the answer comes out far too big.

The enormous computed figure is the size of the whole energy of empty space. What a measurement takes in is a share of the whole.

I agree with every measured fact that Cham and Whiteson report. I also agree with the popular idea of what dark energy is: the energy of empty space. I part from Cham and Whiteson on the size of that energy.

Faster, Not Slower

Throw a ball upward, and the ball slows as it rises, because the Earth pulls the ball back. For most of the twentieth century, astronomers expected the expansion of the universe to slow the way the ball slows, because every galaxy pulls on every other galaxy as the Earth pulls on the ball. Astronomers took the pull of the galaxies on one another as a brake on the expansion. The only question seemed to be how hard the brake was pressing.

In the 1990s two teams of astronomers set out to measure the braking of the expansion. The two teams used one sort of exploding star, the type Ia supernova. A type Ia supernova blows itself apart with very nearly the same true brightness every time. Every type Ia supernova is therefore a *standard candle*: a lamp of known brightness, whose faintness as seen from Earth shows how far away the star is, as the faintness of a known lamp shows how far down the road the lamp stands. One team was led by Saul Perlmutter at the Lawrence Berkeley National Laboratory. The other team was led by Brian Schmidt at the Australian National University. Adam Riess was the lead author of the paper that Schmidt's team published in 1998.

The distant supernovae were too faint for a slowing universe: in the 1998 paper, Schmidt's team reported that, on average, the distant supernovae were ten to fifteen percent farther away than a slowing universe would put them. Perlmutter's team measured forty-two distant supernovae and published its paper in 1999. Perlmutter's team found the same thing: the distant supernovae were farther away than a slowing universe would put them. In 2011 Perlmutter, Schmidt and Riess shared the Nobel Prize in Physics for the discovery that the expansion of the universe is speeding up.

We now know how the expansion has changed over the whole history of the universe. For the first seven or eight billion years, the expansion slowed, braked by the pull of matter. Since then the expansion has sped up. The expansion changed from slowing to speeding up because matter and the energy of empty space thin out differently as space grows. Matter thins as space grows, because a fixed amount of matter is spread through more room. The energy of empty space stays the same in every cubic meter. Every new cubic meter of space holds as much energy of empty space as every old cubic meter. So, as the universe grows, the energy of empty space comes to outweigh the matter, and from then on the expansion speeds up.

In Einstein's equations, the cosmological constant is the term that carries the energy of empty space. Chapter 1 named the cosmological constant as the bend of time. The cosmological constant is the same everywhere and at every time of our epoch, the era of the world in which we live (Chapter 2 called each era of the world an epoch). The cosmological constant is what astronomers call dark energy.

The shape of our space explains why the cosmological constant counts as a bend of time. On the largest scale our space is *flat*: lines that start out parallel stay parallel. A flat space has no bend. So on the largest scale, the whole bending lies in how the universe runs from one time to the next. The bending of time increases the distance between every pair of distant places.

Empty Space Hums

Pump all the air out of a jar, and the jar holds what people call nothing in everyday life. Physicists find something in the jar. The particles of the world are the ripples of fields, and the field of light is one of those fields. Every field that makes up the particles keeps a small quiver that cannot be stilled. The quiver remains even when the field is as quiet as a field can be. The *vacuum* is empty space at its lowest energy: every field at its quietest, with no particles present. The quiver carries energy, and physicists call the quiver the hum of the vacuum.

Physicists have measured one effect of the hum. In 1948 the Dutch physicist Hendrik Casimir computed that two flat metal plates, set parallel and very close together, are pressed toward each other. The plates are pressed together because the field of light between the plates can vibrate only in the ways that fit the gap, while the field of light outside the plates can vibrate in every way. In 1997 the physicist Steve Lamoreaux measured the push between a flat plate and a gently curved plate, and the push he measured was within about five percent of the value computed. The hum of empty space is real.

Now add up the hum of every field, at every frequency, down to the smallest length at which our present theories still apply. The smallest length is about the size that Chapter 2 gave the six small dimensions of possibility (the six further dimensions of the world, beyond the three dimensions of space and the one dimension of time). The smallest length and the six small dimensions are both about a hundred billion billion times smaller than a proton. The sum gives each cubic meter of empty space about ten to the one hundred twenty-three times more energy than the sky shows a cubic meter of empty space to hold. Ten to the one hundred twenty-three is a one followed by one hundred twenty-three zeros: the number takes about two minutes to write out, typed at one digit a second. Different ways of doing the sum give different enormous figures.

Every way gives a figure vastly larger than the figure the sky shows. Physicists have long called the gap between the sum and the sky the worst numerical prediction that a successful theory has made.

A Cup Dipped in the Sea

Take your cup of coffee from the table, empty the cup, and carry the cup down to the sea. Dip the cup in the sea. The cup is real, and what the cup holds is real sea water. You can taste the salt, feel the cold, and see the small creatures swimming in the water. From one cupful you can learn a great deal about the sea. And the cup holds a cupful, never the whole sea.

A measurement of empty space is in the cup's position, with one difference that puts the measurement still further inside. The cup is made of something other than the sea, but the measuring instrument is made of the very fields whose hum the instrument measures. So the instrument has no place outside the fields to measure from: the instrument is a cupful of the sea trying to know the rest of the sea, with no boat to stand in.

The instrument is also joined to the fields it measures, as two dancers in a close dance are joined. Much of what a dance is lies in how each dancer moves in answer to the other dancer, and watching one dancer, however closely, shows none of the part of the dance that lies in the answering. The instrument is like one dancer, and the vacuum is like the other dancer. The joining between the instrument and the vacuum holds a part of what could be known about the vacuum, and neither the instrument alone nor the vacuum alone holds that part. Every instrument is joined to the vacuum in the same way, so no better instrument can measure the part that lies in the joining. The instrument and the vacuum together make one system, and a system cannot fully measure itself.

This book is called *A Cup of the Sea* after the cup's position: the position of a measurement made from inside the world being measured, by an instrument that is part of that world. Every finding in science is made from inside the world, and for most measurements being inside changes almost nothing: a thermometer is a tiny part of the room whose warmth the ther-

mometer measures. A measurement of the energy of empty space is wholly inside the thing measured. The reason is that the instrument is made of the very fields whose energy the instrument measures. A cup dipped in the sea holds a cupful, and a measurement of the vacuum's energy holds a share of that energy, never the whole.

A *degree of freedom* is one independent way in which something can hold energy or vary, as each string of a piano can ring on its own. The vacuum holds its energy in a vast number of independent ways, and each independent way is one degree of freedom of the vacuum. Within everything we can see, the vacuum has about ten to the one hundred twenty-three degrees of freedom. A measurement takes in a few of the vacuum's degrees of freedom, never all of them at once.

The first answer of this chapter follows from the picture of the cup. The first answer is about the enormous sum of the hum. The vacuum's total energy is real, and the total is of the size computed from quantum theory. But the total bends no space at all.

Recall what bends space, to see why the total bends no space. Chapter 1 showed that gravitation, the bending of space, is the response of space to matter. In Einstein's equations space responds to energy: the energy of matter, of light and of moving particles alike, and more energy means more bending. I identify energy with the rate at which findings (the outcomes of comparisons, each laid down as a record) can be made: the more that can be found of a thing in a given time, the more energy the thing holds. A rock on a shelf bends the space around it, even while nothing about the rock changes. The rock bends space because so much could be found of the rock: every atom in the rock could be found, and found again.

Press a finger into the stretched sheet of rubber from Chapter 1, and the dent is deepest under your finger, while the sheet is pulled for a long way around the finger. Space bends the way the rubber sheet bends. The bending of space starts where findings can be made, as the dent starts under the finger, and the bending is in proportion to how many findings can

be made at that place. From each place where findings can be made, the bending spreads outward, as the pull spreads across the sheet. So space is bent only by what can be found by a comparison.

The vacuum's total energy, taken as a whole, is found by no comparison, for two reasons. The first reason is the picture of the cup. Every measurement takes in a few of the vacuum's degrees of freedom and never all of them. The second reason is the shape that the total would have if the total were taken whole. Taken whole, the total would be the same at every place and the same for every instrument moving steadily at any speed, and the total would have no break anywhere. So the total, taken whole, would be perfectly symmetric (the same across every change of setting) and perfectly continuous (with nothing sudden anywhere) at once. The Incommensuration Theorem of Chapter 1 says that nothing found by a comparison is both perfectly symmetric and perfectly continuous at once. So the vacuum's total is never found whole by a comparison, and therefore the total bends no space.

Physicists have looked for something that would cancel the enormous sum almost exactly, leaving only the small amount that the sky shows. On the account in this book, the sum needs no cancelling, because the total never bent space. The gap came from comparing the sky with the total, which no measurement could find. Comparing the sky with the total is like comparing a cupful of water with the whole ocean, and being astonished that the cup holds so little. A much smaller question remains: how much does the cup hold?

The Share We Find

I identify the cosmological constant with the share of the vacuum's energy that a measurement made from inside the vacuum can take in, and not with the vacuum's total energy.

Picture the edge of everything we can see as a vast surface around us, tiled like a floor: the tiles give the size of the share. The edge I mean is the *particle horizon*: the edge of everything whose light has reached us. Light

from the particle horizon set out near the beginning of our epoch. Space has stretched while the light traveled, so the particle horizon is now about forty-six billion light-years away. An astronomer can draw many edges around us, and the particle horizon is the only one of them drawn by what has actually reached us. So the particle horizon is the edge of what a measurement made here and now holds.

Each tile on the particle horizon represents one degree of freedom of the vacuum inside the horizon. In the 1970s the physicists Jacob Bekenstein and Stephen Hawking found a rule that counts the tiles on the edge of a black hole. Chapter 2 explained that a black hole is a region from which nothing that falls in comes back out. The rule of Bekenstein and Hawking says that the count of tiles on an edge grows with the area of the edge: there is one tile for each tiny patch of one fixed size, far smaller than a proton. In 1998 the physicists Willy Fischler and Leonard Susskind applied the rule of Bekenstein and Hawking to the edge of what we can see. For our particle horizon, the count of tiles is a little over two times ten to the one hundred twenty-three.

The size of the share follows in three steps. First, every tile holds an equal part of the vacuum's energy. The vacuum is the same at every place, and the tiles are laid at one fixed size over the whole particle horizon, so no tile differs from any other tile. A cake cut into equal slices gives three slices' worth to whoever takes three slices: the cake is the vacuum's energy, and each slice is the part that one tile holds.

Second, a measurement registers three kinds of content (content is what a finding finds), one kind in each of the three settings (space, time and possibility). Chapter 1 showed the three kinds of content with three ordinary findings: a map, a push and a forecast. A map is a pattern laid out in space, a push is a force acting over a time, and a forecast is a probability spread over what could happen. A setting is where a content is registered, as a page is where a word is written. So a setting is no further kind of content of its own, as the page is no second word.

Third, each kind of content takes in one whole tile, and each kind takes in a different tile. I hold that each kind takes in exactly one tile, because content comes whole, in steps, like the steps of the staircase in Chapter 1. No two kinds of content take the same tile, because the three kinds are distinct and no kind can take the place of another. Chapter 1 said the same of the three settings in which the three kinds are found: the settings are distinct, and no setting can take the place of another. So a measurement takes in three tiles out of the whole count of tiles. The measurement receives the energy that the three tiles hold.

The total energy that the tiles share is the hum of all the fields, less a small trim. The six small dimensions of possibility are small and curved tight, as Chapter 2 described. A curved shape stores energy, as a sheet of spring steel rolled into a tight coil stores energy in its curve, and the curve of the six small dimensions stores energy in the same way; nothing curled them from a larger size, as I show in Chapter 11. The stored energy draws space together, so the stored energy subtracts from the total of the hum. The trim is the amount subtracted, and the trim is about twelve percent of the total of the hum.

Take what is left of the hum after the trim, divide the remainder among all the horizon's tiles, and keep three tiles' worth. Three tiles' worth is a density of energy within two percent of the density that astronomers measure. Without the trim the share would come out about fifteen percent too large. Taken at face value, the sum from quantum theory missed the density that astronomers measure by a factor of ten to the one hundred twenty-three.

The size of the share also fixes the size of the gap. Three tiles are about one part in ten to the one hundred twenty-three of a count of ten to the one hundred twenty-three tiles, and one part in ten to the one hundred twenty-three is also the gap that the sum of the hum produced. So the cosmological constant is small because what we can see is large: the smallness of the cosmological constant is the largeness of what we can see, counted in tiles.

Two Ways to One Number

Two people set out to find the height of one tree: one climbs the tree with a tape, and the other measures the tree's shadow. The two people measure one tree, so their answers must agree. The agreement of the two answers can tell the two people something that neither person found alone.

The energy of empty space can be found in two ways. The two ways must agree, as the two measurements of the tree must agree. The first way is the share: three tiles' worth of the trimmed total. The share depends on the strength of gravity, which sets the total, and on the distance to our horizon, which sets the count of tiles.

The second way is the astronomers' way. In 1922 the physicist Alexander Friedmann found from Einstein's equations that, in a flat universe such as ours, the rate of expansion fixes how much energy the universe holds in all. Picture the universe's total energy as the pie of Chapter 1: the matter is one slice, the energy of empty space is another slice, and light is a thin sliver. In the astronomers' way, the energy of empty space is its own slice of the total that the rate of expansion fixes.

Measure the distance to our particle horizon in a unit that the expansion itself sets: the distance at which the expansion carries things away from us at the speed of light. Our particle horizon is a little over three units away, in the unit that the expansion sets. The number of units depends only on how the pie has been divided over the history of the universe, because the division of the pie in each era set how much the path of the light was stretched in that era.

When the share and the astronomers' slice are set equal, the strength of gravity and the rate of expansion cancel. One relation is left, in pure numbers (numbers with no units), and I call that relation the *identity*. In words, the identity says: the square of the distance to the particle horizon in the unit that the expansion sets, times the slice of the pie held by the energy of empty space, equals eight minus a fraction, three divided by pi, and the result is about seven. On the left of the identity, the distance and

the slice depend only on how the pie is divided. In a flat universe, one number fixes how the pie is divided: the matter slice. So the identity is one equation for the matter slice alone. Solving the identity gives about thirty-one percent matter, which leaves about sixty-nine percent to the cosmological constant. The Planck satellite mapped the oldest light in the sky, the light set free in the early universe and now a faint glow of microwaves. In the results of 2018, the Planck team measured the matter slice from the Planck map at thirty-one and a half percent.

One Number for Our Whole Epoch

Picture a map with its scale printed in one corner: one inch to one mile. The scale belongs to the whole map at once. If a map's scale changed from corner to corner, the map would not be a single map.

The cosmological constant is the scale of the one space and time of our epoch: like the scale of the map, the cosmological constant is one number that belongs to the whole of our epoch's space and time at once. Einstein's equations require strict bookkeeping of energy and of momentum (the amount of motion): as the universe changes, energy and momentum are moved from place to place, and neither is made or lost. If the constant term varied from place to place, or from one time to another, the term would break the bookkeeping exactly where the term varied. So, within one *geometry* (one shape of space and time, such as our epoch has), the cosmological constant is one number.

The particle horizon grows every year as light from a little farther away arrives, so the count of tiles grows too, and the share is three tiles out of a growing count. Even so, the cosmological constant stays one number, because one measurement fixes its value: the measurement made now, at the present particle horizon. We piece together every picture we have of the past from the light and other traces of the past that we receive now. So a history built from the present measurement has the one present value of the cosmological constant at every time of our epoch, after the present as well as before the present.

Think of a full deck of playing cards: the deck holds exactly fifty-two cards, and a fifty-third card would need a fifth suit. The kinds of particle form a full deck, as the playing cards do. A kind is a sort of particle whose every member is found exactly like every other. The full list of the kinds of particle contains one field that fills all of space with a settled value: the Higgs field, which gives the particles their masses. Chapter 5 names the settled value of the Higgs field the condensate. Physicists have calculated how the early universe behaved. The calculations report that the Higgs field took its present value long before the expansion began to speed up. The energy of the Higgs field has been constant since then. So the speeding up is driven by the constant term, and by no new field whose energy drifts with time. The Planck team published its final analysis in 2020, and in the final analysis the team combined its map of the oldest light with measurements of the spacing of galaxies and of the supernovae. The combined measurements found the dark energy behaving as an unchanging density behaves, to within about three percent.

Cham and Whiteson write that because they do not know what drives the speeding up, they have "almost no way to predict what it will do in the future" (*Frequently Asked Questions About the Universe*, ch. 12, "The Big Crunch"). The speeding up could even reverse, they say, into a Big Crunch, in which the universe falls back on itself. Once the cause of the speeding up is identified as the cosmological constant, the future course of the expansion is fixed. The cosmological constant is one number for our whole epoch, so the push of the cosmological constant stays the same: the push never turns into a pull, and the push never grows strong enough to tear bound things such as planets and galaxies apart. Measurement agrees. The map of the oldest light, joined with the spacing of galaxies and with the supernovae, finds the push of empty space behaving as one unchanging number, to within about three percent. Since 2024, one family of combined analyses, which joins the galaxy maps of the Dark Energy Spectroscopic Instrument with the supernovae, has reported a push that changes slowly over the history of the universe. In the appendix "What the Coming Measurements Will Find", I say what the coming measure-

ments will find: one number, the same in every era of our epoch. Chapter 29 follows the course of the expansion to the end of our epoch, when the sky empties and the emptying ends in a turn that begins the next epoch.

Why Now?

Cham and Whiteson point out that the speeding up began only about five billion years ago (*We Have No Idea*, ch. 3, "What Could Dark Energy Be?"). They also observe that we seem to live at a special moment, when the pull of gravity and the push of dark energy "seem to be perfectly balanced" (*We Have No Idea*, ch. 15, "How Did It Get This Way?"). Physicists put the puzzle of the special moment as a question about two amounts: the amount of matter and the energy of empty space. Matter thins as the universe grows, and the energy of empty space does not thin. So for most of the history of the universe, the two amounts were wildly different. Today the two amounts are of similar size: thirty-one percent matter and sixty-nine percent energy of empty space. Why are the two amounts of similar size now?

On the account in this book, the puzzle has three parts, and each part has its own answer. The first part is how far our universe has come in its growth. A universe holding only the energy of empty space grows by a fixed factor, about two and three quarters, in each span of time of one fixed length, called its growth time. The factor of about two and three quarters is the number mathematicians call e, the natural measure of steady growth. The present age of our universe follows from the division of the pie that the identity fixes, and the present age of our universe comes to about four fifths of one growth time. The measured age of the universe is about 13.8 billion years. The Planck measurements give a growth time of about seventeen and a half billion years. Divide the measured age by the measured growth time, and the ratio agrees with the ratio from the identity to within one percent.

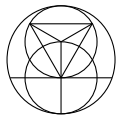
The second part is the date itself, about 13.8 billion years after the beginning. The date is a fact about the content of the world: a fact about when measurers exist. We read the date from the world as we find the world.

The third part is the question why our measurement falls in the one era in which the identity holds, of all the eras in which measurers could be. Whoever asks the third question pictures every era laid out at once, with us placed in one of the eras. On the account in this book, only the present act of measuring is given, and we piece together the history of every era afterward, from the evidence that we receive in the present act of measuring. So the nearness of the two amounts today is the identity itself: the identity holds in the era of the present measurement, and the present measurement fixes the cosmological constant.

> **The short answer**
>
> Dark energy is the cosmological constant, the share of the energy of empty space that a measurement made from inside takes in, one number for our whole epoch, and its smallness is the largeness of what we can see.

The short answer says what the bend of time is, and the short answer is also the reason for this book's title: a cup dipped in the sea holds a cupful, and a measurement made from inside the vacuum holds a share of the vacuum's energy. Now that the dark matter and the dark energy are both named, two of the three bends of the settings make up the ninety-five percent of Cham and Whiteson's pie: the bend of time and the bend of possibility.

The ninety-five percent is two bends of the settings. What, then, is the remaining five percent made of, at bottom, and why does the five percent hold extra kinds of particle that nothing we are made of uses?



Chapter Four

What Is the Most Basic Element of Matter?

In which every finding is shown to have three positions, every kind of matter comes three times, and the list of kinds is closed

What is the most basic element of matter, and why are there extra particles nobody needs?

> What this chapter uses
>
> A *comparison* is the act of finding whether two things are the same or different in some respect, and every measurement is a comparison; a *finding* is the outcome of one comparison, laid down as a record; a *comparer* is whatever makes a comparison, whether or not the comparer has a mind (Chapter 1).
>
> The *content* of a finding is what the finding finds, as the warmth of your coffee; the *context* is where the content is found, and the context has three sides, the three settings of space, time and possibility (Chapter 1).
>
> Three things in nature do the bending: gravitation bends space, the cosmological constant bends time, and the dark matter bends possibility (Chapter 1).

Joseph John Thomson was professor of experimental physics at Cambridge. On the evening of Friday, 30 April 1897, Thomson spoke about cathode rays at the weekly evening meeting of the Royal Institution in

London. Cathode rays are the glow that streams from the negative metal plate of a glass tube from which nearly all the air has been pumped. For decades physicists had argued over what cathode rays were: a wave of some kind, or a stream of particles. Thomson had filled his tube in turn with hydrogen, with air, with carbonic acid and with the vapor of methyl iodide. The densities of the four gases differ by about seventy times. In each gas Thomson had photographed the path along which a magnet bent the rays. The paths were the same in every gas. So whatever gas the rays came from, the particles that carried the rays were the same. Thomson had also measured how much mass the particles carry for each unit of their charge. The ratio came out about six hundred times smaller than the same ratio for an atom of hydrogen, the lightest atom known. So either the particles were far lighter than any atom, or each particle carried a far larger charge than an atom of hydrogen carries. Thomson chose the first answer, that the particles were far lighter than any atom, and he said himself how strange that answer was: "The assumption of a state of matter more finely subdivided than the atom of an element is a somewhat startling one". Thomson proposed that the atoms of every element are built from very small particles, all alike. He gave the particles a name: "We shall call such particles corpuscles". Today we call Thomson's corpuscles electrons. Every particle of the cathode rays was an electron, the same thing whatever gas the particle came from.

From Cham and Whiteson's pages

What Cham and Whiteson Showed

In *We Have No Idea*, Jorge Cham and Daniel Whiteson begin their answer to this chapter's question with a triumph of physics. Everything we can see or touch is built from atoms. Every atom is built from protons, neutrons and electrons, and every proton and every neutron is built from two particles that Cham and Whiteson call the up quark and the down quark. So the long list of everything in the world comes down to three particles: the up quark, the down quark and the elec-

tron. Cham and Whiteson call the view that a few particles build everything the Lego philosophy: a few sorts of block, put together in different ways, build stars, rocks, ice cream and llamas. Then they ask why the world should be built from a few blocks at all, and they answer: "As far as we know, there is no reason why such a simplification is even possible" (*We Have No Idea*, ch. 1).

The puzzle grows when Cham and Whiteson set out the whole table of the particles of matter. Physicists have found twelve particles of matter: six quarks and six leptons. In Chapter 1 we met the quarks as the particles that, bound together, build the core of every atom. The quarks are the particles of matter that feel the strong force, the force that binds the inside of a proton. A *lepton* is a particle of matter that does not feel the strong force, as the electron does not. Three of the twelve particles build everything around you, and Cham and Whiteson ask about the other nine: "So what are the other nine particles for? Why are they there? We have no idea" (*We Have No Idea*, ch. 4, opening). Cham and Whiteson compare the nine extra particles to nine ingredients that a baker finds unused after the cake has been baked and tasted. In their picture, the cake is everything around you, and the nine unused ingredients are the nine particles that everything around you does without.

Cham and Whiteson also tell what the table does show. The columns of the table repeat. Each column holds particles with the same charges and the same forces as the particles of the first column, and only the masses differ. Cham and Whiteson call each column a generation, and the table has three generations. They report that the discovery of the Higgs boson ruled out a fourth generation (*We Have No Idea*, ch. 4, "What Are All These Particles For?"). The Higgs boson is the particle of the Higgs field. In Chapter 3 we saw that a field is something spread through all of space whose smallest ripples are the particles. We also met the Higgs field in Chapter 3. The Higgs field fills all of space with a settled value and gives the quarks and the electron their

masses at rest. Chapter 6 describes how physicists at CERN found the Higgs boson in 2012, and shows that most of your own weight comes from the binding of quarks and not from the Higgs field. Cham and Whiteson write that physicists have no good explanation of why the number of generations is three. They add that physicists cannot say how many kinds of particle there are in all. Cham and Whiteson weigh three answers to the question of why the extra particles exist. The first answer is that the list of particles is simply the bottom of matter, long for no particular reason. Cham and Whiteson think the second answer probably right: the particles we know are built from smaller particles not yet found, as atoms turned out to be built from smaller particles. The third answer is that the heavy particles seem useless only because the universe is now cold and large (*We Have No Idea*, ch. 4, "What Is the Most Basic Element of Matter?").

Cham and Whiteson add one more fact in their second book, *Frequently Asked Questions About the Universe*. In a chapter on what makes you the person you are, Cham and Whiteson note that no electron in you is special: "From the point of view of physics, all electrons are the same" (*Frequently Asked Questions About the Universe*, ch. 13, "A You Beyond You"). Swap every electron in your body for a fresh electron, put each fresh electron where the old one was, and nothing about you changes.

Cham and Whiteson have now given us three facts and three questions. The three facts are that three particles build ordinary matter, that the table of the particles of matter has three columns, and that every electron is the same as every other electron. The three questions are why there are so few building blocks, why there are extra columns, and whether the known particles are built from smaller pieces not yet found.

I take the three questions as one question, the question in this chapter's title, because my account has one answer to all three, from one ground: what every comparison must contain.

Every Electron Alike

Start with the fact that Cham and Whiteson share with Thomson: every electron is the same as every other. Later in 1897 Thomson published a paper, "Cathode Rays", in the *Philosophical Magazine*. In the paper Thomson reported that the ratio of mass to charge came out the same whatever metal the plate was made of, as well as whatever gas filled the tube. Since 1897 physicists have found the electron leaving metals struck by light, bound in every atom, and arriving in every detector, and every electron they find is the same as every other. Every snowflake is found a little different from every other snowflake. Each snowflake differs because it grew in its own way on its own path through the cloud. Two electrons are always found exactly alike, even when one was made in a laboratory this morning and the other in the first second of our history. An electron carries no trace of where it came from.

I use one word for a sort of particle whose members are exactly alike, as the electrons are. A *kind* of particle is a sort of particle whose every member is found exactly like every other: the same mass, the same charge, the same behavior, wherever and whenever the member is found. The electron is a kind. The snowflake is not a kind in this book's sense, because no two snowflakes are found alike.

I draw a consequence from the fact that every electron is the same: no two electrons are ever found in one state. The consequence needs nothing but the act of comparing. In Chapter 1 we saw that a *comparison* is the act of finding whether two things are the same or different in some respect, and that every measurement is a comparison. The ground of the consequence is one principle: what no comparison can tell apart, in any respect at all, even in principle, is one thing and not two. Every electron has *spin*, a built-in amount of turning, like a top that never runs down. The

spin of an electron points one way or another. We tell two electrons apart by where each one is, how each one moves and which way its spin points. Place, motion and direction of spin together make up the state of an electron. In everything else two electrons are alike. If two electrons were in one state, nothing at all could tell the two apart, so the two would be one electron. Save a letter on a computer under one name in one folder, then save an identical copy under the same name in the same folder, and afterward the folder holds one file, because nothing tells the second copy from the first copy. The two copies are like two electrons, and the one name in the one folder is like one state. So no two electrons are ever found in one state. The physicist Wolfgang Pauli found the same rule in 1925: no two electrons share one state. Pauli found the rule as the rule that orders the electrons of every atom. I make the same argument: Pauli's rule follows from the sameness of the electrons alone, with no further law. In Chapter 1 we named the two sides of every finding: the content of a finding is what the finding finds, and the context is where the content is found. Every electron is the same content, found in different contexts.

Three Positions in Every Finding

Now look at your cup of coffee. The coffee is there on the table, and you see its color. Three things are present when you see the color. First, light passes from the coffee to your eye: the passing light is the act by which you see the color. Second, you take in a color, dark brown with a lighter rim: the color is what is found. Third, the cup holds more than you see: the coffee below the surface, the warmth of the coffee and what the coffee is made of are all there, and all of them are beyond the one look you took.

Every comparison has three positions like the three things at your cup, and each position has a name. The first position is the *act of comparing*: the relating, the bringing of two things into relation. The second position is the *thing compared*: what is known, the thing the instrument reports. The third position is the *thing compared against*: what the act reaches toward

and never contains in one act, the beyond. At your cup, the passing light is the act of comparing, the color you see is the thing compared, and the coffee beyond your one look is the thing compared against. Place two stones side by side to see which is heavier, read a thermometer, or hold a color card against a wall: in every case the three positions are present. The three positions differ from one another, none can stand in for another, and every comparison has all three.

I take the next step, and with that step I answer Cham and Whiteson's "no reason why". I ask what a world must contain for any comparison to happen in it, and I find one particle for each position of comparison. At the scale at which we measure, every comparison is made with light, and at that scale the *photon*, the particle of light, is the act of comparing: two charged particles act on each other by exchanging photons. The electron is the thing compared: the electron is what every detector registers, the unit in which every report is given. The proton is the thing compared against: the heavy object, built of parts, that the comparison reaches toward and never contains in one act. I call the photon, the electron and the proton the *carriers*: they are the three positions of comparison, present in the world as particles.

Each carrier has the character that its position requires, and I argue for each character in turn. The act of comparing is separate from the two things that the act relates (the thing compared and the thing compared against), so the photon carries no charge. The act of comparing is not a lasting pattern, so the photon has no mass at rest. The photon always travels at the greatest speed the world allows, because the photon has no mass at rest. The thing compared must serve as a unit, and a unit must have a fixed mass and a fixed charge, so the electron has a fixed mass and a fixed charge. The electron's charge is the whole unit in which every other charge is counted. The thing compared against is the other side of the pair that it forms with the thing compared. So the proton's charge is opposite to the electron's charge. The beyond also has an inside, open to a finer comparison, so the proton is heavy and built of parts.

Its conclusion about the carriers in one sentence: "The three carriers are the minimum cost of admission for a world in which anything can be known". In plain words, any world in which anything can be known must have at least the three carriers. So the simplification that Cham and Whiteson celebrate has a reason. The world reduces to a few building blocks because every comparison, in any world, has three positions, and each position needs one carrier.

Cham and Whiteson's three building blocks are the up quark, the down quark and the electron. The three carriers of my account are the photon, the electron and the proton. The two lists are connected in three ways. First, the electron is in both lists. Second, the up quark and the down quark are the inside of the proton: the beyond is exactly what is open to a finer comparison, and when physicists opened the proton they found the quarks. Third, the photon is in my list because the photon is the act of comparing. In Cham and Whiteson's table the photon is listed among the force particles.

Why the Electron Shows No Inside

The three positions of comparison also contain the answer to one of Cham and Whiteson's questions about the smallest pieces. The proton has an inside, and the electron shows no inside. The reason comes from the electron's position: the electron is the unit of measurement, and one does not measure the unit itself by opening it up. The proton, the beyond, is the thing that is open to a finer comparison. The story of the quarks is the story of how physicists opened the proton.

The measured record agrees: physicists have found no internal structure in the electron at any resolution yet reached. Cham and Whiteson report the same record: no collider (the machine that drives particles together at high energy), the largest included, has found smaller parts of the electron or of the quarks (*We Have No Idea*, ch. 16, "The Smallest Particles").

Why the Other Nine Are There

The nine extra particles are the nine of the twelve particles of matter that ordinary matter does not use. Picture a pencil with three flat faces, lying in a groove with one face up. Turn the pencil one step and a different face is up, and the groove has not moved. Turn the pencil twice more and the first face is up again.

Every particle of matter can be read (found in a comparison) in three respects, and each respect belongs to one position of comparison. The first respect belongs to the act of comparing, which joins a point of view to what the point of view looks at: in the first respect, the particle is read as an object, seen from a point of view. The second respect belongs to the thing compared, which is known by what it shares with other things and where it differs from them: in the second respect, the particle is read as the same as other things, or as different from them. The third respect belongs to the thing compared against, the whole that holds more than any one look: in the third respect, the particle is read as content, within the context where the particle is found. In every comparison the three respects come in one order: first a point of view and something seen from it; then sameness and difference; then the thing within its context.

A single act of comparing reads a particle in one respect at a time, because one reading is one comparison in one respect. In the picture of the pencil, the respect that faces the act of comparing is the face that is up. When a particle is turned so that another respect faces the act, while the position stays where it is, I call the turn a *rotation of the content*. In a rotation of the content, the content is the particle of matter, because content, as Chapter 1 said, is what a finding finds. For particles, the picture of the pencil needs one change. Each face turned up is a separate particle: the groove holds three pencils in turn, one pencil for each face. Each of the three pencils is one *instance* of the position: one particle that fills the position, with one respect facing the act.

Every particle of matter holds all three respects at once. None of the three respects can stand in for another, just as none of the three positions can. So each respect faces the act in an instance of its own. Two instances read through different respects are two particles, because a comparison can tell the two instances apart. So the position of the electron is filled three times. The first particle in the position is the electron itself, read by its charge, with the first respect facing the act. With the second respect facing the act, the position holds a particle with the same charge, the same spin and the same forces as the electron, and only a greater mass: the *muon*, about two hundred times the electron's mass. With the third respect facing the act, the position holds the *tau*, about three and a half thousand times the electron's mass. I describe the muon in four words: "The electron one turn on".

A *generation* is one of the three instances of a position: every kind of matter occurs three times, alike in charge and in every force, and differing in mass. Cham and Whiteson's three columns are the three generations, the pencil's three faces turned up in turn. Every kind of matter comes in three, as the electron does. In Chapter 2 we met the neutrino, the very light particle that passes through almost everything. The neutrino is the electron's uncharged partner, and the neutrino comes in three. The quarks come in three pairs: up and down; charm and strange; top and bottom. Only matter comes in three generations. The reason is that a rotation of the content makes a new instance, and only matter comes in separate instances, counted one by one. Light, the act of comparing, has no fixed charge or mass of its own, and so light has no respect to turn toward the act. The weak force is the feeble force we met in Chapter 2, and the weak force turns one kind of quark or lepton into another. The strong force and the weak force have force particles too. Each force particle is a smallest ripple of a field whose instances are not separate from one another. Each field of a force shows all three respects at once, as one continuous field, so the force particles come in one generation only.

Why are the second and third instances of each kind of matter heavier than the first instance? Picture three descriptions, each taking in more than the one before: "a penny"; "a penny like this one, but newer"; "every penny this one could have been". The three readings of a particle grow in the same way, each reading taking in more than the reading before. The first generation is read by the least that a reading of matter can hold: its fixed charge and the mass it has at rest, nothing more. The second generation is read as the same as the first generation and as different from the first generation. The second generation agrees with the first in charge, in spin and in every force. So the difference between the two generations lies in the one thing left, the mass. The third generation is read within its context. So the reading of the third generation takes in every instance its content could be: the first two instances, and more. The last step of the answer: what a reading holds beyond the fixed charge and the mass at rest is held as energy, and energy held at rest in a particle is the particle's mass. So the second generation is heavier than the first, and the third heavier than both.

So each turn up to a later generation costs energy, and a collider supplies that energy when it makes a muon. Each turn back down to an earlier generation releases energy, and the release of energy is a decay. So the muon and the tau decay, and the electron lasts. The electron lasts because it is the lowest instance of its position, with no turn below the first, and because measurement finds no lighter particle of any other kind that carries the electron's charge.

None of the nine extra particles is an unused ingredient. No particle in the zoo is optional. In that sentence, the zoo is the physicists' name for the whole collection of the kinds of particle. The muon, for one, is the electron's position filled a second time, as the structure of comparison (what every comparison must contain) requires.

Three generations also do work that two generations could not do. *Antimatter* is matter whose particles have the same masses as the particles of ordinary matter and the opposite charges. Take any process that the weak force drives, and picture its mirror image: the same process with every

particle exchanged for its antimatter partner, and with left and right exchanged, as in a mirror. Measurements show that the weak force treats some processes and their mirror images slightly differently. The weak force turns quarks of one generation into quarks of another, and the table of those turnings can carry a *phase*, a position on a circle, like the position of the hand of a clock. The state of each quark also carries a clock hand of its own, and resetting the quarks' clock hands changes nothing that can be measured. With two generations, resetting the quarks' hands cancels every phase in the table. With three generations, exactly one phase remains that no resetting cancels. The one phase that remains is how the weak force comes to treat a process and its mirror image differently, so the difference between a process and its mirror image needs the third generation.

Cham and Whiteson's own third answer also has a place for the heavy particles: the heavy particles look useless only because the universe is now cold and large, and in a hotter, denser world they would be common. I agree with Cham and Whiteson's third answer. The heavy kinds exist as surely as the light kinds, and the heavy kinds are made wherever enough energy is gathered: in collisions in the laboratory, and when fast particles from space strike the upper air. Left alone, the heavy kinds decay toward the first generation.

Three, and No Fourth

Turn the pencil a fourth time and the first face is up again. After a fourth rotation of the content, the first respect faces the act again, as the first face of the pencil is up again. A reading already made is not a new instance, because what no comparison can tell apart is one thing. So a fourth generation is the first generation over again.

I close the count of generations from both sides. The turns of the content follow the one order in which the three respects come in every comparison, so the first respect faces the act again after three turns, and there

are at most three instances. Each respect faces the act in an instance of its own, so there are at least three instances. So the generations number exactly three.

You can try for yourself the test that I set. Look for a fourth position in an act of comparing: something that is neither the act, nor what is known, nor what the act reaches toward, and that is more than a variation of one of the three. My answer is that the three positions are all the positions that comparison has. If you find no fourth position, you have found again why there are three generations.

So on my account there is no fourth generation at any mass: the turns of the content come back to the first respect after three turns, and a fourth turn makes no new particle. It is not that the fourth generation is too heavy to produce.

A second count, made on separate ground, also comes to three. The strength of the strong force changes with the energy at which physicists probe the force. Two things set how fast the strength changes: the force particles of the strong force, and how many kinds of quark there are. Each kind of quark adds a fixed amount to the rate of change. Physicists have measured the rate across the energies where all six quarks are active. The measured rate is the rate that exactly three generations of quarks give. I make the count, with the standard arithmetic of how the strength of a force changes with energy, and the count uses nothing from the turns of the content. So two separate lines of reasoning come to three: the turns of the content, and the change of the strong force with energy.

Two measurements already made also agree with three. At CERN, the Large Electron-Positron Collider drove electrons into positrons, the antimatter partners of electrons, and made Z bosons. The *Z boson* is the heavy, uncharged force particle of the weak force. The collider's detectors recorded how each Z boson fell apart. A Z boson falls apart into every pair of particles light enough to come from it, neutrinos included, and the neutrinos escape every detector. So the share of Z decays that no detector sees measures how many kinds of light neutrino there are. There is one kind of

light neutrino for each generation. In 2020 the physicists Patrick Janot and Stanisław Jadach refined the count from the collider's data. The count came out within about one part in a thousand of three. The second measurement came from the Higgs boson. The standard theory of the particles allows a fourth generation with heavy quarks that take their mass from the Higgs field. In 2012 the physicists Abdelhak Djouadi and Alexander Lenz showed that a fourth generation of that sort would make the Large Hadron Collider produce the Higgs boson several times more often than it does. After the Higgs boson was found, physicists measured how often the collider makes the Higgs boson. The measured rates rule out a fourth generation with heavy quarks that take their mass from the Higgs field. Cham and Whiteson report the same measured fact when they write that the discovery of the Higgs boson ruled out a fourth generation. We now know that the two lines of argument come to three, and that the two measurements agree with three. Physicists count three kinds of light neutrino in the decays of the Z boson that no detector sees, and the rate at which the Higgs boson is made excludes a fourth generation of the kind the standard theory allows. The measurements exclude every fourth generation that they can test, and the structure of comparison excludes every other fourth generation.

No Smaller Pieces Waiting Below

Last come two things that Cham and Whiteson raise: their guess that the known particles are built from smaller particles, and their worry that there is no limit to how many kinds of particle there could be. Their reason for the guess is the table of particles itself: the table of the elements had patterns, the patterns were a sign of smaller parts, and the table of particles has patterns too.

I find another source for the patterns. The patterns of the particle table are the structure of comparison: three positions, three respects to turn toward the act, and three forces acting on what is found. The three forces are the strong force, the weak force and the force that light carries, the

electric and magnetic force. Chapter 7 shows that there are three forces because comparison has three positions, one force for each position. The structure of comparison is finite. We tell a kind of particle from every other kind by three things and by nothing else. The first thing is the particle's labels, the marks by which each of the three forces acts on the particle. The second thing is the particle's generation. The third thing is the sort of field that the particle is a ripple of: a field of matter, a field of one of the forces, or a field of the sort the Higgs field is. If a proposed new kind agrees with a known kind in all three things, the proposed kind is the known kind. The structure contains three labels, three generations and three sorts of field, and every known label is in the place that the structure has for it. So a new kind would need a fourth label, a fourth generation, a fourth sort of field, or a known label in a place that the structure forbids, and the structure has no such place. Physicists have now found a particle for every place in the structure. They ran out of structure.

The list of kinds is closed, because every place in the structure now has its particle. Every kind of particle has been found. The closed list is a claim about kinds of particle, and a great deal is still left to find. Heavier things built from the known kinds wait at higher energies, as heavier nuclei extend the table of the elements. Physicists still have to measure the masses of the particles and the strengths of the forces ever more finely. Only the list of kinds will not grow.

In the years since the last kind was found, every measurement has agreed with a closed list. Physicists at the Large Hadron Collider have searched for heavier copies of the force particles, for particles that would join quarks to leptons, and for proposed partners of the known particles, and they have found none. In 2025 physicists made the final measurement of the muon's magnetism. Any kind of particle, known or unknown, would shift the muon's magnetism by its presence. The measured value agreed with the value calculated from the known kinds alone.

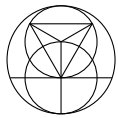
Cham and Whiteson end their search for the bottom of matter with a picture of their own: an onion of layers, each built from the layer below, and the possibility that the layers never end (*We Have No Idea*, ch. 16,

"What Is a Theory of Everything?"). On my account, the descent through the particles has a bottom, but the bottom is not a smallest layer. That book sums up the descent through the levels of the particles: the descent "was not a journey into smaller and smaller things. It was a journey into deeper and deeper aspects of what comparison is". The descent ends because the act of comparing has a finite structure, and every aspect of that structure now has its particle. So the list of particles is a portrait of the act of knowing the world. In plain words, the list shows what every act of knowing the world contains. One list of kinds therefore serves every place where anything is measured, from Thomson's tubes to the largest collider, because the kinds are the kinds of any place in which comparison is made.

> **The short answer**
>
> The basic elements of matter are a closed list of kinds of particle: the kinds are few because every comparison has three positions, each kind of matter comes three times because the content turns three ways, and there is no fourth generation and no smaller piece waiting below.

The closed list is the answer to Cham and Whiteson's question about the five percent of the universe that is stuff, and the answer comes from the structure of the act that every measurement performs. So the list of kinds now has the same ground as the bends of the three settings that Chapter 1 found: what every comparison must contain. The list fixes which kinds there are, and it fixes that each later generation of a charged particle is heavier than the generation before. How large the masses are is a separate question from the list.

If the kinds are fixed, are their masses and charges fixed too, or are they numbers nature simply picked?



Chapter Five

Are the Particles' Numbers Just Arbitrary?

In which the charges of the particles turn out to have one possible value each, and their masses stand on a ladder counted in halvings

Are the masses and charges of the particles just numbers nature picked, with no pattern?

What this chapter uses

A *comparison* is the act of finding whether two things are the same or different in some respect, and every measurement is a comparison; a *finding* is the outcome of one comparison, laid down as a record; a *comparer* is whatever makes a comparison, whether or not the comparer has a mind (Chapter 1).

The *content* of a finding is what the finding finds, as the warmth of your coffee; the *context* is where the content is found, and the context has three sides, the three settings of space, time and possibility (Chapter 1).

Continuous: nothing is sudden, as along a ramp; *discontinuous*: something is sudden, as at the edge of a step; *symmetric*: what is found stays the same across a change of setting, as each step of a staircase is like every other; *asymmetric*: different everywhere, as the height along a ramp is (Chapter 1).

The *Incommensuration Theorem*: at the foundation of any event or comparison, symmetry and continuity cannot both be perfect together, and neither can asymmetry and discontinuity. The Incommensuration Theorem is a structural fact about the nature of knowing (Chapter 1).

Every comparison has three positions: the *act of comparing*, the relating; the *thing compared*, what is known; and the *thing compared against*, what the act of comparing reaches toward and never contains in one act, the beyond (Chapter 4).

The basic elements of matter are a closed list of kinds of particle: the kinds are few because every comparison has three positions, and each kind of matter comes three times, in three *generations* (Chapter 4).

In 1885 Johann Balmer looked at four measured numbers that no theory of the time explained. Balmer was a teacher at a girls' school in Basel, and he was then about sixty years old. Pass an electric current through a thin tube of hydrogen gas, and the gas glows. Pass the glow of the hydro-

gen through a prism, and the light comes out as four sharp lines of color with darkness between the lines: a red line, a blue-green line, and two violet lines. Each color of light has a *wavelength*, the length of its wave, and the wavelength sets the color. The Swedish physicist Anders Ångström had measured the wavelengths of the four lines of hydrogen with great care. Counted in millionths of a millimeter, the red line's wavelength is about six hundred fifty-six, the blue-green line's about four hundred eighty-six, and the two violet lines' about four hundred thirty-four and four hundred ten.

Balmer found one rule from which all four wavelengths follow. Take a whole number, starting from three, square the number, divide the square by the square less four, and multiply the result by one fixed length, a little under three hundred sixty-five millionths of a millimeter. For three, the square is nine, and nine less four is five. Nine fifths of the fixed length is the red line's wavelength. In the same way four gives the blue-green line, and five and six give the two violet lines. For the number seven, Balmer's rule then gave a fifth line, at about three hundred ninety-seven. Balmer's friend, the physicist Eduard Hagenbach-Bischoff, told Balmer that a line had already been observed at that wavelength, together with further lines of hydrogen.

Balmer's rule worked before anyone knew why the rule worked. For twenty-eight years the rule agreed with the lines of hydrogen, line after line. Nobody knew what kind of atom stood behind the rule. In 1913 the Danish physicist Niels Bohr gave the reason. The energy of the hydrogen atom comes in levels counted one, two, three, and so on. Each of Balmer's lines is the light the atom gives off when the atom drops from a higher level to the second level, so the four in Balmer's rule is two times two, the square of the level on which every one of those lines ends. So Balmer's rule had been a clue the whole time, because the rule agreed with the measured lines, and the clue pointed to where the reason was: the second level of the atom.

We can ask the same two questions about the charges and the masses of the particles: do the charges and the masses follow a rule, and what is the reason for the rule?

Clueless and Surrounded by Clues

Jorge Cham and Daniel Whiteson set out the puzzle of the particles' numbers in their book *We Have No Idea*, in two parts: one part for the masses and one part for the charges.

Take the masses first. Cham and Whiteson recall that the masses of the atoms formed a pattern in the periodic table of the elements, and that physicists worked out from that pattern how many protons and neutrons each nucleus holds. Chapter 4 described the generations: the three copies of each kind of matter. The authors report that nobody has found a pattern in the masses of the fundamental particles, beyond a general rise from one generation to the next. The top quark alone weighs as much as the nucleus of a gold atom. The masses of the particles span thirteen powers of ten. The heaviest is heavier than the lightest by a factor of a one followed by thirteen zeros. In the authors' words: "We are both clueless and surrounded by clues" (*We Have No Idea*, ch. 4, "What's the Pattern of the Masses of the Particles?"). The authors add that the Higgs field gives the particles of matter their masses. In their account the Higgs field turns the question into another question. The masses differ because the particles feel the Higgs field differently. Why the particles feel the Higgs field differently is the question of why the masses differ, asked again. The authors also say what they expect the answer to be: "There is probably a pattern to the masses, but it's one that has so far escaped us" (*We Have No Idea*, ch. 5, "The Higgs Boson").

Now take the charges. The quarks carry fractions of the electron's charge: plus two thirds for the up quark and minus one third for the down quark. Two up quarks and a down quark make a proton with a charge of exactly plus one. The proton's plus one balances the electron's minus one. So atoms come out exactly neutral, and chemistry and life are possible.

The authors point out that in the theory physicists use, the charges could have been anything at all, and the theory would work just as well. From inside that theory the exact balance looks like a coincidence, and the authors call the balance a coincidence: "This is an exact zero-difference coincidence" (*We Have No Idea*, ch. 4, "What's Up with Those 1/3 Electric Charges?"). Then the authors ask a sharper question. If you lost two thousand dollars on the same day your neighbor found two thousand dollars, would you call the match chance before you had tried every simpler explanation? The authors write that the balance "screams for a simpler explanation" (the same section). They name two places where a simpler explanation might be found: the exact match might be a sign of deeper components underlying the quarks and the electron, or the quarks and the electron, two kinds of particle, might be two sides of the same coin.

We Have No Idea has a chapter on a theory of everything, and there the authors add a way to tell how deep a theory goes: count the theory's arbitrary numbers (*We Have No Idea*, ch. 16, "How Will We Know If We Are Done?"). Their picture is a smallest particle, which they name the "tinyon". One physicist's theory needs the tinyon's mass measured and plugged in, while another physicist's theory works only at one exact value of the tinyon's mass, so the second theory says what the mass has to be. The authors judge that we learn more from the second theory, because the second theory says why the tinyon's mass is what it is. The Standard Model is the established theory of the kinds of particle and of the three forces among the particles (the strong force, the weak force, and the electric and magnetic force). By the authors' measure, the Standard Model has many arbitrary numbers, and the authors list twenty-one. Their list holds twelve masses for the quarks and the leptons, four mixing angles that set how quarks change into each other, three numbers for the strengths of the forces, and two numbers for the Higgs theory.

The Charges Have One Answer

Take a pencil and work out the charges of one generation: the electron, its neutrino, the up quark and the down quark. Each quark comes in three *colors*. Color is the physicists' name for the charge that the strong force acts on, and color comes in three kinds (the word is only a name, and nothing about a quark is colored). Four premises are given, and each premise has its reason.

First, the up quark and the down quark form a pair that the weak force turns into each other. The weak force also turns the neutrino and the electron into each other, so the neutrino and the electron form a second pair. The two members of each pair differ by exactly one unit of charge. Each pair is one thing seen from its two sides, and the two sides differ in one respect: their charge. I show that the quark pair and the lepton pair are the same two sides, met in two places, so the step of charge between the two sides is equal in the two pairs. The lepton pair shows that the step is one whole unit. The neutrino carries no charge and the electron carries minus one (the second and third premises below), so the two charges differ by one unit.

Second, the neutrino carries no charge. Charge is the mark by which light reads matter: light acts on a particle only through the particle's charge. The neutrino is the electron's shadow: the same kind of particle as the electron, carrying none of the marks by which light finds the electron.

Third, the electron carries the unit of charge, minus one. Chapter 4 showed that the electron is the unit in which every report of a measurement is given, and that the electron's charge is the unit in which every other charge is counted. Which sign is called minus is a convention. The fact to be found is the ratio of every other charge to the electron's charge.

Fourth, when each quark is counted once for each of its three colors, the charges of one whole generation add up to zero.

The fourth premise is the premise that fixes the values of the charges, and the reason for the fourth premise comes from the act of finding, the act by which anything at all is found out. Picture a ledger, an account

book in which every entry records an amount set against another account in the same book. Add up every account in the book, and the total is zero, because each amount was written against another amount inside the book. The clerk who writes the entries holds no account in the book. A total other than zero would be an amount set against no account at all. Every entry of the ledger sets its amount against another account.

Chapter 1 described every measurement as a *comparison*, one thing held against another. For electric charge, the comparing is done by light. Light reads each charge against the other charges that light reads, as each entry of the ledger is set against another account, and light itself carries no charge, as the clerk holds no account. A whole generation holds one complete copy of everything in matter that light reads: the up quark and the down quark in each of their three colors, the electron, and the neutrino, in which light reads no charge. Across that whole generation, light is the only thing left to read the total against, and light carries no charge. A total other than zero would be a charge read against nothing. A charge read against nothing is no reading at all. So the charges of one generation add to zero.

Now do the arithmetic. The electron and the neutrino give minus one and zero, so the quarks, three colors of each, must give plus one. Each quark is counted three times, once for each color, so the up charge and the down charge together make one third. Two thirds and minus one third add to one third and differ by one, and no other pair of numbers does both. So the up quark carries plus two thirds, and the down quark carries minus one third. Every charge of a particle of matter is therefore a whole number of thirds of the electron's charge. Check the result on the proton, two up quarks and a down quark: two thirds and two thirds, less one third, is exactly one. The neutron is one up quark and two down quarks, and its charge comes to exactly zero. The same result follows: the fractional charges are the unique solution of the four premises (the pairs one unit apart, the neutrino's zero, the electron's minus one, and the zero total of a generation), and the proton's charge is exactly plus one.

Physicists find the same charges by a second road, an argument from inside their own theory. The physicists' description of the forces is consistent exactly when certain sums over the particles of one generation come to zero. Physicists call a failure of those sums an anomaly. They call the requirement that the sums come to zero *anomaly cancellation*. Work the sums through, with the members of each pair one unit of charge apart. Four of the sums are not satisfied automatically, and I show that all four come down to one rule: the charges of a generation add to zero. The quarks alone fail the sums, and the leptons alone fail the sums too. The quarks and the leptons cancel only together, so a generation is one whole. The same arithmetic has one more result. Keep the rule that the members of each pair differ by one unit, keep the rule that the charges of a generation add to zero, and let the neutrino carry any charge at all: the proton and the electron still come out exactly opposite. So hydrogen, one proton and one electron, is neutral for every charge the neutrino could carry.

A third road needs no anomaly sums. A further argument uses the mathematics of the particles' inner labels as its starting point. The labels are the marks, such as color, that a particle carries besides its place and its motion. In that mathematics each label can be turned, as the hand of a dial is turned. The argument has two premises: the particles of one generation, each set in its place in that mathematics, and one rule, that over all the states together the turns cancel. The charges follow from these two premises by computation. The charges that come out are the charges of the Standard Model, with none of them put in.

So three roads start from three different places and arrive at the same thirds, plus two thirds for the up quark and minus one third for the down quark: the pencil sum from the act of finding, the physicists' anomaly sums, and the turning labels of non-commutative geometry. The balance that the Standard Model leaves unexplained is the one arrangement the charges can have.

A Number That Lands Is a Question

Go back to Balmer. Balmer's rule agreed with the measured lines before anyone knew why. The agreement turned out to be the most useful thing about the rule. I call a number like Balmer's a *value that lands*: a value that agrees with what is measured. Before its reason is found, a value that lands is a question, "why does it land?", and the value is evidence of a reason not yet known. When we write the agreement as a question, we keep its clues together, and the clues show where the reason lies. In Balmer's rule the clue was the four, the square of two, which showed an atom whose energy comes in whole steps.

The question states exactly what is known about the agreement of a value that lands with what is measured. The agreement holds, and its reason is still to be found. The word "coincidence" says more than that: the word says that the agreement has no reason at all. So a question, and not the word "coincidence", is the right way to write a value that lands. Cham and Whiteson and I agree that the balance of the charges needs an explanation. Cham and Whiteson's two-thousand-dollar picture is the question "why does it land?", asked about the charges: why does the balance hold? The three roads of the previous section answer the question: the pencil sum, the anomaly sums and the turning labels.

A Ladder Counted in Halvings

The masses look wilder than the charges, so start with something you can do with your hands. Physicists state the masses of particles in units of energy, and a mass can be stated as an energy because mass and energy at rest are one currency, as Chapter 6 shows. An *electron volt* is the energy one electron gains in crossing one volt, about the push of a single small battery. A GeV is a billion electron volts, a little more than the mass of one proton. An MeV is a million electron volts, a thousandth of a GeV.

Take a strip of paper and let its length stand for the mass of the top quark, about a hundred seventy-two and a half GeV. Fold the strip in half, and its length stands for half the top quark's mass. Fold the strip again,

and its length stands for a quarter. Each fold is one *halving*, a factor of two in mass. Seven folds bring the strip down to the top quark's mass divided by one hundred twenty-eight, about one and a third GeV, and the charm quark weighs about one and a quarter GeV. Counted in folds, the charm quark's mass is seven halvings below the top quark's mass, and a little more. The electron weighs about half an MeV and is about three hundred thirty-eight thousand times lighter than the top quark. A ratio of three hundred thirty-eight thousand is more than eighteen folds and fewer than nineteen. Counted in halvings, a ratio of hundreds of thousands becomes a count you can hold in your head.

Why should masses be counted in twos, and not in thirds or tenths? Play a guessing game with a friend who has chosen a number from one to one thousand and twenty-four. Each question answered yes or no rules out half of the numbers still open. With ten yes-or-no questions you always find the number. A comparison works the same way as a yes-or-no question. A comparison has two outcomes, same or different, so one comparison divides what is still open in two. That division, counted in mass, is a division of the mass by two. So one comparison is one halving, and the ladder of masses (the masses set out one below another in halvings) is counted in twos.

I then state one rule for every charged particle of matter. Each charged particle of matter sits a counted number of halvings below the top quark. The rule applies family by family. The up quarks (up, charm and top) are one family. The down quarks (down, strange and bottom) are another, and the charged leptons (electron, muon and tau) a third. Picture each family's three members as three houses on a road that runs downhill from the top quark. Each house stands a counted number of halvings down the road, and the distance down the road is the number of halvings by which that member's mass lies below the top quark's mass. Number the generations down from the heaviest: zero for the heaviest member, one for the middle member, two for the lightest.

Each family has three numbers. The first of each family's three numbers is the family's *starting place*, how far down the road the family's heaviest member stands. The second of each family's three numbers is the family's *step*, a number of halvings taken once for each generation down. The third of each family's three numbers is the family's *widening*, a number of halvings taken as many times as the square of the generation number. A widening above zero makes the second gap between the houses (from the middle member to the lightest) longer than the first gap (from the heaviest member to the middle member). A widening below zero makes the second gap shorter.

Walk the rule for the up quarks, whose starting place is zero, whose step is six and whose widening is one. The top, at generation zero, stands at zero. The charm, at generation one, stands at one step and one widening: six and one, seven. The up, at generation two, stands at two steps and four widenings, since two squared is four: twelve and four, sixteen. So the first gap is seven, from the top to the charm, and the second gap is nine, from the charm to the up.

Last, one shared factor applies to every family. The shared factor is a little more than one and the same for every family, and it lengthens every count by about one and a quarter percent, so each counted step is a little more than a plain halving. The excess over a plain halving has two parts: the main part, a small leftover of about one and four tenths of a percent, and a much smaller correction that takes back about a tenth of a percent. A count comes in whole steps, like the staircase of Chapter 1, and a smooth measure rises without steps, like the ramp. So, by the Incommensuration Theorem, a count read by a smooth measure always leaves a residue. I show that the small leftover is that residue, as the residue appears in the particles: the mismatch between a counted measure and its smooth reading.

The step of each family, the number of halvings taken once for each generation down, comes out of the structure of comparison (what every comparison must contain). For both quark families the step is six halvings per generation, and the reason for six is this. Chapter 4 showed that every

particle of matter can be read in three respects, one for each position of comparison. A particle can be read as the same as other things or different from them; as an object, or as seen from a point of view; and as something found, or as part of the context it is found in. Each respect has two sides, so every comparison has six aspects in three pairs: sameness and difference, the side the comparison is made about and the side it is made from, and content and context. Each new generation adds a new copy of the content, and in this chapter the content is a particle of matter. With each new copy, each of the six aspects is settled once, one of two ways. None of the six aspects is fixed by the other five. Six settlings of two ways each are six comparisons, and six comparisons are six halvings.

For the charged leptons the step is shorter: six times three eighths, which is two and a quarter halvings. The quarks' ladder is the whole, and the charged leptons' ladder pays a share of the whole. So the leptons' step is the quarks' step taken in proportion to the charged leptons' share of what light reads in one whole generation. That share comes from the pencil sum, done once more with each charge squared. Square each charge and count each quark three times: the up quark gives four thirds, the down quark one third, the electron one, and the neutrino nothing, eight thirds in all. The electron's one is three eighths of eight thirds.

The widenings are one for the up quarks, sixteen ninths for the charged leptons, and minus seven twelfths for the down quarks. The three widenings are tied together exactly: three times the leptons' widening, plus four times the down quarks' widening, equals three times the up quarks' widening.

The ladder is a pattern, and more than a list, because of its numbers. Each of the ladder's numbers is a simple fraction made from three, four and five and from the two of comparison (its two outcomes, same or different). Nine quarters, the leptons' step, is three halves multiplied by itself. Sixteen ninths, the leptons' widening, is four thirds multiplied by itself. Three eighths, the leptons' share, is three over the sum of three and five. Three, four and five are the sides of the right triangle that I build from the two whole numbers of comparison: three, the count of its posi-

tions, and two, the count of content and context. And the ladder's numbers are tied to one another, as the widenings are, so the ladder's numbers hold together as one set.

The measured masses put the quarks' step at six halvings per generation, to within about two parts in ten thousand, and the leptons' step divided by the quarks' step comes out at three eighths, to within about one part in twenty thousand. Counted up from the electron, the leptons' starting place drops out, because only the gaps between the houses of one family count, so the masses of the muon and the tau follow from the electron's mass and the ladder's own numbers alone. With no correction at all, the ladder's mass for the muon lies within one percent of the muon's measured mass, and the ladder's mass for the tau lies within a quarter of a percent of the tau's.

So the masses that the authors see scattered over thirteen powers of ten stand on one ladder: by one rule, every charged particle of matter sits a counted number of halvings below the top quark. The authors expected a pattern, and the pattern is there. The pattern is counted in halvings, and its numbers are simple fractions made from the sides of one triangle. Measurement still supplies some of the ladder's values: the starting place of the down quarks comes from the measured bottom quark, and the starting place of the charged leptons comes from the measured tau. Each starting place sets where its family stands below the top quark. The gaps within each family, from which the masses of the muon and the tau follow, use only the step, the widening and the shared factor. The electron's own mass is the unit in which every other mass is stated, so measurement supplies the electron's mass too.

The Ceiling and the Whole Reach

The authors' sharpest form of the mass question is about the Higgs field: why do the particles feel the Higgs field differently? Chapter 3 showed the Higgs field to be the one field that fills all of space with a settled value. Physicists call that settled value the *condensate*. A particle of

matter gets its mass from the condensate through its *coupling*. A coupling is a number that says how much of the particle the condensate takes hold of.

Close your hand around a ball. Your hand can hold a little of the ball, or most of the ball, or all of the ball. Your hand cannot hold more than all of the ball. A coupling is a reach of the same kind: the condensate is the hand, the particle is the ball, and the coupling is the share of the particle that the condensate takes hold of. So every coupling lies between zero and one. Standard physics turns a coupling into a mass: the mass is the coupling times the condensate's value, divided by the square root of two. The largest coupling, one, gives the largest mass, about a hundred seventy-four GeV. So no particle of matter can be heavier than about a hundred seventy-four GeV. I call that limit the *ceiling*, and the structure of comparison sets the ceiling.

One particle has the whole reach, a coupling of exactly one. That particle is the top quark. Lay a ruler against itself, and the ruler is exactly one ruler long, whatever the ruler. In my argument, the up quarks' family belongs to the position of the act of comparing. The up quarks' family is comparison turned on its own content, measuring itself, like the ruler laid against itself, and a thing measured against itself yields exactly one. Chapter 4 showed that the reading of the third generation takes in every instance its content could be. So the top quark's reach takes in the whole, because the top quark is the third member of the up quarks' family. The top quark's coupling is one. The up quark and the charm quark reach less: their couplings are less than one.

The top quark was found in 1995 at the Fermilab laboratory by two experiments named CDF and D0. Physicists have measured the top quark's mass since then by rebuilding the mass from the particles the top quark breaks into, and they find a mass of about a hundred seventy-two and a half GeV, give or take about a quarter of a GeV. We now know the heaviest particle of matter stands just under the ceiling, less than one percent below the mass that a coupling of exactly one would give. Every other particle of matter has a mass far below the ceiling. The coupling of every

other particle is a part of the whole reach, less than one. So the authors' question has an answer in three parts. First, a coupling is the measure of how much of each particle the condensate takes hold of. Second, the top quark's reach is the whole: its coupling is one. Third, for every other particle, the size of the reach (the coupling) is the particle's place on the ladder of halvings.

Three Masses in Balance

The charged leptons carry one more pattern, older than the ladder and independent of the ladder. In 1983 the Japanese physicist Yoshio Koide published a relation among the masses of the electron, the muon and the tau. Koide's relation can be pictured in a room. The square root of a number is the number that, multiplied by itself, gives back the number you started with. Stand in the corner of a room, where two edges run along the floor and one edge runs up the wall. Walk along one floor edge a distance equal to the square root of the electron's mass. Then walk along the other floor edge a distance equal to the square root of the muon's mass. Then rise up the wall edge by the square root of the tau's mass. Draw an arrow from the corner to where you stand, and draw the room's diagonal, the line along which all three distances would be equal. Koide's relation says that the arrow leans exactly forty-five degrees away from the diagonal: half of the arrow's squared length lies along what the three masses share, and half lies across, in the ways the three masses differ. In numbers, the sum of the three masses is exactly two thirds of the square of the sum of their square roots.

Koide's number is the sum of the three masses divided by the square of the sum of their square roots, and Koide's relation says that Koide's number is exactly two thirds. When Koide's number is worked out from the three measured masses, it agrees with two thirds in its first five decimal places. The three charged leptons are three copies of one kind. The mass of each charged lepton is read against one thing only, the condensate. The relation divides the arrow's squared length equally between the

one way three things can be the same and the two ways they can differ. The same reason says why the quarks are not expected to obey the relation: a quark's mass is read against color as well as the condensate. A quark is found only inside a whole bound by the strong force, and the strength of that binding changes with the energy at which the quark's mass is read. For both quark families, Koide's number comes out well above two thirds.

With Koide's relation, the tau's mass follows from the electron's mass and the muon's mass, so the charged leptons carry one free number fewer than a list of three masses. By Koide's relation, the tau's mass is about one thousand seven hundred seventy-seven MeV. The Particle Data Group gathers the measured values of particle physics, and in its average of 2024 the Particle Data Group gave a measured tau mass about four hundredths of an MeV below that value, with a give or take of about nine hundredths. We now know that the tau mass set by the measured electron, the measured muon and Koide's relation lies inside the tau's measured range.

How Many Numbers Are Left?

The authors ask one more thing with their tinyon story: how many numbers does an account of the particles need from measurement, and how would anyone know the account was finished?

A tailor's pattern gives every proportion of a coat: the length of the sleeve against the back, the width of the collar against the chest. The one thing the pattern cannot give is the size of the person who will wear the coat. The tailor measures that size. I use the tailor's picture for the particles: the structure of comparison fixes the proportions, as the pattern does, and measurement supplies what the proportions do not fix, as the tailor's tape does.

I use the authors' measure to count the numbers: the numbers that a theory needs from measurement. The Standard Model as first written needs nineteen numbers from measurement, and the neutrinos add seven, for twenty-six. The authors' twenty-one are among the twenty-six. The

twenty-six add five numbers to the authors' list: the three angles and the one phase by which the neutrinos mix, and the strong force's angle, by which the strong force could tell matter from its mirror image.

Every one of the twenty-six numbers has its *standing*, which says where the number's value comes from. There are four standings. Some numbers are set by the structure of comparison, as the charges are. Some are set by the structure once one stated step is taken, as the tau's mass is set through Koide's relation. Some are measured, as the size of the coat is. Some agree with measurement and are kept with the question of why they land, and with the clues to their reason, as Balmer's lines once were.

I give two accounts of the numbers. In the *working account* of the masses, measurement supplies six numbers. The six are the electron's mass, the strength of light (how strongly light acts on charge), the strength of color (how strongly the strong force acts on color), the condensate's value, and two of the ladder's starting places. I also give a second account, the *closure account*, with one further stated step in the way the ladder's step is written. With that step, the calculation runs from one measured number, the electron's mass, up to the condensate's value, the mass of the top quark and the mass of the Higgs particle.

By the authors' own measure of depth, then, the Standard Model as first written needs twenty-six numbers from measurement, the working account needs six, and the closure account needs one for its chain of calculation. The electron's mass is the unit in which every other mass is stated, and a unit is bookkeeping: no comparison's verdict, same or different, more or less, ever depends on the unit. When an argument shows that no law fixes a number, the number is accounted for as fully as a derived number, because the argument says exactly why no law fixes the number. So an account is finished when every number has reached one of two ends: derived through its law, or shown to be of a kind no law can fix.

What the Measurements Found

Between 1909 and 1913, at the University of Chicago, Robert Millikan watched tiny charged drops of oil float between two metal plates and measured the charge on each drop. Every drop carried a whole number of one basic charge, and every particle found standing alone since then has carried a whole number of the electron's charge too. The reason is that only a whole that is complete in color can stand alone, such as a proton or a neutron with one quark of each of the three colors, and every whole complete in color carries whole units of charge.

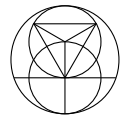
In the late 1960s, at the Stanford Linear Accelerator Center in California, physicists fired electrons at protons and counted how the electrons bounced. Far more electrons came off at wide angles than a proton with its charge spread smoothly through it could produce, so the electrons were striking small, hard parts inside the proton. Later experiments found those parts carrying the charges of plus two thirds and minus one third that the pencil sum gives. We now know the fractional charges are real, and that a fractional charge is never found alone.

The top quark, found in 1995, has a mass just under the ceiling. Koide's number agrees with two thirds in its first five decimal places, when it is worked out from the three measured masses of the charged leptons. Several experiments have measured the tau's mass. The average of their measurements in 2024 lies where the electron, the muon and Koide's relation put the tau's mass.

> **The short answer**
>
> The charges of the particles are forced, the one solution that keeps the forces consistent, and the masses sit on a counted ladder beneath a ceiling that the structure of comparison sets, with measurement supplying the values the structure does not fix.

In the rest of this book I read every number in the same way: a number found in the world is a question with a reason behind it. The work is to find the reason, or to show that the number is one no law can fix. The authors' clues turn out to be a pattern, and the pattern has its reasons in the act of comparing.

What is a mass, that a particle can have one at all?



Chapter Six

What Is Mass?

In which most of your weight turns out to be the binding of quarks, and mass turns out to measure one relation of a thing to its context

What is mass, and why does energy equal mass times the speed of light squared?

> What this chapter uses
>
> A *comparison* is the act of finding whether two things are the same or different in some respect, and every measurement is a comparison; a *finding* is the outcome of one comparison, laid down as a record; a *comparer* is whatever makes a comparison, whether or not the comparer has a mind (Chapter 1).
>
> The *content* of a finding is what the finding finds, as the warmth of your coffee; the *context* is where the content is found, and the context has three sides, the three settings of space, time and possibility (Chapter 1).
>
> Every comparison has three positions: the *act of comparing*, the relating; the *thing compared*, what is known; and the *thing compared against*, what the act of comparing reaches toward and never contains in one act, the beyond (Chapter 4).

On 4 July 2012, two experiments reported what they had found, at a seminar held at CERN, the laboratory for particle physics near Geneva. The two experiments are called ATLAS and CMS. Each is a detector on

the Large Hadron Collider, the great ring at CERN in which protons are smashed together. Fabiola Gianotti was the spokesperson of ATLAS, and Joe Incandela was the spokesperson of CMS. Incandela said, in the laboratory's statement of that day: "This is indeed a new particle". CERN had invited the theorists who had worked out the idea of the particle in the 1960s, and two of them, François Englert and Peter Higgs, were there on the day. When reporters pressed Higgs for comment, he replied that the day belonged to the experiments, and that there would be plenty of time to talk to the theorists later.

The new particle was the Higgs boson. The Higgs boson is the smallest ripple of the Higgs field. Chapter 3 also said that every kind of particle is the smallest ripple of a field of its own kind. The Higgs field gives the electron and the quarks their masses. From that day it is easy to carry home a wider sentence: that the Higgs field gives everything its mass.

Now step on a bathroom scale. The scale shows a number, and about ninety-nine parts in a hundred of that number come from the binding of the quarks inside you. Quarks are the small particles of which your protons and neutrons are made. The Higgs field sets almost none of that binding. So the wider sentence fails for most of your weight, and the day the Higgs field was found is a good day to ask what mass is, and why energy and mass go together in the most famous equation in physics.

From Cham and Whiteson's pages

What Cham and Whiteson Showed

Jorge Cham and Daniel Whiteson give a whole chapter of *We Have No Idea* to mass, and a whole chapter of *Frequently Asked Questions About the Universe* to the equation $E = mc^2$. In words, the equation says that the energy a body holds at rest equals its mass times the speed of light times the speed of light again.

In *We Have No Idea*, Cham and Whiteson begin by saying exactly what they mean by mass. For them, mass is how hard a thing is to speed up or slow down: push a tissue and a sleeping elephant with the same

force, and the tissue moves far more. A thing's resistance to being moved is called its *inertia*, and the mass measured by that resistance is called inertial mass.

Then they show that the mass of a whole holds more than the masses of its parts. Break a llama into its atoms, and the pieces weigh a little less than the llama. Break the llama's protons and neutrons into quarks, and the quarks weigh about one part in a hundred of what the protons and neutrons weighed. They put the lesson in one sentence: "In our universe, the mass of something includes the energy needed to keep that stuff together" (*We Have No Idea*, ch. 5, "The Stuff of Stuff"). They add that physicists do not know why the energy holding the parts together should make a body harder to push.

Next they look at the smallest particles themselves. They explain that in current theory a quark or an electron is a point with no size, so the mass of a quark or an electron cannot be an amount of stuff packed into it. They advise treating a particle's mass the way we treat its electric charge: "just think of it as a label that we apply to an infinitesimal quantum object" (*We Have No Idea*, ch. 5, "Particularly Confusing Particle Masses"). The Higgs field sets the size of that label.

In *Frequently Asked Questions About the Universe* they tell Einstein's argument about a rock in space that gives off heat as light. The rock keeps every one of its atoms. Still, the rock's mass goes down by the energy of the light divided by the speed of light squared. They go on to the proton, whose quarks supply about one percent of its mass, and to the Higgs field, which supplies the mass of the quarks and the electron. They draw their conclusion from two clues, the proton and the Higgs field: "what we thought of as 'mass' doesn't really exist. It's all just energy" (*Frequently Asked Questions About the Universe*, ch. 15, "A Massive Conclusion"). They add that a hot rock is more massive than the same rock cold.

My account and theirs agree on the share of a proton's mass that the binding supplies, and on the hot rock, because on both points the two accounts use the same standard physics. My account also agrees with theirs on the Higgs field, and my account adds what the Higgs field joins together in each particle of matter. Cham and Whiteson leave open why the binding makes a body harder to push. I answer that question, why the binding makes a body harder to push, by starting from what the act of finding something is. I give a different answer from theirs to what mass is: mass and energy each measure relations of a thing to its context, which is where the thing is found.

Where Your Weight Comes From

Picture a sealed box whose inner walls are perfect mirrors, and fill it with light. Light has no mass at rest. Still, the box with its light weighs more than the same box dark, by the energy of the light divided by the speed of light squared. No part of the box has become heavier: the extra mass is the energy held inside the walls.

A proton is also a whole whose held energy counts as mass. In a proton the held energy is nearly the whole of the mass. A proton holds three quarks, the small particles that the protons and neutrons of every atom are made of. Gluons hold the three quarks together. Gluons are the carriers of the strong force, the force that binds the inside of a proton. The strong force acts on a charge that quarks carry, which physicists call color, as Chapter 5 said. Physicists call the field of the strong force the *color field*. The three quarks of a proton together supply about one percent of its mass. About ninety-nine percent comes from the color field: from the motion of the quarks and gluons inside the proton, and from the energy of the binding that holds the quarks and gluons there.

Standard physics has a rule by which held energy counts as mass. A whole that sits still has a mass equal to its total energy divided by the speed of light squared. The total energy holds three things: the energies the parts have at rest, the energies of their motion inside the whole, and

the energy of the field that binds them. In a proton, almost all of the total energy is the energy of the quarks' motion and the energy of the binding field.

When a binding gives energy up, the rule by which held energy counts as mass works the other way: the bound whole weighs less than its parts held apart. A hydrogen atom weighs less than a free electron and a free proton held apart, by the energy that binds the electron to the proton. The difference is about one and a half parts in a hundred million of the atom's mass.

Nearly all the mass of your body is the mass of its protons and neutrons. When you weigh yourself, you are mostly weighing the binding of quarks.

Physicists have computed the proton's mass from the theory of the strong force. No one can switch off the binding of the quarks and weigh the pieces one by one, so physicists solve the theory on a computer, on a fine grid of points in space and time. In 2008 the physicist Stephan Dürr and his colleagues solved the theory on such a grid. They took from measurement only the masses of three particles made of quarks, and those three masses set the scale of the grid and the masses of the quarks. They computed the mass of the nucleon (a proton or a neutron), and their result came out within a third of one percent of the measured mass. So we now know that the mass of nearly all the ordinary matter in the world, which is the mass of its protons and neutrons, is the energy of the color field and of the quarks moving inside the protons and neutrons.

Why the Binding Is Inertia

Cham and Whiteson ask the question that the box of light raises, and they ask it with a bag of beans. If you push a bag of beans, why should the energy holding the beans together make the bag harder to push? They say that it should not matter whether the beans are held together by spit or by Super Glue, and yet it does matter. In their words, "we don't really know what inertia is" (*We Have No Idea*, ch. 5, "The Stuff of Stuff").

I answer their question from what it is to find something, and from what motion is. Picture an otherwise empty universe with a single spacecraft in it. Nothing in the ship can tell whether the ship is spinning, because to spin is always to spin relative to something, and there is nothing else to compare the ship with. Add a second ship, and each ship's turning becomes a relation of that ship to the other. Rest, steady motion and turning are each always relative to something. In our world that something is everything else: the earth, the stars, all the matter there is to compare against.

So a state of motion is a relation of a content to its context. The content is what is found, and the context is where it is found. Inertia is the resistance of a thing to a change in its relation to its context. To set a body moving is to change where the body is found, and how it is found to be moving, against everything else. The body resists that change.

Now take the binding of the quarks. The binding of the quarks stays inside the proton and cannot pass out of it. The binding is found again with the proton every time the proton is met. So when the proton is set moving, its binding moves with it, and the binding is part of what resists the push: the binding is part of the proton's own inertia. I make the argument I have just given, from the binding of the quarks to the proton's inertia.

The bag of beans works the same way as the proton. The energy held in the bag is part of what is found when the bag is found, and moving the bag moves all of that energy. The glue counts toward the bag's inertia because the glue is there to be found, wherever the bag goes.

The Cup That Weighs a Little More

Put a lid on your cup of coffee while the coffee is hot, so that no steam escapes. Take the cup from the table and lift it. Lift the cup again an hour later, when the coffee has cooled to the warmth of the room. The hot cup weighed a little more.

The difference is tiny. Take a cupful of coffee, about three hundred grams, that cools by sixty degrees Celsius. The coffee gives up its heat to the room, and the cup's mass goes down by that heat divided by the speed of light squared: by a little less than a millionth of a milligram. No kitchen scale will show so small a difference. Yet the cup has lost mass, while every molecule of coffee is still in the cup. Your lidded cup is Cham and Whiteson's hot rock, set on your table. Like the rock, the cup gives off heat, keeps every one of its pieces, and loses mass.

In 1905 Albert Einstein published a short paper whose title asks whether the inertia of a body depends on its energy content. He showed that a body that gives off light loses inertia in proportion to the energy it gives off. So the answer to the question in his title is yes: the inertia of a body does depend on its energy content, and a body's inertia is its energy content divided by the speed of light squared.

Think of everything about the hot coffee that could be found. Each molecule has its own motion, faster in the hot coffee than in the cool. The molecules have an arrangement, and the bonds between the molecules hold a strain. Each motion, each arrangement and each strain is something that could be found in a comparison. I give a name to how much of a thing there is to be found: the thing's *pattern*. A thing's pattern is an amount, counted by how many comparisons the thing can enter and how many findings can be made of it. Every motion, arrangement and strain of the parts adds to that amount. To compare two things is to have them act on each other, so every finding is an interaction. So a thing can be found exactly as much as it can interact, and physicists measure how much a thing can interact by its energy and, for a thing at rest, by its mass.

So the mass of a thing follows its pattern. In the hot coffee the molecules move faster, so the hot coffee holds more motion to be found, and the cup is harder to move. A wound spring is curled steel that stores energy in its shape, as the coil of spring steel in Chapter 3 does. A wound spring weighs more than the same spring unwound, because its parts are arranged under strain. The box of light weighs more than the empty box. The proton weighs a hundred times as much as its quarks, because nearly

all of what there is to find in a proton is the motion and binding of its parts. In every case the arrangement and motion of the parts set the mass, and a count of the pieces does not set it.

So mass is found three times over, and you can make each of the three findings with your cup. First, mass is found by how much of the cup there is to be found: the cup's pattern. Second, mass is found by how hard the cup is to set moving: the cup's inertia, the resistance you feel when you set the cup moving. Third, mass is found by how strongly the earth holds the cup: the cup's weight, the pull you feel when you lift it.

To join the three findings, I identify the hold that the context takes on a thing (its weight) with the thing's resistance to a change of its place in that context (its inertia). The context offers a thing only one relation, which is to be found there, so the hold and the resistance are that one relation, and nothing is left by which they could differ. Weight and inertia are then one quantity, and from the same identification I read what that quantity measures. To take part in the context is to be found in the context, and the degree to which a thing can be found is how much of the thing there is to find: its pattern. So pattern, inertia and weight are one relation of a thing to its context, found three times. Mass is the measure of that one relation of a thing to the thing's context.

Three Meanings of Mass

Cham and Whiteson ask a sharp question about the smallest particles. The top quark and the up quark have the same charge and the same spin, and both are points with no size, yet the top quark is about seventy-five thousand times as massive as the up quark. How can one point have more mass than another, with no more stuff in it? And how can the photon, the particle of light, have no mass at all and still be a particle of something?

Chapter 4 showed that every comparison has three positions: the act of comparing, the thing compared, and the thing compared against. Chapter 4 also showed that three particles, which it called the carriers of the world

we measure, fill those three positions: the photon is the act, the electron is the thing compared, and the proton is the thing compared against. The word mass means something different for each of the three carriers.

For the electron, mass is *rest mass*: the fixed characteristic a lasting thing keeps when it sits still. Rest mass is the mass of everyday life: the weight of a thing and its resistance to being pushed.

For the photon, mass is *exchange mass*: the mass that carried energy shows. A photon has no mass at rest, because a photon is never at rest, and so a photon's whole pattern is carried in its motion. Shut light in the box of mirrors, though, and the box gains the mass of the light's energy. Exchange mass is the mass of the act of carrying, and of no thing.

For the proton, mass is *confinement mass*: the mass of a whole whose parts cannot get out. Picture a rubber band. Stretch the band, and the energy stored in it grows. Stretch it far enough, and it snaps into two shorter bands, so that neither end ever goes free. The band stands for the color field between two quarks, and its two ends stand for the two quarks. The color field does the same as the band: when the two quarks are pulled apart, the field snaps by making a new pair of quarks from its own energy, and no quark goes free. So the quarks of a proton can never be taken out and weighed alone, and nearly all of the proton's mass is the energy of the binding that keeps the quarks in. I call confinement mass the mass of the force that binds things: the weight of structure itself.

So the word mass covers three kinds of mass, one for each position of comparison. A famous number of physics is the proton's mass divided by the electron's, about eighteen hundred and thirty-six, and that number is a ratio across two meanings of mass: a confinement mass over a rest mass. Two different laws set the two masses in that ratio: the binding of the strong force sets the proton's mass, and the electron's coupling to the Higgs field sets the electron's. So the number eighteen hundred and thirty-six is a statement about the strength of the strong force where that force binds the proton, because the law of binding sets the proton's mass. The muon is the electron's heavier copy. The muon's mass over the elec-

tron's is a ratio within one meaning, rest mass over rest mass, and that ratio belongs on the ladder of masses, counted in halvings, that Chapter 5 climbed. The two kinds of ratio raise different questions. Once you know which kind of ratio a number is, you know which law to look for behind the number.

Cham and Whiteson are right that a particle's mass is no amount of stuff. But a mass also tells more than a label tells: a mass tells which position a thing holds in comparison, and how much of its one relation to its context the thing carries in that position.

What the Higgs Field Does

Now we can say what was found at CERN on that July day, and what the discovery settled. Chapter 5 gave names to two things. The condensate is the settled value that the Higgs field keeps throughout empty space. A particle of matter gets its mass by meeting the condensate with a coupling of its own: the stronger the coupling, the larger the mass. Cham and Whiteson give the same account of how a particle gets its mass from the Higgs field, and so does this book.

I add what the coupling joins together. Picture a football thrown in a spiral: the ball spins about the direction in which it flies, the way a screw turns as it goes in. A particle of matter spins too. When the particle moves fast, its spin turns about its direction of motion either as a right-handed screw turns or as a left-handed one, and that sense of turning is the particle's *handedness*.

Now run beside the football, faster than it flies, and look back at it. From where you run, you see the ball move backward, falling behind you, while it spins the same way as before, so to you it turns as a screw of the other hand. A particle with mass moves slower than light, so someone can always overtake it as you overtook the ball. To that overtaking observer, the particle's handedness is reversed. So a particle with mass has no fixed handedness: its mass joins its left-handed and right-handed parts into one particle.

The weak force turns one kind of quark or lepton into another. The weak force acts on the left-handed part of a particle, and not on the right-handed part. The weak force treats the two parts differently, so a particle's mass, which joins the two parts, needs something to join them, and the Higgs field does the joining. The condensate joins each particle's left-handed part to its right-handed part, and that joining is the particle's mass. A particle's coupling measures how much of that join the condensate makes. For the top quark the coupling is exactly one, the whole join, as Chapter 5 showed.

Imagine the condensate switched off: the mass that the Higgs field sets then comes apart from the mass of binding. The electron and the quarks would have no mass at all. The protons and neutrons would keep most of their mass, the mass of their binding. The pions are the lightest particles made of quarks, and the little mass that pions have comes from the masses of their quarks, so the pions would lose all of their mass. The carriers of the weak force would become nearly massless, and the weak force would act almost as far as the force that light carries. Electrons would travel at the speed of light and could not be held in atoms, so there would be no atoms and no chemistry.

So the Higgs field, found in 2012, shapes the world in two ways. The Higgs field sets the electron's mass, and the electron's mass mainly sets the size of every atom and the wavelengths of the sharp lines of light that glowing atoms give off. The Higgs field also sets the masses of the quarks, which are a small part of what you weigh. The color field sets the rest of your weight, and nearly all of that weight would stay with the Higgs field switched off.

Mass and Energy, One Currency

Cham and Whiteson end on their conclusion that mass does not really exist, and that it is all just energy. They are right that mass is no stuff, and right that all mass is energy at rest. Their conclusion leaves one more question: what is energy?

Picture a stone at the top of a hill, and the same stone at the bottom. The stone at the top has more energy. Where is that extra energy? The extra energy belongs to a relation among four things: the stone's mass, the height of the hill, the pull that would bring the stone down, and the two possible states, up and down, of which one is the case.

Among my physics books, one is on what a measurement is. I count six kinds of measure that every physical measurement needs. The six are how much of a thing there is (its pattern, measured as mass), distance in space, force, time, probability (how likely each outcome is), and possibility (the range of what could be found). Energy is no seventh measure. It is a relation expressible in the six. The stone on the hill is the example that I give: the stone's pattern, the difference of place that is the hill's height, the force that pulls the stone down, and the two possibilities, up and down; and the energy is the relation of all four.

So energy, too, is a measure of relations. Mass and energy are two measures of relations of a thing to its context. The famous equation is the rate of exchange between the two measures. A body at rest holds energy equal to its mass times the speed of light squared, while a body with no mass at rest carries energy by its motion, as light does. Cham and Whiteson liken the equation to trading dollars for euros, and the likeness is exact: mass and energy are one currency counted in two units, and the sources of mass are distinct. The electron's mass is the rest mass of the electron's kind, set by its coupling to the condensate. The mass of a box of light comes from the energy of the light in it. Nearly all the mass of a proton comes from the energy that binds its parts.

A measure of a relation is as real as anything you can hold. When you lift the hot cup, you hold three things that are one: how much of the cup there is to be found, how hard the cup is to move, and how strongly the earth holds the cup.

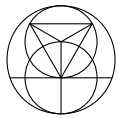
> **The short answer**
>
> Mass measures one relation of a thing to its context, found as its pattern, its inertia and its weight; mass and energy at rest are one currency; and most of your own weight is the binding of quarks.

Every finding has two sides, as Chapter 1 said: the content, which is what is found, and the context, which is where it is found. The short answer joins the two sides. The content of the world is the kinds of particle of Chapters 4 and 5, and mass is how each kind is held in its context, so in every weight you feel the content and the context are joined.

If weight and resistance to motion are one relation to the context, is gravity a force at all?

PART TWO

FROM THE PIECES TO THE ARENA



Chapter Seven

Why Is Gravity So Different from the Other Forces?

In which a hammer and a feather fall together on the Moon, and gravity turns out to be the arena of space and time in which every finding is made

Why is gravity so different from the other forces: so weak, and the same for everything that falls?

What this chapter uses

A *comparison* is the act of finding whether two things are the same or different in some respect, and every measurement is a comparison; a *finding* is the outcome of one comparison, laid down as a record; a *comparer* is whatever makes a comparison, whether or not the comparer has a mind (Chapter 1).

The *content* of a finding is what the finding finds, as the warmth of your coffee; the *context* is where the content is found, and the context has three sides, the three settings of space, time and possibility (Chapter 1).

The three *settings* in which anything is measured are space, the place of a finding; time, the moment of a finding; and possibility, the range of what could have been found instead; a setting is *bent* when one part of the setting differs from another part (Chapter 1).

Three things in nature do the bending: gravitation bends space, the cosmological constant bends time, and the dark matter bends possibility (Chapter 1).

Every comparison has three positions: the *act of comparing*, the relating; the *thing compared*, what is known; and the *thing compared against*, what the act of comparing reaches toward and never contains in one act, the beyond (Chapter 4).

The basic elements of matter are a closed list of kinds of particle: the kinds are few because every comparison has three positions, and each kind of matter comes three times, in three *generations* (Chapter 4).

On 2 August 1971 the astronaut David Scott, of the Apollo 15 crew, stood on the Moon at the Hadley landing site. Scott stood beside the lunar module, which the crew had named Falcon, during the crew's third walk on the lunar surface. A television camera was aimed at Scott's hands. "Well, in my left hand, I have a feather; in my right hand, a hammer", he said. The hammer was a geologist's hammer of aluminum, with a mass of

about one and a third kilograms. The feather had a mass of about thirty grams, and the feather came from a falcon. Scott called the feather a falcon feather, "for our Falcon". Scott recalled that the Italian scientist Galileo, long before, had made "a rather significant discovery about falling objects in gravity fields", and Scott said that the Moon was a good place to confirm Galileo's findings. He held the hammer and the feather at about the same height, a little more than one and a half meters above the ground, and let both go at the same moment. The Moon has no air to hold a feather back. The hammer and the feather fell side by side and struck the ground together. The astronaut Joe Allen was speaking to the crew from the ground, in Houston, and Allen answered, "How about that!" Scott added, "Which proves that Mr. Galileo was correct in his findings".

The hammer had more than forty times the mass of the feather, and the Moon pulled on the hammer more than forty times as hard as the Moon pulled on the feather. The hammer also resisted being set moving more than forty times as much as the feather did. The larger pull and the larger resistance matched exactly, and so the hammer and the feather fell at one pace. Gravity's pull on every body matches the body's resistance to being set moving, whatever the body is made of. No other force in physics matches its pull to a body's resistance to being set moving.

From Cham and Whiteson's pages

What Cham and Whiteson Showed

Jorge Cham and Daniel Whiteson list four ways in which matter interacts: gravity, electromagnetism, the weak nuclear force and the strong nuclear force (*We Have No Idea*, ch. 2, "How Matter Interacts"). Cham and Whiteson describe the list as a record of what has been observed, and they write that physics has no account of why any one of the four forces exists. Cham and Whiteson open their sixth chapter by setting gravity against the other three forces: "It is weirdly weak, it nearly always attracts rather than repels, and it doesn't play nice with a quantum view of the world" (*We Have No Idea*, ch. 6, opening).

Cham and Whiteson picture how weak gravity is with a test you can try at home. A small kitchen magnet lifts a nail against the pull of the whole Earth. The pull of a small magnet beats the pull of a planet. Cham and Whiteson put the size of the difference at about ten to the thirty-six: in their telling, gravity is weaker than the other forces by a factor of a one followed by thirty-six zeros. They also explain why so weak a force still governs the motions of the planets and the galaxies. Electric charges come in two signs, and the Earth and the Sun each hold nearly equal amounts of both signs, so the electric pulls between the Earth and the Sun cancel. Mass comes in one sign only, as Cham and Whiteson describe mass. So the pulls of gravity never cancel, and at large scales gravity is the force that remains.

Cham and Whiteson set out a second puzzle about gravity in their chapter on mass. Chapter 6 called a body's resistance to being set moving the body's inertia, and called the mass measured by that resistance the body's inertial mass. A body's *gravitational mass* is how strongly gravity pulls on the body. Every measurement ever made has found a body's two masses equal. Cham and Whiteson write of the equality of the two masses: "In our current formulation of physics, we don't know why that is" (*We Have No Idea*, ch. 5, "Are the Two Kinds of Mass the Same?"). They write that physics assumes the equality, and that the assumed equality is central to Albert Einstein's *general theory of relativity*, which describes gravity as a bending of space. They grant that Einstein's theory makes the equality more natural, but hold that the theory still does not say why the equality is there. Cham and Whiteson answer the question of why gravity is so different with the refrain that gives their book its title: we have no idea. Cham and Whiteson also name one possibility with care: if gravity turns out to be special, "It might mean that gravity is something deeper that is ingrained in the fabric of the cosmos" (*We Have No Idea*, ch. 6, "Maybe Gravity Is Special").

I take that possibility at its full strength: gravity is the fabric of the cosmos itself, the space and the time in which everything in the cosmos is found.

Three Forces, One for Each Position

I begin with the forces that act on particles. Watch a candle burn for an hour; the candle was tall before the hour, and after the hour the candle is short. To say that the candle has changed is to find that the candle after the hour differs in length from the candle before. Chapter 1 called the act of finding whether two things are the same or different in some respect a comparison. So a change is itself a comparison: a comparison of what was before with what is after. A force, at root, is a change in what the force acts on, from one way before the interaction to another way after. When a force acts on a particle, then, a comparison is acting on what the particle carries.

Chapter 4 found that every comparison has three positions. The first position is the act of comparing. A particle of matter carries three things that a comparison can act on, one thing for each of the three positions. The first thing a particle carries is color: Chapter 5 described color as the charge that the strong force acts on, in three kinds. The second thing is the *doublet*, a pair of particles alike in kind and different in one respect, such as the up quark and the down quark, or the electron and its neutrino. The third thing is a phase: Chapter 4 described a phase as a position on a circle, like the position of a clock's hand. Chapter 4 met a phase carried by the mixture of the generations, the three copies of every kind of matter, which differ in mass. The phase in this chapter is a different phase, the phase of the particle itself. When light acts on a particle's charge, the light acts on how the angle of the particle's phase turns.

Color, the doublet and the phase each belong to one position of comparison. Color belongs to the thing compared, what is known, because color is the arrangement that the thing known holds inside itself. The two

sides of the doublet belong to the thing compared against, the beyond. The phase belongs to the act of comparing, because the act of comparing reads every particle through the particle's phase.

Carrying a thing that belongs to a position differs from filling the position as a whole particle. Chapter 4 placed three whole particles in the three positions, in the world we measure: the photon as the act of comparing, the electron as the thing compared, and the proton as the thing compared against. The question in this chapter is a different one: what does a piece of matter carry inside itself for a force to change? The arrangement of the three colors is the three positions of comparison held inside a piece of matter. Only some matter holds the three positions inside itself: every quark carries one of the three colors, and a lepton carries none. The electron is a lepton, so the electron carries no color and feels nothing of the strong force. Chapter 4 found the electron's place as the thing compared, and that place is the place of a whole particle in the world we measure, not a thing that the electron carries. The quarks inside the proton carry color.

A force can change color in one way, the doublet in one way and the phase in one way, so there are three forces. The strong force turns one color into another, and the strong force has eight carriers, called gluons. The weak force turns one side of a doublet into the other, and the weak force has three carriers. The force on the phase has one carrier. Comparison has three positions and no fourth, so the particles carry three things for a force to change, and no fourth thing.

Where, then, is electromagnetism, the force of Cham and Whiteson's kitchen magnet? Picture two jugs, one of water and one of milk. Pour both jugs into two glasses, so that each glass holds some water and some milk. The glasses hold the same two liquids as the jugs, in two new mixtures. Two carriers of the forces mix the way the water and the milk mix. The Higgs field settles into one steady value everywhere, and Chapter 5 called that steady value the condensate. When the Higgs field settles, two carriers combine into two new carriers, as the water and the milk combine in the glasses. The two old carriers are the one carrier of the force on the

phase and the uncharged carrier of the weak force. One new carrier is the photon, the particle of light, which stays without mass. The other new carrier is a heavy particle called the Z. So the force of light, electromagnetism, is the force on the phase as we encounter that force at everyday energies, after the two old carriers have mixed. The phase belongs to the act of comparing, and Chapter 4 found the photon to be the act of comparing, so the photon is the carrier that the force on the phase has at everyday energies. Cham and Whiteson state the mixing of the two forces in their own terms: they write that the weak force and electromagnetism are two parts of one "electroweak" force (*We Have No Idea*, ch. 2, "How Matter Interacts").

The three positions of comparison are the answer to Cham and Whiteson's first question about the forces: why does any force exist at all? A force exists because comparison acts on what a particle carries, and there are three forces because comparison has three positions. Gravity is the one item of Cham and Whiteson's list of four that has no place among the three forces.

The Stage and the Actors

Picture a play. The actors move and speak, and each actor acts on the others. The stage is where all the actors stand. The stage has a shape, and every actor walks on the stage, yet the stage is not one of the cast.

Chapter 1 found that every finding, the outcome of one comparison, has two sides: the finding's content, which is what is found, and the finding's context, which is where the content is found. Space and time together are the *arena*: two of the three settings, the space and time in which every finding of physics is made. The three forces of particle physics are the strong force, the weak force and the force on the phase. The three forces are fields laid out within the arena, and the three forces act on the content. The carriers of the three forces belong with the context in a first, narrow sense: each carrier belongs to a field that spreads without a break through space, within the arena. Gravity belongs with the context in a

wider sense: gravity is the arena itself. The arena takes a shape around matter and energy, and the pull we feel as gravity is the shape of the arena. Gravity is not a fourth force with a carrier in this sequence. It is the arena. So the list has three forces and the arena, and gravity is the stage, not one of the actors.

Cham and Whiteson give an account of Einstein's theory that is close to the idea of the arena. They write that in Einstein's picture space bends around matter and energy, and that the Earth circles the Sun by following the bent space, with no force pulling the Earth round. Einstein described the shape of the arena with great exactness. Four marks set the context of every finding of physics apart from the three forces, whatever that context is. Gravity carries all four marks because gravity is the arena.

Four Marks of a Context

Chapter 1 also found that content and context go together: every content is found in a context, and from that fact alone we can ask what any context must be like, before anything is called gravity. Any context has four marks, which I derive. Each mark has a plain reason.

The first mark is that a context takes hold of everything. Everything found is found somewhere, in a context, so a context takes hold of everything found in the context. The three forces each leave some things untouched. A neutron and a ray of light pass through an electric field undeflected, and an electron feels nothing of the strong force. Gravity takes hold of everything. Gravity bends the light of stars that passes the Sun, and gravity takes hold of the energy of motion and the energy that binds a body, as well as of the matter at rest. Gravity takes hold of antimatter too. Antimatter was the hardest case to test. Chapter 4 said that antimatter is matter whose particles have the masses of the ordinary particles and the opposite charges. *Antihydrogen* is the antimatter counterpart of a hydrogen atom: a particle with the proton's mass and the opposite charge, bound to a particle with the electron's mass and the opposite charge. In 2023 the ALPHA-g team at CERN, near Geneva, released atoms of anti-

hydrogen in a tall upright trap and watched where the atoms went. The atoms fell downward, at a rate in agreement with the rate for ordinary matter. E. K. Anderson reported the fall with the other members of the ALPHA-g team. We now know that matter and antimatter both fall toward the Earth.

The second mark is that a context reaches through every barrier, so no wall can shut a context out. Think first of a shield that works. Step into a metal elevator, and your phone loses its signal, because the metal walls keep the radio waves out. The metal holds electric charges of both signs, free to move. A field from outside pushes the positive charges one way and the negative charges the other. The charges settle where the charges' own field cancels the field from outside. A shield therefore needs two things: something opposite to the source, and parts that the field pushes apart. A region of space, though, is itself a stretch of the arena. So a region with the arena taken out would be no region at all. A shield for the arena would remove what makes the shielded place a place, and so the arena is in every place.

The elevator also shows, from the side of matter, why nobody can build a shield for gravity. Gravity takes hold of energy, and the energy of every body yet weighed is positive, matter and antimatter alike, as the antihydrogen that fell in the ALPHA-g trap showed for antimatter. So nothing is opposite to a source of gravity, and nothing can cover the source. The positive energy of every body yet weighed is also the answer to Cham and Whiteson's puzzle that gravity only attracts. Every pull of gravity measured between two bodies has been an attraction, because gravity takes hold of energy and all energy yet weighed is positive. Every body also falls alike, so gravity never pushes the parts of a body apart into the opposed arrangement that a shield would need. So no arrangement of matter covers a source of gravity.

Physicists have tested, on the largest scale near us, whether matter soaks up gravity. If the Earth absorbed some of the pull of the Sun, part of the Earth's own mass would be hidden, and the Earth and the Moon would fall toward the Sun at different rates. Scientists send laser pulses to

the Moon and time the pulses on their return, and the timing follows the Moon's path very finely. In 2009 three scientists reported from the laser timing that the Earth and the Moon fall toward the Sun at one rate. The three scientists were James Williams, Slava Turyshev and Dale Boggs. The absorption that they measured was smaller than the uncertainty of the measurement. We now know that the Earth soaks up none of the Sun's pull, as finely as the laser timing can tell.

The third mark is that a context has one mass for the context's pull on a body and for the body's resistance to being moved, as the hammer and the feather showed on the Moon.

The fourth mark is that a context takes hold of a quantity that varies smoothly, with no steps in it. Electric charge comes in whole multiples of one third of the electron's charge, and every quark carries one of exactly three colors. Charge and color are exact labels, and both labels come in steps. Gravity takes hold of the whole energy of a body, and the whole energy varies smoothly: the body's matter at rest, the body's motion and heat, and the energy that binds the body's parts. Chapter 6 found that the cup on your table weighs a little more hot than cold, and the hot cup shows the fourth mark at your own table: the cup's heat varies smoothly, and the cup's heat adds to the cup's weight.

Gravity has all four marks. The three forces of particle physics have none of the four. The four marks come together because the four marks are four results of one fact: whatever has the four marks is the context of what is found, and no content within the context. Gravity's pull is the shape that space and time take around matter and energy, as Einstein described the pull, so of the three sides of the context, gravity is the two sides that are space and time. I identify gravity with the arena because gravity matches all four marks: the arena is the space and time of every physical finding, the stage on which the three forces act.

Why Everything Falls Alike

Now try Scott's test at home. Fold a towel on the floor. Hold your empty cup in one hand and a spoon in the other, a hand's width above the towel, and let go of both together. The cup and the spoon land together. The cup has many times the mass of the spoon. Over so short a fall, the air hardly slows the cup or the spoon. You have found the third mark: the pull of gravity on a body equals the body's resistance to being moved, whatever the body is.

In 1907 Albert Einstein asked why a body's two masses agree, and he found the beginning of an answer in a picture. Picture a person falling freely from the roof of a house: while he falls, he feels no weight, and an apple let go beside him falls with him and seems to him to float. Later Einstein drew a second picture beside the first. Picture a small closed room far out in space, with no planet near the room, pulled steadily upward by a rope. Everyone inside the room is pressed to the floor, and an apple let go falls to the floor, exactly as an apple would fall in a room resting on the Earth. Nobody inside the closed room can tell, by any experiment, whether the room is resting on the Earth or being pulled through space. In the room pulled upward, the apple only seems to fall: the floor speeds up toward the apple, and the floor reaches a hammer and a feather at the same moment, because the floor is what moves. Einstein stated that gravity and a steady speeding up cannot be told apart in a small closed room. Physicists call Einstein's statement the *equivalence principle*. The plainest part of the equivalence principle is the equivalence of weight and inertia: a body's gravitational mass equals the body's inertial mass.

The reason that the two masses are equal lies in the difference between a force and the arena. Where one of the three forces acts on a body, the body has two separate properties. One property is the body's charge, a label the body carries as content, and the other property is the body's inertia: the body's resistance to a change of its place in the arena. A label of the content is one thing, and a relation of the content to its context is another. So nothing ties a body's charge to the body's inertia, and charge and

inertia differ freely from one body to the next. The electron and the proton carry charges of equal size and opposite sign, and the proton has about eighteen hundred and thirty-six times the inertia of the electron. In one electric field, the electron and the proton respond very differently.

For gravity, the case is different, because gravity is the arena itself. Chapter 6 identified a body's weight with the body's inertia. A body has only one relation to its context: the body is found there, so the hold and the resistance cannot differ. The pull of gravity on a body is the hold that the arena takes on the body, so the pull and the body's inertia are one quantity, found twice, whatever the body is, and every body falls alike. Chapter 6 found the one relation of a body to its context three times: as the body's pattern (how much of the body there is to be found), as its resistance to being moved, and as its weight. The equality of weight and inertia is two of the three findings, inertia and weight, side by side.

The equality of the two masses is no longer a law recorded and not interpreted. It follows from what gravity is. The arena is the ground for reading the equality as following from what gravity is: for the arena, there is only one mass to measure.

Scientists have measured the equality of the two masses for more than three centuries, each time more finely. In 1687 the physicist Isaac Newton described a test with pendulums in his *Principia*. Newton hung two equal wooden boxes on equal cords, and he filled one box with wood and the other with an equal weight of gold. Newton made other pairs filled with silver, lead, glass, sand, salt, water and wheat. The pendulums swung together for a long time, and Newton reported that he would have seen a difference of a thousandth part. Between 1889 and 1909 the Hungarian physicist Loránd Eötvös compared many materials with a delicate twisting balance. The balance was a rod hung on a fine thread, and the rod turns at the faintest difference in the pulls on the rod's two ends. Eötvös found the materials equal to a few parts in a billion. From 2016 to 2018 the French satellite MICROSCOPE carried test masses of titanium and platinum in orbit, and in 2022 the physicist Pierre Touboul and his colleagues reported that the titanium and the platinum fell alike to within a few parts

in a million billion. Scientists also use the laser timing of the Moon to test the energy of gravity itself: the energy bound up in the pull of a body's own parts on one another. The Earth and the Moon hold very different shares of the energy of gravity, and the Earth's share is much the larger. Williams, Turyshev and Boggs found that the Earth and the Moon fall toward the Sun alike: the Earth's ratio of gravitational to inertial mass and the Moon's ratio agree to about one part in ten trillion. We now know that every material ever tried, and the energy of gravity itself, falls at one pace in one field, as the arena requires.

Why Gravity Feels So Weak

Stand on a mountain and look down. The houses in the valley look small because the houses are far away, though each house is as large as a house anywhere. Someone in the valley who looks up sees the figure on the ridge as small too. One distance makes the houses look small from above and the figure look small from below. The distance is real. The smallness is a matter of where you stand. I use the mountain and the valley as a picture of how weak gravity is. The picture contains the whole reason that gravity is weak.

First, consider how weak gravity is, as measured. Between two hydrogen atoms, gravity is weaker than the electric pull between one atom's electron and the other atom's proton by some thirty-six powers of ten. A hydrogen atom has nearly two thousand times the electron's mass. Thirty-six powers of ten is Cham and Whiteson's figure of ten to the thirty-six. *Newton's constant* is the measured number that sets how strongly gravity acts. Using Newton's constant, a physicist can write gravity's strength on a body as a pure number, a number with no unit. The pure number is the pull of gravity between two bodies, each of the given mass, measured against a fixed yardstick that nature supplies. The yardstick is a force made from the distance between the bodies and two constants of nature, the speed of light and the constant that sets the size of every quantum effect, with no property of the bodies in the yardstick. The yardstick weak-

ens with distance exactly as the pull of gravity does, so the pure number comes out the same at every distance between the bodies. Gravity's strength on a body grows as the square of the body's mass: double the mass, and the strength becomes four times as large. The *Planck mass* is the mass at which gravity's strength on a body reaches one: two bodies of the Planck mass pull on each other by gravity exactly as strongly as the yardstick. The Planck mass is about twenty-two millionths of a gram, about the mass of a grain of quartz sand a quarter of a millimeter across.

Now count the distance between the electron and the Planck mass. Chapter 5 measured masses in halvings. A halving is a factor of two in mass. The Planck mass is about seventy-four and a third halvings above the electron's mass. Gravity's strength grows as the square of the mass, and squaring a ratio doubles the ratio's count of halvings. So gravity's strength on the electron is one, halved about a hundred and forty-nine times. A hundred and forty-nine halvings come to about forty-five powers of ten. Two parts make up the step from Cham and Whiteson's thirty-six powers of ten to the electron's forty-five. First, each electron is nearly two thousand times lighter than a hydrogen atom, and gravity goes as the square of the mass, so between two electrons gravity is weaker than the electric push by a number forty-three digits long. Second, the electric push between two electrons is itself about one part in a hundred and thirty-seven of the same yardstick. A factor of a hundred and thirty-seven adds about two powers of ten. Physicists call the number one part in a hundred and thirty-seven the strength of light. Gravity is weaker by far, and the reason is a distance. The weak force is feeble at everyday energies for a different reason, because the carriers of the weak force are heavy, while gravity has no carrier, and gravity's feebleness comes from the distance between the electron and the Planck mass.

Look at the distance between the electron and the Planck mass from both ends. From the electron, looking up, gravity seems feeble. From the Planck mass, looking down, the electron seems light. Gravity's feebleness and the electron's lightness are one distance, read from the two ends of that distance. So two questions are one question: "why is gravity so weak

on the electron?" and "why is the electron so light?" On a body of the Planck mass, a grain of sand you could just see on your fingertip, gravity's strength is one. The particles of our world are very light against the Planck mass, so gravity between any two of the particles is very weak. Gravity becomes strong where masses add up, as masses do in planets, stars and galaxies, and there Cham and Whiteson's account of why gravity governs the large scales applies in full.

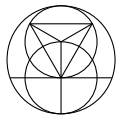
One more difference between gravity and the three forces follows from gravity being the arena. Each of the three forces has its carriers among the kinds of particle, because a field laid out within the arena comes in particles. The shape of the arena is not a field within the arena, so the list of the kinds of particle has no carrier of gravity. A graviton would be a particle that carries gravity, as the photon carries light. The zoo has no graviton. The missing graviton is the third difference that Cham and Whiteson name, gravity's poor fit with a quantum view of the world, seen from the side of the context. Chapter 8 treats the third difference in full: a graviton is at most a step in the description of small waves of the arena.

> **The short answer**
>
> Gravity is the arena, the stage of space and time on which the three forces act: so everything falls alike, nothing shields gravity, and gravity is feeble on the electron because the electron is very light against the Planck mass.

Chapter 1 named three bends, one in each of the three settings, and two of the three bends lie in the arena. A setting is bent when the setting is out of its plain shape, the shape it has when nothing bends it. Gravitation, the bend of space, is the shape the arena takes around matter and energy. The cosmological constant is the arena's bend of time. General relativity is Einstein's theory of gravity, and general relativity describes the

shape of the arena. Quantum theory is the theory of the particles and of the three forces that act on the particles: the physics of the very small, which Chapter 3 described.

If gravity is the arena, and quantum theory is the theory of the particles and forces within the arena, how do general relativity and quantum theory meet?



Chapter Eight

How Does Gravity Meet the Quantum?

In which a ripple of space itself is caught, and the two great theories turn out to be two descriptions of one world

Gravity and quantum mechanics seem incompatible: how do they meet?

What this chapter uses

A *comparison* is the act of finding whether two things are the same or different in some respect, and every measurement is a comparison; a *finding* is the outcome of one comparison, laid down as a record; a *comparer* is whatever makes a comparison, whether or not the comparer has a mind (Chapter 1).

The *content* of a finding is what the finding finds, as the warmth of your coffee; the *context* is where the content is found, and the context has three sides, the three settings of space, time and possibility (Chapter 1).

Continuous: nothing is sudden, as along a ramp; *discontinuous*: something is sudden, as at the edge of a step; *symmetric*: what is found stays the same across a change of setting, as each step of a staircase is like every other; *asymmetric*: different everywhere, as the height along a ramp is (Chapter 1).

The *Incommensuration Theorem*: at the foundation of any event or comparison, symmetry and continuity cannot both be perfect together, and neither can asymmetry and discontinuity. The Incommensuration Theorem is a structural fact about the nature of knowing (Chapter 1).

Three things in nature do the bending: gravitation bends space, the cosmological constant bends time, and the dark matter bends possibility (Chapter 1).

Gravity is the *arena*, the stage of space and time on which the three forces act, and so gravity stands beside the three forces and is not a fourth force (Chapter 7).

At 11:53 in the morning, local time, on 14 September 2015, an automated e-mail arrived in the inbox of Marco Drago, a physicist at the Max Planck Institute for Gravitational Physics in Hannover, in Germany. The e-mail held links to two plots. Each plot showed a wave whose swings rose quickly in pitch, like the chirp of a bird. The two plots came from the two

detectors of LIGO, the American observatory built to catch gravitational waves (ripples in the shape of space), and LIGO has one detector in Livingston, Louisiana, and one in Hanford, Washington State. The detector in Livingston had recorded the chirp first, and the detector in Hanford seven thousandths of a second later.

Drago had been trained to look for exactly the chirp shape that the two plots showed. A few members of the LIGO collaboration could put fake signals into the detectors to test the detectors, and those few members kept secret whether a signal was real or planted. So Drago went down to the office of his colleague Andrew Lundgren and asked whether Lundgren knew of a planted signal. Drago then sent an e-mail to the whole LIGO collaboration, about a thousand people, and the scientists on the other side of the Atlantic woke up to Drago's e-mail a few hours later.

The chirp was real. In February 2016 the LIGO collaboration published its finding. The chirp came from two black holes that spiraled together and merged about 1.3 billion light-years away. A black hole is a region where matter is packed so tightly that nothing that falls in, not even light, comes back out, as Chapter 2 said. The two black holes had about thirty-six and twenty-nine times the mass of the Sun. In the last moments of the merger, about three Suns' worth of mass had gone into the gravitational wave. The wave had stretched and squeezed each four-kilometer arm of each detector by far less than the width of a proton, and the shape of the wave matched the shape that Einstein's theory of gravity computes for a merger of two black holes.

The plots that arrived in Hannover that morning recorded a ripple of space itself. Space and time had shaken across more than a billion light-years, and the two detectors of LIGO had registered the shaking. The ripple lets you ask your question in its sharpest form. At the scale of atoms and smaller, what physicists find comes in steps. Light comes in packets, charge comes in whole units, and every atom holds only certain energies. Was the ripple from the two black holes made of steps too? If the shape of space is gravity, and gravity rippled, is gravity a quantum thing, coming in steps like light, charge and the energies of an atom?

From Cham and Whiteson's pages

What Cham and Whiteson Showed

In *We Have No Idea*, the cartoonist Jorge Cham and the physicist Daniel Whiteson give the LIGO detection full credit. Cham and Whiteson write that the detection confirmed Einstein's picture of gravity as the bending of space. Cham and Whiteson are just as clear about what the detection did not settle: "It's like proving that light exists, but not that it is made of photons" (*We Have No Idea*, ch. 6, "So Much for That"). A photon is one packet of light. The point Cham and Whiteson make is that a wave seen as a wave shows nothing about whether the wave comes in packets.

Cham and Whiteson give two reasons why physicists have not joined gravity to quantum mechanics. The first reason is that nobody has ever seen a graviton. A graviton is the particle that quantum mechanics would need to carry gravity, as Chapter 7 described. The second reason is that every attempt to treat gravity by the method that worked for the other three forces gives infinite answers that cannot be removed. Cham and Whiteson name one place where quantum mechanics and relativity plainly disagree: the center of a black hole, where relativity puts a point of infinite density and quantum mechanics allows nothing to be pinned to a single point. Cham and Whiteson sum up the problem in one line: "these two theories are almost completely incompatible with each other" (*We Have No Idea*, ch. 16, "Joining Gravity and Quantum Mechanics").

In their second book, *Frequently Asked Questions About the Universe*, Cham and Whiteson find the same clash at the beginning of the universe. They explain that by quantum mechanics the universe has always existed, while by relativity the universe goes back to a point of infinite density. Cham and Whiteson state their conclusion directly: "It's clear that to answer our questions about the origin of the universe, we're going to need a new theory" (*Frequently Asked Questions*

About the Universe, ch. 11, "Who's Right?"). The authors' conclusion is the standard view of physics, stated fairly. Physics has two great theories, each confirmed wherever physicists have tested the theory, and the two theories must one day be merged into one.

I reach a different result. Quantum theory and general relativity are already joined. No new theory is needed to join quantum theory and general relativity, because the two theories describe two different sides of every measurement. I reach that result in five steps, each a question. What does each theory describe? Why can space and time not come in steps, as the findings of quantum theory do? Where is the gravity of a body when the body is in two places? What was the ripple that LIGO caught made of? And where must quantum theory and relativity both be used at once?

What Is Found and Where It Is Found

Chapter 1 showed that every finding, the outcome of one comparison, has two sides. The content of a finding is what is found: the warmth of a cup, the charge of a particle, the click of a counter. The context of a finding is where the content is found: at one place, at one moment, and among one range of possibilities. Chapter 7 then showed that gravity belongs to the context side. Gravity is the arena: space and time together, two of the three settings of every finding, which are space, time and possibility. Gravity carries all four marks that Chapter 7 found in whatever is the context of every finding: gravity takes hold of everything, nothing shields gravity, everything falls alike in gravity, and what gravity takes hold of, energy, varies smoothly, with no steps.

Now look at what the two great theories of physics, quantum theory and general relativity, describe. Quantum theory describes what a measurement finds. The findings that quantum theory describes come in separate, countable steps, and the findings repeat exactly: every electron has exactly the same charge and exactly the same mass as every other electron.

The geometry of the arena, its shape, is smooth: a small step in place or time brings only a small change. The geometry of the arena also differs from place to place: space near the Sun is shaped differently from space near the Earth. I identify quantum theory as the description of the content of physics, and general relativity as the description of the arena, which is the space and time of the context of physics.

Chapter 1 also gave the Incommensuration Theorem. The theorem sets what any description of content or of context can be. Chapter 1 pictured the theorem with a ramp and a staircase. In that picture, a comparison can be made perfect at its foundation in only two ways. The comparison can be smooth and different from place to place, like the height along a ramp, and the arena has that character. Or the comparison can repeat exactly and come in countable steps, like a staircase whose every step is like every other, and what is found has that character. General relativity has exactly the character of the ramp, and quantum theory has exactly the character of the staircase.

A Question of the Wrong Kind

In the first chapter of his book *The Concept of Mind* (1949), the philosopher Gilbert Ryle told a story about a visitor to Oxford. A guide shows the visitor the colleges, the libraries, the laboratories and the offices. At the end of the tour the visitor asks: "But where is the University?" The visitor has made no mistake of fact, because every building was where the guide said the building was. The University is the way the colleges, libraries and laboratories are organized and work together. So when the visitor looks for the University as one more building, the visitor applies the idea of a building to a thing of another kind.

Ryle's visitor made what philosophers call a *category error*: applying a concept where the concept does not belong, so that the request cannot be met because the request is badly formed, which is a different thing from

being hard to meet. Once the visitor sees that a university and a building are things of different kinds, the category error is gone, and nothing real is lost: the colleges still stand.

Physicists have been asking a question of the same kind as the visitor's for more than ninety years. A field is something spread through all of space whose smallest ripples are the particles, as Chapter 3 said, and a field has a value at every place and moment, as the electric and magnetic field does. To *quantize* a field is to give the field the character of what is found: the waves of the field are then found in countable packets, and the exact symmetries of the field fix which packets can be found. Physicists brought light into quantum theory by quantizing the field of light, and then, by the same method, the strong force and the weak force, the two other forces of the particle world. Quantizing worked every time because light and the strong and weak forces are content, things found at places and times in the arena, and when physicists quantized light, the light gained steps and the space that the light crosses gained none.

Physicists counted gravity as the next force in line, and in the research programs of *quantum gravity*, the search for a quantum theory of gravity, physicists set out to quantize gravity the way they had quantized light. But gravity is the arena itself, so to quantize gravity is to ask the arena, where every finding is made, to take on the character of the things found in the arena. A quantized arena would have to do one of two things. Either the arena keeps its smoothness and gains the exact sameness of what is found, which joins continuity with symmetry. Or the arena keeps its differences from place to place and gains steps, which joins asymmetry with discontinuity. The Incommensuration Theorem forbids exactly those two pairings: continuity with symmetry, and asymmetry with discontinuity. Quantizing the arena has a second fault. When physicists change the character of their description of light, the arena stays in place to hold the new description. When physicists ask the arena itself to change its character, nothing stays in place to hold the new description, because the arena is where every describing happens.

So physicists make a category error when they search for one theory that quantizes the arena. The error has the same form as the error of Ryle's visitor, who looked for the University as one more building. Once the category error is set aside, quantum theory and general relativity remain exactly as experiments have confirmed them. Nothing in either theory has to be given up. The question that Cham and Whiteson asked remains, now in its proper form: how does a smooth arena go together with matter whose findings come in steps?

Where Is the Gravity of a Body in Two Places?

Quantum theory often describes a small body as being in two places at once. The phrase "in two places at once" is a shorthand. Quantum theory describes two alternatives, the body here and the body there, held together with a definite relation between the two alternatives until a finding is made, and the finding is one alternative or the other. Physicists call a combination of alternatives held together with a definite relation a *superposition*.

In 1957, at a conference on gravitation at Chapel Hill in North Carolina, the physicist Richard Feynman put to his colleagues the plainest form of the question of how gravity and the quantum fit together. Feynman imagined a quantum event that puts a small ball into a superposition of two places. Feynman asked what the gravitational field of the ball would then be. Feynman's own answer was that the gravitational field must be in a superposition too, and so that gravity must be quantized.

In the account of this book, Feynman's question has a different answer. Each alternative of the matter has its own smooth geometry, shaped by the energy of that alternative. In the sense Chapter 3 gave the word, the geometry of a region is the shape of space and time in the region, the shape of the arena. In the alternative where the ball is here, the arena has the shape that a ball here gives the arena. In the alternative where the ball is there, the arena has the shape that a ball there gives the arena. Neither alternative has a blend of the two shapes.

Each alternative has its own geometry because the two sides of every finding, its content and its context, never come apart. Wherever there is content, there is context. Each alternative of the ball is a possible content: one of the things that a finding could find. So each alternative of the ball has a context. The two alternatives are never found together, since the ball is never found both here and there. So no single context belongs to both alternatives, and each alternative has a context of its own. The geometry is the context of the matter, and so each alternative of the matter has its own geometry.

Think of an architect who draws one house on two possible sites, and you can see why each alternative needs its own geometry. The architect makes one drawing for each site, and each drawing shows the house and the shadow that the house casts at noon. Each drawing stands for one alternative of the ball, and each shadow stands for the shape that one alternative gives the arena. Lay the two drawings over each other and average the two drawings, and the averaged drawing shows half a shadow on each site, cast by half a house on each site. No house that could be built casts half a shadow on each of two sites. Each drawing is right about the shadow on its own site, and the averaged drawing is right about no shadow that any house could cast.

When each alternative has its own geometry, nothing is quantized. Inside each alternative the arena is smooth, with no least step, as relativity describes the arena, while the alternatives are separate because the alternatives belong to the matter, and the findings of matter come in steps. When the matter is sharply one alternative, as a star, a planet or a black hole of definite mass is, there is one alternative and one geometry, the familiar geometry of relativity. So astronomers keep every calculation they make with Einstein's equations as it is. A coming experiment, proposed by Bose and colleagues in 2017, will hold two small masses each in two places at once and look for the two masses to become entangled through their gravity alone, linked so that their measured results agree in a pattern that no instructions carried by the masses could give. In the appendix "What the Coming Measurements Will Find" I say, as Prediction 1, that

the experiment will find the two masses entangled, and on my account that finding shows no steps in the arena, since each placement of the masses has its own smooth geometry.

Physicists have already tested the rival answer, which matches the averaged drawing of the architect. In the early 1960s the physicists Christian Møller and Léon Rosenfeld kept one geometry for all the alternatives together, shaped by the average of the energies of the alternatives. In 1981 the physicists Don Page and C. D. Geilker put the averaged geometry to a direct test. Page and Geilker used a torsion balance, the instrument that the scientist Henry Cavendish had used in 1798 to weigh the Earth. In a torsion balance a light bar hangs level from a thin wire, with a small lead ball at each end, and large lead balls placed nearby turn the bar a little by the pull of the large balls. A Geiger counter is an instrument that clicks once for each particle a radioactive source gives off. Before each run, a Geiger counter registered the decays of a radioactive source, and each decay is a quantum event. The counter's reading fixed which of two positions the large balls took. In one position the large balls turned the bar one way. In the other position the large balls turned the bar the other way.

If the quantum event is never reduced to one outcome, the averaged geometry gives half a pull each way, which is no pull at all, so on the averaged account the bar would stay still. The bar turned on every run. Each time, the bar turned the way that the actual position of the large balls required, sometimes one way and sometimes the other, so the gravity followed the outcome of the quantum event, not the average of the outcomes. One geometry for each alternative predicts exactly the result that Page and Geilker found. And one geometry for each alternative needs no geometry that comes in steps.

What the Ripple Was Made Of

Now return to the chirp that reached Hannover. A gravitational wave is a ripple in the geometry itself: as the wave passes, the wave stretches distances in one direction and squeezes distances in the other direction,

and then the reverse. The two detectors of LIGO have a partner of the same kind: Virgo, the European detector near Pisa, in Italy. The smooth geometry of general relativity describes everything that LIGO and Virgo have measured, including the shape of the first chirp. The authors and my account agree on what the wave showed. Gravity is the bending of space, and the wave by itself does not show that gravity comes in steps.

The authors, like Chapter 7, call the particle that would carry gravity the graviton. In physics, "graviton" is the name for one packet of energy in the description of small waves of the arena, counted in the way that packets of light are counted, and describing small waves by packets of energy is established physics. In 1994 the physicist John Donoghue showed how to treat gravity at ordinary energies as an *effective theory*, a description that holds within a stated range and states its own range, and for gravity the range is gentle curving and small waves. Inside the range of gentle curving and small waves, physicists can count the energy of each way the geometry ripples in equal steps. With the energy of the ripples counted in steps, the effective theory of gravity gives finite corrections to Newton's law of gravity. For two masses a meter apart, the correction is about one part in a number seventy digits long. So, within its range, the description by steps has finite answers, which make the description working physics, and the description's corrections are negligible everywhere that physicists have tested the smooth law of gravity.

A crystal shows what one step in the description of a wave is. A crystal is a lattice of atoms held in place by the bonds between the atoms, as Chapter 2 described. Strike a crystal, and a wave of motion runs through the crystal: each atom swings a little about its place and passes the swing to its neighbors, and the wave of motion is sound. Quantum theory says that each way the lattice can vibrate takes up energy only in equal steps, and one step of energy in one way of vibrating is the phonon, which Chapter 2 named. Physicists count phonons every day, and phonons carry heat through a crystal. Yet nobody concludes from phonons that a crystal is made of phonons, because the crystal is made of atoms, and the phonon is a step in the description of how the atoms move together.

The word "graviton" has its nearest sense in the phonon, and that nearest sense has a limit. A crystal is a held structure, a structure whose parts are held in place by bonds. The arena is not a held structure: the arena has no parts that bonds hold in place, and the matter and energy in the arena set the shape of the arena. So the word "graviton" names at most a step in the description of a small wave of the arena, and never a piece of space and time, a step of the arena itself, or a particle that carries gravity. The arena is smooth at every scale, so gravitation itself has no steps. Physicists can still describe the small waves of the arena by steps.

Cham and Whiteson compared the wave with light, and the answer to their comparison is the difference between a held structure and the arena. Light is content, a field found within the arena, so quantizing light gave light steps and gave the space that light crosses none. A gravitational wave is of another kind: a gravitational wave is a ripple of the arena itself, and counting the energy of the ripple in steps is a way of describing the ripple, while the arena that ripples stays smooth. A detector that clicked once for each step would register steps of its own, and the clicks would not show that gravitation is quantized. In 2024 the physicists Daniel Carney, Valerie Domcke and Nicholas Rodd showed that single clicks in a detector come equally from a smooth wave acting on a detector whose own energies come in steps. Physicists had already learned from light that single clicks do not show a wave to be made of steps. In the photoelectric effect, light knocks single electrons out of a metal. The photoelectric effect is explained equally well by a smooth wave of light acting on the atoms of the metal, whose energies come in steps. A click is a step of the detector, and so a step of content, registered against the arena as the context of the click.

The record of gravitational waves agrees with the smooth description. No one has ever detected a single graviton. Cham and Whiteson report one calculation by which a detector the size of Jupiter, even near an intense source of gravitons, would see about one graviton in ten years (*We Have No Idea*, ch. 6, "Black Hole Colliders"). The detectors have measured smooth ripples with the features that relativity gives gravitational waves.

One of the features is speed: relativity gives gravitational waves exactly the speed of light. A neutron star is the collapsed core of a burned-out star, as dense as the nucleus of an atom. On 17 August 2017 LIGO and Virgo caught the waves of two neutron stars merging. Telescopes caught a burst of gamma rays, light of the highest energies, from the merger of the two neutron stars. The ripples and the light had crossed about 130 million light-years and arrived within about two seconds of each other. Physicists compared the two arrival times: the ripples travel at the speed of light, to within a few parts in a million billion.

Where the Two Descriptions Meet

Cham and Whiteson name a place where quantum theory and relativity must both be used at once. They are right that there is a place where both theories are needed. Every body has two lengths of its own, one from each theory. The first length is the body's *gravitational size*, which measures how strongly the body curves the arena. The gravitational size is the body's mass times Newton's constant, divided by the speed of light squared. If the body were squeezed inside twice its gravitational size, the body would be a black hole, so the gravitational size is half the radius of a black hole of the same mass. The gravitational size grows with the mass. For the Sun the gravitational size is about one and a half kilometers, and for the Earth about four and a half millimeters. The second length is the body's *quantum size*: the length within which, by quantum theory, the body cannot be pinned down. The quantum size shrinks as the mass grows, and for a proton the quantum size is about an eighth of the proton's own width.

For a proton the quantum size is far the larger, so quantum theory describes the proton, and the proton's own gravity is a faint background. For the Earth the gravitational size is far the larger, so relativity describes the Earth's gravity, and the Earth's quantum spread is negligible. The gravitational size grows with the mass and the quantum size shrinks, so there is one mass at which the two sizes are equal. The two sizes are equal at the

Planck mass, which Chapter 7 met: about twenty-two millionths of a gram, the mass of a grain of quartz sand a quarter of a millimeter across. At the Planck mass both sizes come to one length, the Planck length, about a hundred billion billion times smaller than a proton. The *Planck scale* is the scale at which a body's gravitational size equals its quantum size.

At the Planck scale the two lengths are equal, so neither description dominates, and both descriptions are needed. If a single description made both the ramp's character and the staircase's character perfect at the Planck scale, the description would hold at least one of the two pairings that the Incommensuration Theorem forbids: continuity with symmetry, or asymmetry with discontinuity. So the Planck scale is the place where two descriptions are both needed and stay two, each complete in its own character, and the Planck scale needs no third theory to replace quantum theory and relativity.

The Planck length also limits how sharply a comparison made from inside the world can place a body. To place something within a very short distance, a comparison needs a probe of very short wavelength. A probe of very short wavelength carries a great deal of energy. At the Planck length the probe would carry enough energy into the region being probed to make a black hole larger than the region. A light microscope shows how to read a limit on how sharply something can be placed. A light microscope cannot show details much finer than about half the wavelength of its light, and nobody concludes that a cell is built of tiles of that size. The limit is a limit of the looking, and the cell has whatever fine detail the cell has. In the same way, the Planck length limits how finely a finding can place a body, and the arena itself has no least length, area or duration. A *grain* of space and time would be a least step of length or of duration, a smallest piece below which there is nothing smaller, as a printed photograph has a smallest dot. Chapter 10 describes light from distant bursts that arrives together at every energy, and the light from the distant bursts shows that any grain of space that would slow light in proportion to the energy of the light is smaller than the Planck length.

The infinities that Cham and Whiteson describe agree with my account of the Planck scale. When gravity is quantized by the method that worked for the other three forces, the calculations give infinities that cannot be removed. The physicists Gerard 't Hooft and Martinus Veltman found the infinities in 1974, and Marc Goroff and Augusto Sagnotti found the infinities in 1986. The failure of the direct method is established. I take the failure as it is. The infinities show the scale at which the description of small waves stops holding: the *Planck curvature*, the amount of bending of space at which the quantum corrections grow as large as the effects they correct. At the Planck curvature a ripple would bend space as strongly as the background that the ripple rides on, and nobody could tell the wave apart from the background. Physicists met an infinity of the same kind as the infinities of quantized gravity around 1900, when the smooth theory of light of the nineteenth century predicted that a hot oven holds unlimited energy at the shortest wavelengths. The physicist Max Planck removed the infinity with a law that lets the energy passing between the light and the walls of the oven come in steps, which are steps of the content, and Planck's law gave space no steps at all. The infinity of the oven showed that physicists had carried a description of light beyond its domain.

I read the center of a black hole in the same way: as a place where a description is carried beyond its domain. At the center of a black hole the bending that relativity computes grows until the bending reaches the Planck curvature. At the Planck curvature the smooth description stops holding: the smooth description reaches the edge of its domain. The edge belongs to the smooth description. In Chapter 21 I walk with you into a black hole. We find that the end inside the black hole is the edge of the smooth description. In 1974 the physicist Stephen Hawking found that every black hole gives off a faint glow. By the glow, a black hole slowly gives up its mass. The calculation of Hawking's glow already uses quantum theory and relativity together. Hawking found the glow by lay-

ing quantum fields (fields such as light, described by quantum theory) on the smooth geometry of a black hole, and the geometry in Hawking's calculation is never quantized.

Already Joined

Go back once more to the detector in Livingston on 14 September 2015. A laser beam ran down each four-kilometer arm and back, and the two beams were combined at a light detector. The light of the laser is content: the light detector counts the light in photons. The stretching of the arms is a change of the arena: a smooth change of length, far less than the width of a proton. The detector registered steps of its own light against a smooth change of the arena. So quantum theory and relativity both applied in one instrument.

In every measurement the two theories meet in the same way: content is counted in steps, against an arena that changes smoothly. Quantum theory describes what is found, and relativity describes where the content is found. Each alternative of the matter has its own smooth geometry, and every finding is a finding of content in a context. Quantum theory and relativity are already unified, in the only way they can be: as the two conjugate sides of one domain of comparison, met in the act of measurement. Two things are *conjugate* when neither comes before the other, and neither can be made perfect except at the expense of the other. The *domain of comparison* is the range within which comparisons can be made. Quantum theory and relativity are set side by side and joined through the act of measurement, and never merged into one.

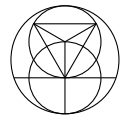
Cham and Whiteson called for a new theory, and the call therefore has its answer. Quantum theory and relativity seem to disagree at places of two kinds. At places of the first kind, physicists ask the arena to come in steps. At places of the second kind, physicists carry the smooth description past the edge of its domain. The second kind includes the beginning of the universe and the end inside a black hole. Chapter 20 shows that the

beginning is a limit drawn as a first moment, and Chapter 21 shows that the end inside a black hole is a moment ahead of every path within the black hole.

> **The short answer**
>
> Gravity and the quantum are two descriptions of one world, joined side by side, with one smooth geometry for each alternative of the matter, and neither has to be given up or quantized.

Once the two theories are joined side by side, nothing is left of the clash that Cham and Whiteson place at the origin of the universe and inside black holes. At both places the smooth description reaches the edge of its domain, and the two descriptions meet there with neither given up. Because the two theories are joined, I can walk with you to the beginning of the universe and into a black hole with the two theories that physics already has.

If the two great theories are joined and not merged, is there a theory of everything at all?



Chapter Nine

Is There a Theory of Everything?

In which one account of everything is found, made of descriptions set side by side

Is there a Theory of Everything, and would we know it if we found it?

What this chapter uses

A *comparison* is the act of finding whether two things are the same or different in some respect, and every measurement is a comparison; a *finding* is the outcome of one comparison, laid down as a record; a *comparer* is whatever makes a comparison, whether or not the comparer has a mind (Chapter 1).

The *content* of a finding is what the finding finds, as the warmth of your coffee; the *context* is where the content is found, and the context has three sides, the three settings of space, time and possibility (Chapter 1).

The *Incommensuration Theorem*: at the foundation of any event or comparison, symmetry and continuity cannot both be perfect together, and neither can asymmetry and discontinuity. The Incommensuration Theorem is a structural fact about the nature of knowing (Chapter 1).

Every comparison has three positions: the *act of comparing*, the relating; the *thing compared*, what is known; and the *thing compared against*, what the act of comparing reaches toward and never contains in one act, the beyond (Chapter 4).

Gravity is the *arena*, the stage of space and time on which the three forces act, and so gravity stands beside the three forces and is not a fourth force (Chapter 7).

Gravity and the quantum are two descriptions of one world, joined side by side, with one smooth geometry for each alternative of the matter (Chapter 8).

In January 1974 Howard Georgi was a physicist at Harvard University, in Cambridge, Massachusetts. Through the end of 1973, Georgi and the physicist Sheldon Glashow had tried to join the weak and the electromagnetic forces in one scheme. One evening that January, Georgi went home and, after dinner, worked out in a few hours a way to fit the strong force, the weak force and the electromagnetic force together as one. Georgi

found two things in the new scheme. First, the quarks and the leptons fit together into one larger pattern. Leptons are the particles of matter, such as the electron, that do not feel the strong force. Second, the three forces measured in the laboratory came out as three parts of one larger force. Then Georgi saw what the larger force would do to matter. In Georgi's scheme a quark could turn into a lepton. So a proton, which is made of three quarks, could break up into a positron (the electron's mirror partner, with the opposite charge) and a pion, one of the lightest particles made of quarks. "I finally went to bed when I found out that the proton decayed", Georgi recalled, "which to me was rather depressing".

When Georgi described the scheme to Glashow, the decaying proton was the part of the scheme that excited Glashow, and Georgi later granted that Glashow was right, because an experiment could look for the decay of the proton. Georgi and Glashow worked out how long a proton could last, given that the searches of the day had seen no proton break up, and then they wrote a short paper. The journal *Physical Review Letters* published the paper in February 1974 under the title "Unity of All Elementary-Particle Forces". The summary of the paper says that the strong, electromagnetic and weak forces are conjectured to arise from a single fundamental interaction.

Keep Georgi's picture in mind: one larger force, and every proton in the world able to break up. In Georgi's picture each proton has a door it can leave by. Is there one force, or one theory, from which everything else in physics follows? And if there were one larger force, would the protons in your own body show that larger force by breaking up?

From Cham and Whiteson's pages

What Jorge Cham and Daniel Whiteson Ask

In *We Have No Idea*, Jorge Cham and Daniel Whiteson give their largest question a chapter of its own: is there a Theory of Everything? They define the words of the question with care. For them a Theory of Everything is "the simplest possible mathematical description of

space and time and all the matter and forces in the universe at its deepest level" (*We Have No Idea*, ch. 16, "What Is a Theory of Everything?"). In Cham and Whiteson's definition, simplest means with as few unexplained numbers as possible. Deepest means at the smallest scale, with the tiniest building blocks and the most basic ways the building blocks fit together.

Cham and Whiteson then give the picture that their whole chapter uses: the universe, they say, is layered like an onion. Each layer has its own good theory, and the theory of each layer works without describing what happens in the layer beneath. A gas can be described as billiard balls bouncing off one another, the atom can be described as a little solar system, and the atom can be described again, and better, as quantum waves. So a theory could seem to describe the bottom layer and turn out to describe only one more layer. Cham and Whiteson put the worry that the layers may never end in one line: "What if it's baboons all the way down?" (*We Have No Idea*, ch. 16, "What Is a Theory of Everything?").

Cham and Whiteson walk the reader through three searches for the bottom layer. In the first search, physicists look for a smallest distance. In the second, physicists look for the smallest pieces of matter. In the third, physicists ask how many forces there are, and Cham and Whiteson tell the history of joining the forces. In the nineteenth century, physicists joined electricity and magnetism into one force. Later, physicists wrote the electromagnetic force and the weak force as one force. So the list of forces came down from four to three, and Cham and Whiteson ask the next question and answer it with their own refrain: "Is there just one force in the universe? We have no idea" (*We Have No Idea*, ch. 16, "The Most Fundamental Forces").

Next Cham and Whiteson report how far the search has come: so far, physicists have failed in every attempt to merge gravity and quantum mechanics into one theory. Cham and Whiteson describe two candidates for a final theory. In *string theory* each particle is one way a tiny

string can vibrate, and, the authors report, space and time in string theory have ten or eleven dimensions, if not more. String theory does not yet make any prediction that anyone can test, so believing in string theory, Cham and Whiteson say, is a question of philosophy, mathematics or faith, and not of physics. Cham and Whiteson name a second difficulty for string theory. The dimensions of string theory can be chosen in something like ten to the five hundred ways. So string theory still has far to go by the count of its unexplained numbers. In *loop quantum gravity* space itself is built of tiny loops, each the size of the Planck length. Cham and Whiteson report that loop quantum gravity has the same difficulty as string theory: no one can yet check loop quantum gravity. Loop quantum gravity makes one specific prediction, that the Big Bang was one turn of a cycle of bounces, but the prediction could be checked only after billions of years. Cham and Whiteson add that a final theory would be of little practical use, since each layer of the onion already has a theory good enough for the work done at that layer. They close the chapter with a plain statement of scope: there is no guarantee that a Theory of Everything exists at all.

Two Meanings of One Phrase

Picture a railway. The railway's timetable lists the departures as separate entries, which you can count, and each entry repeats exactly from week to week. The railway's track is one unbroken line through country that changes from mile to mile. Every train in the timetable runs on the track, and the timetable and the track meet at every station. Nobody asks the track to be made of timetable entries, or the timetable to be made of track. No one could build an object that was, in the same respect, both a list of separate entries and one unbroken, changing line. The working railway is the pair: the timetable and the track, side by side.

The phrase "theory of everything" has two meanings, and the railway shows the difference between the two meanings. In the first meaning, a theory of everything is an account that leaves nothing out. Every finding,

of every kind, has its place in the account. In the second meaning, a theory of everything is one description from which everything else follows as a special case. A theory of everything in the second meaning has one character throughout: it is the same kind of description everywhere. A theory of everything in the first meaning is like the railway, with its timetable and its track. A theory of everything in the second meaning is like the object that no one could build.

Chapter 8 showed what the Incommensuration Theorem means for the two great theories of physics, quantum theory and general relativity. Quantum theory is the description of the content of a comparison, what is found, perfected in one character: the findings come in separate, countable steps, and each step is the same wherever it is found. General relativity is the description of the context of a comparison, where the content is found, perfected in the other character: the arena of space and time is smooth and different from place to place. Each theory is complete in its own character, and each describes what the other leaves out.

The Incommensuration Theorem permits unity in the first meaning, an account that leaves nothing out, and I call unity of that kind a common source. When two descriptions arise from the same act of comparison and apply to the same world, and each is perfected in one of the two characters a comparison allows, the two descriptions have a *common source*. Two descriptions with a common source, joined side by side, describe between them everything that each one alone leaves out, just as the timetable and the track together run the railway.

The Incommensuration Theorem forbids unity in the second meaning, one description from which everything follows, and I call unity of that kind a merger. A *merger* is one description in which the directions of space and time themselves carry both characters at the foundation: smooth and different from place to place, and also coming in exact, repeating steps. A theory that quantizes the arena itself is a merger: the theory breaks space and time into least steps. The obstacle to a merger is a limit on what any

comparison can perfect, and not a difficulty in the mathematics. So the Incommensuration Theorem excludes a merger in principle, and therefore in all future practice: no cleverer equation will make a merger succeed.

So the answer to Cham and Whiteson's question comes in two parts, and each part answers one of the two meanings of "theory of everything". In the first meaning, there is one account of everything, and that one account is made of two descriptions joined together. In the second meaning, there is no single description from which everything follows, and there never will be.

The joined account (the one account of everything, made of the two descriptions joined side by side) is already in daily use. Whenever physicists work out what quantum matter does near a large mass, they lay quantum fields (fields such as light, described by quantum theory, as Chapter 8 met them) on a smooth, curved geometry. In 1974 Stephen Hawking used exactly that pairing of quantum fields and smooth geometry when he found that black holes glow. Chapter 8 added one step to that pairing: when matter is in two places at once, each place carries its own smooth bending. Quantum theory and general relativity also connect at definite points, which work as bridges between the two descriptions. Between findings, quantum theory describes a thing by smooth mathematics, and the probability rule, which gives from that smooth mathematics the odds of each separate finding, is one bridge. Another bridge is the Planck scale of Chapter 8, the scale at which a body's gravitational size equals its quantum size.

Three Forces That Stay Three

Whether the three forces are one force is a second question, and answering it takes a separate argument. The Incommensuration Theorem forbids one description that carries the character of content and the character of context together. The forces are content, as Chapter 8 found: things found at places and times that the arena supplies. When one kind of content is joined to another kind of content, the joined description car-

ries one character only. So the Incommensuration Theorem by itself neither requires nor forbids a joining of the three forces into one. The answer for the forces depends on what each force acts on.

Picture two pots of paint, one blue and one yellow. Stir the blue paint and the yellow paint together and you get green, and neither the blue nor the yellow can then be taken back out. Now picture a triangle. The triangle has three sides, three angles and three corners. Every side, angle and corner belongs to the one shape, while each side stays a side and each angle stays an angle. The stirred paint is a picture of three forces blended into one larger force. The triangle is a picture of the three forces as I find them in this chapter: three distinct forces that all belong to one structure.

Chapter 7 showed where the forces come from: the act of comparison. A force is a change, and a change is itself a comparison, of before with after. A piece of matter with structure carries three things a comparison can act on, one for each of the three positions of comparison (the act of comparing, the thing compared, and the thing compared against). First, the piece of matter holds a pattern of the three positions of comparison inside it, and physicists call that pattern color. Second, the piece of matter presents two sides, a pair the same in kind and different in one respect. Physicists call the two sides a doublet. Third, the piece of matter has a phase, like the direction in which the hand of a clock points. The act of comparing reads the matter by the matter's phase. There is one force for each of the three: the color force (the strong force), the weak force and the force on the phase. Gravity is the arena, the space and time in which every finding is made, and Chapter 7 found that gravity stands beside the three forces, outside their count: gravity is not one of the three.

Each of the three forces acts on its own label (color, the doublet or the phase) and on no other label. A change of color moves only the colors. A change of the doublet moves only the doublet's two sides. A turn of the phase moves only the phase. Each change moves a particle within a structure that the particle already carries. A quark carries the three positions of color, and a lepton carries none, so no change of any of the three forces turns a quark into a lepton.

Picture three knobs on a stove, each turning the flame of its own burner. Turning one knob changes only the flame of that knob's burner. So the knobs can be turned in any order, and the flames end the same. Now picture a puzzle cube with faces that turn. Each turn of one face also moves pieces that belong to the faces beside the turned face, so the turns of the cube cannot be sorted into separate sets that each move only their own pieces.

Physicists gave the family of changes behind the hoped-for larger force a precise name, a *unifying group*. A unifying group is one larger family of changes, containing the changes of all three forces, under which the laws stay the same, so that at some very high energy the three forces would act as one force with one strength. The changes of a unifying group are like the turns of the puzzle cube: the changes cannot be split into independent sets. The changes of the three forces are like the knobs of the stove. Each force acts only on its own label, so the three sets of changes are independent of one another, and the order in which the changes are made alters nothing. So the three forces have no unifying group. At every energy the changes of the forces are three families side by side, one for each force, each with its own strength. A unifying theory also adds particles that the structure of the forces does not have: carriers that would turn a quark into a lepton.

So the three forces are three views of one structure, the way a triangle has three sides that are all aspects of one shape. The three forces are distinct, since each has its own strength and acts on its own label. The three forces cannot be pulled apart, since the forces stay consistent only when the quarks and the leptons of one generation are taken together, as Chapter 5 found from the charges of one generation. And no one of the three forces can take the place of another.

Once I place each force at one of the three positions of comparison, Cham and Whiteson's step from four forces to three means something different, although every fact in their history stays as they tell it. Physicists did write the electromagnetic force and the weak force as one theory. The photon, the W and the Z do come out of the theory that joins the two

forces. At the foundation, though, there were three forces all along: the color force, the weak force and the force on the phase. Light's own force, electromagnetism, is a mixing of the weak force and the force on the phase. The mixing happens when the Higgs field settles into its value in empty space. Gravity is the arena, and so gravity is not counted among the forces. So Cham and Whiteson bring their list down to three forces, but the list is three forces and the arena. The list comes down no further.

What the Proton Did

Return now to Georgi and Glashow, and to the door their larger force opened in every proton. The door was the chance for each proton to break up. A tank of water holds a vast number of protons. If each proton lasted, on average, even ten to the twenty-four times the age of the universe, a big enough tank would still show the odd proton breaking up, as a faint flash of light in the dark.

Physicists built big tanks of water and watched each tank for a faint flash from a breaking proton. The experiment Super-Kamiokande is one of the big tanks, in a mine at Kamioka in Japan: fifty thousand metric tons of pure water, in a tank whose walls are lined with more than eleven thousand detectors of faint light. Super-Kamiokande began its watch in April 1996. In 2020 the Super-Kamiokande team reported on the whole watch. The team had seen no proton break into a positron and a pion, the break Georgi found on his evening at home, so the proton's lifetime for that way of breaking up is longer than two point four times ten to the thirty-four years.

We now know why the team saw no proton break up. No change of any of the three forces turns a quark into a lepton, so every change open to a single proton keeps the proton's count of quarks less antiquarks the same (an antiquark is the mirror partner of a quark, with the opposite charges). Measurement shows that the proton is the lightest particle with

a count of three quarks, so the proton has nothing lighter to become. So the proton has no door to leave by: every proton, in the tank or in your own body, lasts.

When physicists follow the strengths of the three forces upward in energy, the strengths also show three forces and no one force. A force's strength changes with the energy at which the strength is measured, and physicists follow the force's *inverse strength*, which is one divided by the strength, so a large inverse strength means a feeble force. At the mass of the Z particle, nearly a hundred times the mass of a proton, the inverse strengths are about fifty-nine for the force on the phase, about thirty for the weak force and about eight and a half for the color force. As the energy rises, one inverse strength falls and two rise: the inverse strength of the force on the phase falls, and the inverse strengths of the weak force and the color force rise. So the three numbers move toward one another.

Picture three cars on one long road, each at a different place and each at its own steady speed. Each pair of cars draws level at some point along the road, and the three pairs draw level at three different points. For all three cars to stand side by side at one point, their starting places and speeds must be matched exactly to one another.

The strengths of the three forces behave like the three cars: each car's starting place is a strength's measured value, and each car's speed is how fast that strength changes as the energy rises. When the three strengths are run upward from their measured values, each pair of strengths becomes equal, or crosses, at its own energy. The three crossings come at three different energies. In the first and simplest order of the calculation, the last crossing lies nearly ten thousand times higher in energy than the first crossing. The three strengths are never all equal at one energy. The list of particles sets the spacing between the crossings, and measurement gives the starting gaps between the strengths. Together, the list of particles and the measured gaps give three separate crossings and no single meeting.

At the Large Hadron Collider at CERN, near Geneva, physicists have looked for the particles that a larger force would bring with it: heavier copies of the W and the Z, and particles that join a quark to a lepton. The physicists at the collider have found no particle of either kind.

What Each Search Found

Cham and Whiteson are right that the search for a final theory has been long and hard. They are right, too, to take the candidates for a final theory seriously. Quantum gravity is the search for a quantum theory of gravity. In every program of quantum gravity, the researchers found something real, and much of what they found will last. In 1996 the physicists Andrew Strominger and Cumrun Vafa used string theory to count the inner states of a kind of idealized black hole. The count of Strominger and Vafa matched exactly the number that the physicists Jacob Bekenstein and Stephen Hawking had found for that kind of black hole by a different method. In a program called asymptotic safety, physicists treat the geometry of space and time as one more field whose strength changes with scale. In 2010 the physicists Mikhail Shaposhnikov and Christof Wetterich used asymptotic safety to work out a mass for the Higgs particle (the particle of the Higgs field of Chapters 5 and 6) of about one hundred twenty-six billion electron volts. A billion electron volts is the unit of Chapter 5, and it is a little more than the mass of one proton. In 2012 physicists found the Higgs particle at a mass near one hundred twenty-five billion electron volts.

The researchers in each program also ran into a difficulty. Cham and Whiteson name two difficulties for string theory: no one can yet test string theory, and the dimensions of string theory can be chosen in an immense number of ways. They write that a test of string theory may come one day, from much better experiments or from a clever theorist who finds a prediction at distances that can be tested, and that no such test has come yet. On the source of the difficulties, my result differs from the result of Cham and Whiteson. Beside the lack of a test, the researchers in each program

ran into one difficulty that belongs only to their program. The difficulty follows from the first step of each program, the starting point its researchers chose, so no greater skill on the part of the researchers removes the difficulty.

String theorists begin from quanta, the countable packets of Chapter 8, and derive the arena from the quanta. Beginning from quanta predicts one particular difficulty, too many answers, and string theorists have run into that difficulty. In string theory, six extra dimensions are curled up small, into shapes with many loops. Fields can be threaded through the loops in an immense number of ways. Each way of threading the fields gives a different state for empty space to settle into, with its own particles and forces, and each such state is pictured as a valley. String theorists call the whole many-valleyed country the *landscape*, and estimates of the number of valleys in the landscape run to ten to the five hundred and beyond. String theory contains no principle from which the valley of our own universe follows. I build the law of gravity from geometry alone, and I thread no field through the six small dimensions of possibility met in Chapter 2, so my account has one valley.

Researchers in loop quantum gravity begin from the arena instead of from quanta. The researchers quantize the geometry of space directly, so that areas and volumes come in separate steps. Quantizing the geometry predicts a difficulty with change: the researchers must show that their stepped geometry gives back, at large scales, the smooth and changing geometry that general relativity describes and that every measurement of gravity confirms. The researchers' own work has concentrated on that task.

The programs that leave the arena unquantized have neither too many answers nor the task of getting smooth geometry back from steps. Two of those programs are examples. In 1995 the physicist Ted Jacobson derived Einstein's equation, the law of gravity, from the laws of heat, as a law of the same kind as the law that ties a gas's pressure to its temperature. Alain Connes is a mathematician, and Ali Chamseddine is a physicist. In Connes's program, Connes, Chamseddine and others write the particles

and gravity together in one formula, and they keep the geometry of space and time smooth and unquantized, as the geometry is in Einstein's theory. Jacobson, Connes and Chamseddine each chose to leave the arena unquantized at the first step of their work. Neither Jacobson's derivation nor Connes's program has the difficulties that string theory and loop quantum gravity have. So the many difficulties of the search are one difficulty met many times: the researchers in each program that set out to quantize the arena were setting out to build a merger, which the Incommensuration Theorem forbids.

Is It Baboons All the Way Down?

Cham and Whiteson ask one question about their onion: does the peeling ever stop? The peeling stops, and the bottom of the onion is of a different kind from the layers above the bottom.

Picture a kitchen on a Sunday afternoon. A cook tastes two spoons of honey and finds one sweeter. In the oven a loaf of bread is baking. A recipe, a list of steps in order, lies on the counter. A photograph of last week's loaf hangs on the wall. Taking the photograph needs a loaf, and baking from the recipe needs the work of a kitchen. The baking cannot happen unless things come together and make a difference to one another. The cook's tasting is complete without the oven, the recipe or the photograph.

The kitchen is a picture of what depth means. Take two fields of knowledge. When the first field cannot be carried out, stated or checked without the second field, while the second field can be carried out without the first, I call the second field *deeper* than the first. In order of depth, each field rests on the field beneath it: mathematics (the photograph) rests on step-by-step calculation by fixed rules (the recipe), step-by-step calculation rests on physics (the baking), and physics rests on the act of comparison itself (the tasting). In the sense just defined, depth is different from smallness, from certainty and from elegance.

Cham and Whiteson look for the bottom of the onion by going smaller: a smaller distance, a smaller particle. The kinds of particle do run out, and Chapter 4 showed why. The list of kinds of particle is closed, because every position in the structure of comparison is filled. As physicists went down through the particles, level by level, they uncovered one more part of the structure of comparison at each level, and the descent ends at the act of comparison itself.

Every field of knowledge has to answer the question of what the field rests on. Mathematicians answer the question by climbing. Mathematicians study the consistency of each formal system, its freedom from contradiction, in a stronger system, and the climb has no end. I answer from the Immanent Metaphysics, which is an account of comparison. The account of comparison has a different answer: the account is closed on itself. The account of comparison has three axioms, its basic statements, and the three axioms describe what every comparison contains. The same three axioms also describe how the axioms themselves are found, and the description of their own finding is a second level of description. Suppose we describe once more, as a third level, how the axioms describe their own finding. The third level adds nothing new, because the third level is the same as the second. So the account of comparison needs nothing beneath it, and every other field of knowledge rests on the account of comparison. In the old joke, the world rests on a turtle that rests on another turtle, all the way down. The stack of turtles ends on the ground itself. The ground is the account of comparison, which needs nothing beneath it.

Your question had a second half: how would we know that we had found the bottom? The answer to the second half also lies in the closing of the account of comparison on itself. A particle that seems smallest could always hide a smaller one, as Cham and Whiteson say. The axioms describe how the axioms themselves are found, so no further layer lies beneath the axioms for anything to hide in. You can recognize a ground by one mark: a ground describes how the ground itself is found. Anyone

finds the ground of the account of comparison by asking what every comparison already uses. Every reader can check the ground, since to doubt one of the axioms is already to use that axiom.

Would It Be Useful?

On usefulness I reach the same result as Cham and Whiteson, on separate ground: a final theory would be of little practical use. Cham and Whiteson reach the result from practice: nobody expects a surfer to compute the motion of every particle in a wave. I reach the result from what a description is. A description can come as close as one wishes to the thing described, and the description never contains the thing described. The first step up from physics, to chemistry, already shows that a description never contains what it describes. Everything chemistry studies is made of nothing but electrons, nuclei and light. Even so, physicists can derive chemistry exactly from quantum mechanics, in practice, only for the simplest systems. And in principle no description, however refined, contains everything it describes. Above chemistry, every step (biology from chemistry, and on upward) is harder to carry out than the step from physics to chemistry. So each layer of the onion keeps its own theory, because a description of the layer below never contains the layer above.

Every result that quantum theory or general relativity gives in its own domain stays in the joined account, and the mathematics and the predictions of quantum theory stay as they are. The joined account does change how the two descriptions are related to each other. The two descriptions are set side by side, and both come from one common source.

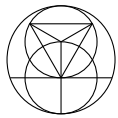
The account of comparison is useful because physicists can use it to sort questions, the well formed from the badly formed. Think of a computer. The computer itself does not choose which program runs, and the rules of the machine limit every program. The account of comparison is to the theories of physics as the machine is to its programs. The account of comparison states the limits that every correct theory satisfies. So physicists can learn from the account of comparison which questions are well

formed before anyone spends a lifetime on them. In this chapter I found two limits that every correct theory satisfies. The first limit is that the forces form one structure with three forces and no larger force. The second limit is that the quantum and the arena join at two bridges (the probability rule and the Planck scale), with the arena unquantized. If physicists know the two limits in advance, they save years of search for two things already excluded: a merger, which the Incommensuration Theorem forbids, and a unifying group, which the structure of the forces does not have.

> **The short answer**
>
> There is one account of everything, three forces and the arena joined side by side, with no single larger force or theory from which the forces and the arena follow, and the ground of that account is known because the ground describes how the ground itself is found.

Cham and Whiteson's largest question gets a yes in one meaning and a no in the other: yes to an account that leaves nothing out, and no to one description from which everything follows. The arena stands beside the three forces, outside their count, as the space and time in which every finding is made.

If the arena stands beside the forces as the space and time in which every finding is made, what is the arena: what is space?



Chapter Ten

What Is Space?

In which a letter of 1716 and a warm cup show what kind of thing space is, why it bends, and why it comes in no pieces

Space is a thing, but what is that thing?

What this chapter uses

A *comparison* is the act of finding whether two things are the same or different in some respect, and every measurement is a comparison; a *finding* is the outcome of one comparison, laid down as a record; a *comparer* is whatever makes a comparison, whether or not the comparer has a mind (Chapter 1).

The *content* of a finding is what the finding finds, as the warmth of your coffee; the *context* is where the content is found, and the context has three sides, the three settings of space, time and possibility (Chapter 1).

The three *settings* in which anything is measured are space, the place of a finding; time, the moment of a finding; and possibility, the range of what could have been found instead; a setting is *bent* when one part of the setting differs from another part (Chapter 1).

Continuous: nothing is sudden, as along a ramp; *discontinuous*: something is sudden, as at the edge of a step; *symmetric*: what is found stays the same across a change of setting, as each step of a staircase is like every other; *asymmetric*: different everywhere, as the height along a ramp is (Chapter 1).

Three things in nature do the bending: gravitation bends space, the cosmological constant bends time, and the dark matter bends possibility (Chapter 1).

Gravity is the *arena*, the stage of space and time on which the three forces act, and so gravity stands beside the three forces and is not a fourth force (Chapter 7).

On 25 February 1716, in Hanover, the German philosopher and mathematician Gottfried Wilhelm Leibniz dated the third paper of a quarrel that he was carrying on by post. The quarrel had begun in 1715, with a letter from Leibniz to Caroline, Princess of Wales. Caroline had gone to London with the court of Hanover the year before. Caroline showed the letter

to the English philosopher Samuel Clarke, and Clarke wrote an answer, and from then on every paper went to the princess, who passed each paper on to the other man. Leibniz opens the fourth numbered paragraph of his third paper with his own position on space. "As for my Own Opinion, I have said more than once, that I hold Space to be something merely relative, as Time is; that I hold it to be an Order of Coexistences, as Time is an Order of Successions". In the next paragraph Leibniz says he has "many Demonstrations, to confute the Fancy of Those who take Space to be a Substance, or at least an absolute Being". In 1717 Clarke printed the whole exchange in London, as *A Collection of Papers*.

Leibniz's two paragraphs contain two pictures of space. In the first picture, space is a substance: something that is there before anything is put into space, a room waiting for furniture. In the second picture, space is an order: the arrangement of the things that exist together, and nothing besides those things. Leibniz chose the second picture, space as an order. Three centuries later, Jorge Cham and Daniel Whiteson set the same two pictures side by side and rejected both. They also put the question "Space is a thing, but what is that thing?" first in their list of what is not yet known about space (*We Have No Idea*, ch. 7, "The Mysteries of Space"). I answer their question by keeping something from each side of the quarrel.

From Cham and Whiteson's pages

What Cham and Whiteson Showed

Cham, a cartoonist, and Whiteson, a physicist, begin with the two pictures in their everyday form. They write that most people imagine space as a big empty warehouse, a void that waits to be filled. The second idea they describe is that space is only the relationship between pieces of matter. On that second idea, beyond the last particle there would be no space at all. Then they give their verdict, which rests on measurement: "Space is definitely not an empty void and it is definitely not just a relationship between matter" (*We Have No Idea*, ch. 7, "Which Space Is the Place?"). Their reason is what space has been

measured to do, and space does three things. Space expands: distant galaxies draw apart without moving through space. Space bends: light curves when the light passes the Sun, or passes a great clump of dark matter. Space ripples: in 2015 the two detectors of LIGO, the American observatory for gravitational waves, registered waves of stretching and squeezing sent out by two black holes spiraling together, as Chapter 8 told.

Because space expands, bends and ripples, Cham and Whiteson ask their readers to picture space as a thick goo, which things move through freely, and which can bend, stretch and wave. They add that "as far as we know (which to date is not very far), the goo does not need to be in anything else" (*We Have No Idea*, ch. 7, "This Sounds Ridic-goo-lous. Are You Sure?"). Even so, they leave open whether the goo sits inside some larger space. In their second book they write: "Space is actually part of the action, not just the backdrop, because it responds to the matter and energy inside of it" (*Frequently Asked Questions About the Universe*, ch. 18, "Wormhole Warp Drives"). In their account, gravity is the response of space: mass and energy bend space, and a falling body follows the bend.

Cham and Whiteson close their chapter with questions about what the goo is. They ask whether space sits inside a larger space, and why space is flat. They also ask whether space is made of tiny pieces, like the pixels of a screen. On the last question, whether space is made of pieces, they lean toward pieces. Their reason is that matter, energy and the forces all come in steps, so a smooth space would be the odd one out. According to quantum physics, they write, there might be a smallest distance that makes sense, about ten to the minus thirty-five of a meter.

I keep every measurement Cham and Whiteson report, and I add an answer to their first question: what the thing called space is.

The Cup and the Moon

Put your hand around your cup of coffee. The warmth of the coffee reaches your palm now. Now think of the Moon, wherever the Moon is in the sky at this same moment. Nothing your cup does at this moment reaches the Moon at this moment. Any news of the cup could arrive at the Moon a little more than a second later at the earliest: light takes that long to cross the gap between the Earth and the Moon.

You have just sorted happenings, with no ruler at all, by one question: which of the happenings can affect which. Chapter 1 called an event anything that happens. In this chapter an event is one happening at a single place and a single moment: the warmth leaving the cup now, your palm warming now, a flash on the face of the Moon now. Two events are joined when one of the two can affect the other. Your cup warming your hand is one pair of events that are joined. An event at your cup now is not joined to an event on the Moon now. Sort every pair of events by whether one can affect the other, and you have a pattern: a complete map of which events can reach which.

The word "space" names the pattern of what can reach what. I give the definition in one sentence: space is the pattern of which events are causally connected with which, and space is no container that exists before the events in space. In plainer words, space is the pattern of which events can affect which, and I use these plainer words from here on.

In the usual account of space, the ideas come in the other order. In the usual account space comes first: an empty box that is already there. Events are set into the box. Then causes are laid on top of the events. Last, a speed limit is applied: every cause that would travel faster than light is struck out. I turn the usual order around. Two events are related exactly when one event can affect the other, and the whole of those relations is space. Space is the pattern of which events can affect which, and nothing more.

My definition of space comes from inside physics. Einstein's general relativity is his theory of gravity as the shape of space and time. In general relativity, space and time have no properties apart from their relations, and the geometry of space and time is the physics of gravity. Within general relativity, if you know only which events can reach which, you already know how space and time hang together (which event lies next to which), apart from any measure of distance. The philosopher of physics David Malament proved one theorem of this kind in 1977: a theorem that the list of which events can reach which fixes how space and time hang together. I go one step further than general relativity: I trace each causal relation back to comparison. Every way one event affects another is an interaction, and every interaction is a comparison. So space is made of comparisons that can be made, and the edges of space are the edges of what can be compared.

Your cup gives a case of one finding and its place in the pattern. When you notice that the coffee is warm, you make one finding from inside the world: a finding is the outcome of one comparison. Chapter 1 called space the setting that gives a finding its place. The "here" of your finding is the finding's place in the pattern: the cup can reach your palm now, and the cup cannot reach the Moon now.

A Thing, or a Relation?

Now we can return to the quarrel of 1716 and to the verdict Cham and Whiteson give on the two pictures of space, space as a substance and space as an order.

My definition is relational, as Leibniz wanted. Space is an order, and there is no space-stuff underneath the order. So I set aside the empty warehouse, the container that would still be there with everything removed, as Cham and Whiteson do.

The relations in my definition, though, are of a different kind from the relations the authors reject. Cham and Whiteson reject space as the relationship between pieces of matter: distances between particles, in a space

that ends where the particles end. The pattern in my definition is made of the connections between events, and events happen in empty space as well as where matter is. When light crosses the empty gap between the Sun and the Earth, the light's crossing is a chain of events, each event able to affect the next. So the pattern includes the emptiest regions there are, and the pattern does not end where the matter ends.

The pattern also has a shape of its own, and the shape of the pattern changes. Around the Sun, in the space where there is no matter, the Sun bends the pattern. A gravitational wave crossing empty space bends the empty space the wave crosses. Cham and Whiteson call space a "physical thing" (*We Have No Idea*, ch. 7, "Which Space Is the Place?") because measurements show space changing its shape, and the shape that changes is the shape of the pattern. Chapter 1 named space one of the three settings of every finding (space, time and possibility): the setting laid out from here to there. So space is a setting with a shape.

So I keep something from each side of the old quarrel. I keep the word "order" from Leibniz: space is an arrangement, and no substance. I keep the bending from Cham and Whiteson, who find space to be a thing: the arrangement has a shape that responds to what is in space. The goo is a picture of the bending, and the pattern of what can affect what is the thing the goo was standing for. The pattern needs nothing to sit in, because the pattern is made of the relations among events and of nothing else. Cham and Whiteson report the same of their goo: so far as anyone yet knows, the goo does not need to be in anything else.

Why the Pattern Bends

Cham and Whiteson take the bending from Einstein. I derive the bending on a second, separate ground: the act of comparison itself.

Picture an old pan balance, a beam with a pan hanging at each end. The beam joins the two pans, and the verdict (heavier on this side or on that) travels along the beam. If you saw the beam in two, the balance weighs nothing, and each pan simply drops. Every comparison is like the

balance, and the act of comparing is like the beam. The act must connect the two things compared without a break, as the beam connects the two pans.

A comparison has a second requirement. A comparer is whoever or whatever makes a comparison. A finding must be the same for every comparer who makes the finding, or the findings of many comparers would never make one history. Two witnesses of one event must be able to reconcile their accounts of the event.

In Chapter 1 we met the Incommensuration Theorem: at the foundation of any event or comparison, perfect symmetry and perfect continuity cannot both be had together, and neither can perfect asymmetry and perfect discontinuity. In this argument, symmetry means sameness for every comparer, and continuity means connection without a break. The finding of a comparison has the sameness for every comparer. The act of comparing has the unbroken connection, which is made perfect in the context, where the act connects. Wherever continuity is made perfect, the Incommensuration Theorem says that symmetry cannot also be perfect there, so asymmetry goes with the continuity. In this argument, asymmetry means a difference from place to place. So every comparison must contain a difference from place to place, and a comparison has three parts that might contain the difference: the finding, the act of comparing and the context.

The finding cannot contain the difference, because the finding has its sameness for every comparer. Think of a handshake across a table, to see why the act cannot contain the difference either. The handshake joins two people, and the handshake is the joining as it happens, not a thing spread out across the room. If one end of the room is warm and the other cold, the difference belongs to the room, and the handshake has no two ends that could differ in that way. The act of comparing is like the handshake: a joining as it happens, not spread out from place to place. A difference from place to place can belong only to something that is spread out from place to place. So the context contains the difference, in the part of the context that is spread out from place to place: the arena, the word Chapter 7 gave us for space and time together, two of the three settings of every

finding (the third setting is possibility). So the arena is smooth, because the unbroken connection is made perfect in the arena. And the arena differs from place to place, because the asymmetry goes with the unbroken connection.

I reason through in full why the arena bends, and I close the reasoning on one sentence: "The arena is where the consistency of the content is paid for in asymmetry". Chapter 1 gave the name content to what a finding finds. In plain words, the quoted sentence says that what is found stays the same for every comparer, and the cost of that sameness is that the arena differs from place to place. Where there is content, the arena differs from one place to the next. When a setting differs from one place to the next, I call the setting bent. So the arena bends.

The reasoning from comparison also shows why the bending is smooth. A bend in steps would put a break into the arena, and at the break the act of comparing would have nothing to join. So the arena may differ from place to place without limit, but the arena differs gradually and never jumps. The smooth bending agrees with a sentence of the authors' second book: "Physics tells us that space might be able to have any smoothly varying shape" (*Frequently Asked Questions About the Universe*, ch. 18, "Wormhole Warp Drives").

The reasoning from comparison says three things: why there must be a bending, why the bending must be smooth, and why the bending must go with what is there. Einstein's equations of 1915 say how much the arena bends, and in what form. I take the form of the bending from general relativity, and I take general relativity as established physics. One number comes from measurement: Newton's constant, which sets how strongly a given amount of matter bends the arena, and which physicists find by weighing the pull between masses in a laboratory.

I apply my account of the arena to the authors' other two observations as well: the expansion of space and the ripples. The expansion of space is a growth of the arena between distant galaxies, and the growth is no signal sent across the arena. Take today's distance to a very distant galaxy,

and ask how fast that distance grows. For the most distant galaxies the distance grows by more than a light-year each year (a light-year, as Chapter 2 said, is the distance light travels in a year), and so, reckoned by today's distance, the growth is faster than light. Even so, no signal travels by the growth, and the growth lets no event affect any other event. The ripples are changes in the shape of the arena, and the ripples spread through the arena at the speed of light, which, as Chapter 15 shows, is the outer edge of comparison itself, the same for every comparer.

Light Bent by the Sun

Astronomers first saw the bending of the arena at a total eclipse of the Sun. On 29 May 1919, while the Moon covered the Sun, an expedition led by the astronomer Arthur Eddington photographed the stars near the darkened Sun. The photographs showed the light of the stars near the Sun bent as the light passed the Sun, by the amount general relativity requires, and F. W. Dyson, A. S. Eddington and C. Davidson published the result in 1920. We now know that the arena bends near a mass, and that light, which has no mass, follows the bend.

Physicists can now see the bending on the scale of a kitchen. An *optical clock* keeps time by the light that a single atom takes in at one exact frequency. In 2010, at the National Institute of Standards and Technology, the physicist Chin-Wen Chou and his colleagues raised one of two optical clocks, each holding one atom of aluminum, by about a third of a meter. The raised clock ran faster than the lower clock, by the amount general relativity gives. The reasoning from comparison says what the arena around the Earth must be like, and the two clocks agree with what the reasoning says. The arena is smooth, so the rate of a clock changes by no step as the height of the clock changes. The arena is uneven, so no two heights above the Earth are exactly alike. And the arena is uneven above the Earth because the Earth is there.

Is Space Made of Pieces?

Cham and Whiteson compare space to air. Air seems smooth, and yet air is made of molecules. They ask whether space, too, is made of tiny pieces that we glide across without noticing.

The authors' picture of air helps once we see which side of every finding air is on: the side of what is found, or the side of where it is found. Air is content: something found, made of particles of a few kinds, every molecule of a kind exactly like every other molecule of that kind. Content comes in steps, and the steps of matter, energy and the forces that the authors list are all steps of content. Space is on the other side: space is one of the settings in which content is found.

The answer to the authors' question follows from the reasoning of this chapter about the act of comparing. The arena has no least step: no smallest length, no smallest area, no smallest duration. A least step would be a break in the arena, and the arena is connected without a break. Nothing is a piece of the arena itself, at any scale. Small ripples of the arena can be described in steps, as the vibrations of a solid are described by phonons. A phonon, which Chapters 2 and 8 met, is one step of vibration of a held structure: a structure, such as a crystal, whose parts are held in place by bonds. The steps belong to the description of the ripples. The arena is no held structure, so the steps of the description of the arena never become pieces of space. So the goo is a picture and no substance: the goo bends and ripples, and holds no stuff to be counted.

What, then, is the smallest distance the authors mention? As Chapter 8 showed, every body has two sizes. A body's gravitational size is its mass times Newton's constant, divided by the speed of light squared, which is half the size of a black hole of the same mass. A heavy body, such as a planet, has a gravitational size larger than its quantum size, and a light body, such as an atom, has a quantum size larger than its gravitational size. At the Planck mass both sizes equal the Planck length, about ten to the minus thirty-five of a meter, the length at which general relativity and quantum theory, the two great descriptions of physics, meet.

Suppose a probe tried to pin a body down more sharply than the Planck length. The probe would need so much energy that the probe would make a black hole larger than the region being probed. So the Planck length is a bound on how sharply a finding made from inside the world can place a body: a bound on findings, and no smallest step of space. The light microscope of Chapter 8 has a bound of the same kind: a light microscope cannot show details much finer than half the wavelength of its light, and nobody concludes from that bound that a cell is built of tiles of that size. The limit belongs to the act of looking, and the arena has no least step.

Light That Arrived Together

Astronomers have used light from the far universe to test whether space has a grain, the least step of length that Chapter 8 described. A *gamma-ray burst* is a brief, enormous flash of the most energetic light, from a galaxy far away. In the simplest pictures of a grainy space, light of higher energy would cross the grain a little more slowly, and over billions of years the small delay would add up.

In 2009 the Fermi space telescope recorded the burst cataloged as GRB 090510. One photon of GRB 090510 carried about thirty-one billion electron volts, in the unit of energy of Chapter 5. Thirty-one billion electron volts is some thirty times the energy held in the mass of a proton. The photon arrived within about a second of the burst's low-energy light, after a journey of billions of years. A. A. Abdo and the Fermi team concluded that any grain of space that slowed light in proportion to the energy of the light must be finer than the Planck length. In 2024 Z. Cao and colleagues reported on the burst GRB 221009A, which the Large High Altitude Air Shower Observatory in China had watched, and placed any grain of space that slowed light in proportion to the light's energy below about a tenth of the Planck length. We now know that light of very different energies

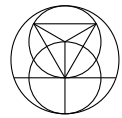
crosses the universe together, and the measurements show no grain of space at the scale where the simplest pictures of pixelated space put a grain.

Your cup belongs to the result about smooth space too: the warmth leaving your cup, the light by which you see the cup and the faint glow of its heat all cross the same smooth space to reach you, each by the same rule of what can affect what.

> **The short answer**
>
> Space is the pattern of which events can affect which: a pattern that bends smoothly wherever there is something to be found, and that has no smallest step.

The authors' "space goo" (*We Have No Idea*, ch. 7, "Space Goo, You're Swimming in It") now has a plain meaning: the goo is a picture of the pattern of which events can affect which. I keep every finding of relativity that Cham and Whiteson report: the bending, the rippling and the growing of space are changes in the pattern of what can affect what. Under the definition, space is also where this book's question needs space to be: one of the three settings of every finding (space, time and possibility), found from inside the world like everything else.

How many directions does the pattern of what can affect what have, and are there hidden directions?



Chapter Eleven

How Many Dimensions Are There?

In which we count the ways two findings can differ, and meet six ways that no one walks through

How many dimensions are there, and are some of them hidden?

What this chapter uses

A *comparison* is the act of finding whether two things are the same or different in some respect, and every measurement is a comparison; a *finding* is the outcome of one comparison, laid down as a record; a *comparer* is whatever makes a comparison, whether or not the comparer has a mind (Chapter 1).

The *content* of a finding is what the finding finds, as the warmth of your coffee; the *context* is where the content is found, and the context has three sides, the three settings of space, time and possibility (Chapter 1).

The three *settings* in which anything is measured are space, the place of a finding; time, the moment of a finding; and possibility, the range of what could have been found instead; a setting is *bent* when one part of the setting differs from another part (Chapter 1).

Every comparison has three positions: the *act of comparing*, the relating; the *thing compared*, what is known; and the *thing compared against*, what the act of comparing reaches toward and never contains in one act, the beyond (Chapter 4).

Gravity is the *arena*, the stage of space and time on which the three forces act, and so gravity stands beside the three forces and is not a fourth force (Chapter 7).

Theodor Kaluza was a young mathematician who lectured at the university in Königsberg. Early in 1919 Kaluza sent a paper to the physicist Albert Einstein. In the paper Kaluza wrote Einstein's theory of gravity for a world of five dimensions instead of four. The familiar four are three directions of space and one of time. In five dimensions, Einstein's one theory contained both gravity and the familiar four-dimensional equations of electricity and magnetism. Kaluza laid down a rule to keep the fifth direction out of sight. He called the rule the cylinder condition: nothing in the world changes as one goes along the fifth direction. On 21 April 1919 Ein-

stein wrote back. Einstein wrote that the idea of reaching a theory of gravity and electricity together through a five-dimensional cylinder world "never dawned on me". Einstein added: "At first glance I like your idea enormously". Einstein held the paper for two years. On 8 December 1921 he submitted the paper to the Prussian Academy of Sciences in Berlin, on Kaluza's behalf. In 1926 the physicist Oskar Klein proposed where the fifth direction could be: curled into a circle so small that anything moving along the circle comes back at once to where it began. A garden hose shows Klein's picture. From far away the hose looks like a line, and the circle around the hose appears only close up. The length of the hose stands for the familiar directions, and the circle around the hose stands for Klein's fifth direction.

Physics still uses Kaluza's fifth direction, curled small as Klein proposed, as its picture of a hidden dimension: one more direction of space, like left and right, too small to see. If some dimensions can be small and hidden, the question of how many dimensions there are has three parts. How many directions does the world have in all? Which of the directions are large, and which are small? And why are the small ones never seen?

From Cham and Whiteson's pages

Directions of Motion, and Where They Might Hide

Jorge Cham, a cartoonist, wrote *We Have No Idea* with Daniel Whiteson, a particle physicist. Cham and Whiteson begin the book's chapter on dimensions with what the word "dimension" means. Cham and Whiteson write that in science and mathematics the word "means a possible direction of motion" (*We Have No Idea*, ch. 9, "What Exactly Is a Dimension?"). A straight line gives one direction, a second line at right angles to the first gives a second direction, and a third line at right angles to both gives up and down. Every motion we know is made of motions along those three directions.

Cham and Whiteson then ask whether space could have more than three directions. They point out that the mathematics works as well for four directions as for seven. We would have noticed a fourth direction of space just like the other three, because things moving along the fourth direction would appear and disappear in front of us, so, Cham and Whiteson reason, any extra direction has to be hidden in some way. Cham and Whiteson give three ways in which an extra direction could be hidden: the direction could be closed to every particle we know, or open to only a few rare particles that are hard to study. Or the direction could be small and looped, so that motion along the direction soon comes back to where the motion started. Cham and Whiteson write that small looped directions, which only a few particles can move in, would explain why no one has noticed the extra directions. They also give one of the biggest reasons physicists have for thinking that small extra directions might exist. If gravity alone could spread into a few small extra directions, gravity would thin out quickly over short distances, and the thinning would explain why gravity is so weak against the other forces. Cham and Whiteson report two searches. In the first search, physicists measured gravity at distances of about a millimeter, and gravity there behaves as it does at large distances. The second search is at the Large Hadron Collider, the great ring at CERN near Geneva in which physicists smash particles together. The collider has found no heavier copies of known particles of the kind that motion around small loops would make. A particle moving around a small loop would carry extra energy, and so the particle would show up as a heavier copy of itself. Cham and Whiteson report that the mathematics of string theory, the proposed theory in which each particle is one way a tiny string can vibrate, is simpler and more natural with extra dimensions of space. They also report that string theories close those extra dimensions up into circles. Cham and Whiteson end the chapter by summing up the measurements made so far in their refrain, the words of their title: “So far, we

really have no idea how many spatial dimensions there are in our universe" (*We Have No Idea*, ch. 9, "Wrapping Up These New Directions").

Cham and Whiteson add a point in their second book, *Frequently Asked Questions About the Universe*. The point matters to anyone who hopes to travel by way of an extra dimension. If there are extra dimensions, they are no doorway to somewhere else: "They only represent extra ways in which your particles might be able to wiggle" (*Frequently Asked Questions About the Universe*, ch. 6, "Options for Teleportation"). Cham and Whiteson make the same point in their chapter on warp drives, where they compare an extra dimension to one more line on your mailing address: the extra line says more exactly where you are, and it brings your mail no faster (ch. 18, "A Hyperspace (or Subspace, or Superspace) Warp Drive"). In that picture the extra line of the address is the extra dimension. An extra dimension would say more about a thing, and no one could travel anywhere faster by way of the extra dimension.

What a Dimension Is

Picture a city map. North-east is also a way to move on the map. But north-east adds nothing new, because north-east is made of east and north together. The map has two dimensions.

I keep the authors' definition, that a dimension is a possible direction of motion. I make one word in the definition exact, the word "direction". In this book a direction is an independent way in which two findings can differ. A finding is the outcome of one measurement, laid down as a record. Chapter 2 already called a dimension one independent direction in which a thing can be placed. So the number of dimensions of a setting is the number of independent ways in which two findings can differ in that setting, where a setting is one of the three sides of where a finding is made: space, time or possibility. When no combination of other ways of

differing yields a way of differing, that way is independent of the others. East is independent of north, and north-east is not independent of the two. Mathematicians use the same definition for a smooth space. The number of dimensions of a smooth space is the number of numbers needed to fix a point near any point of the space. So I count dimensions of space in the ordinary sense.

I count the dimensions from what happens in every act of measuring. We count the ways of differing in each setting by looking at what every comparison contains.

Chapter 5 named the six aspects that every comparison has, in three pairs: sameness and difference; content and context; and the side the comparison is made from and the side it is made about. A thermometer shows all six aspects when the thermometer compares the warmth of a room this morning with the warmth of the room this evening. The thermometer's verdict is one of two, same or different, and the two possible verdicts are the pair of sameness and difference. The verdict is about the warmth, and the warmth is the content. The two times of day make the two readings two readings and not one, and the two times are the context. The thermometer at its post is the side the comparison is made from, and the room is the side the comparison is made about. The two members of each pair always come together, and each member differs from the other. None of the six aspects can do the work of another.

The two sides together are the *point of view* of a comparison: where the comparison is made from, and what it is aimed at. To follow an aspect is to trace the aspect from one thing to the next. Four of the six aspects can be followed apart from the point of view. You can follow the sameness of a shape along a street, from one house to the next, and in the same way you can follow a difference of color from one wall to another. The content and the context of each finding go along with the sameness or the difference that you follow. The two sides cannot be followed in that way, because the two sides together are the point of view itself: wherever you go to follow

either side, the point of view goes with you. The point of view is the place you are following from. So sameness, difference, content and context can be followed apart from the point of view, and the two sides cannot.

Every dimension has to be a way of differing that comparison contains as one of its own elements. A combination of elements is made from the elements, as a necklace is made from its beads. So a combination adds no new element, as a necklace adds no new bead. There are eight ways to choose one member from each of the three pairs, but the eight ways are made from three choices of two, so the eight ways are not eight independent ways. So a count of independent ways is the size of some collection of elements that comparison itself contains. The collections that comparison contains have five sizes. One: the point of view from which a comparison is made, always single, as a thermometer reads from one position. Two: the two members of any pair, such as same and different. Three: the three pairs. Four: sameness, difference, content and context, the four aspects that can be followed apart from the point of view. Six: all six aspects together. Every other collection in comparison either has one of the five sizes or is built from the six aspects, as the eight combinations are, and so adds no size of its own.

I use one rule to choose among the five numbers, one, two, three, four and six, and I call the rule the *minimality principle*: of the numbers comparison supplies, a setting takes the least one that meets every requirement comparison places on it. The reason for the rule is that a further way of differing, beyond the least number, would be a difference that nothing in comparison registers as distinct from the other ways, and so the further way of differing would change no finding that anyone could ever make.

One of Time, Three of Space

Time is the setting of the order in which findings are found. Every finding is made from a single point of view, and from one point of view any two findings stand in one relation: one finding is earlier, and the other is later. On a map, two towns can lie so that neither town is both east and

north of the other. So a map gives the two towns no single order of before and after. Only a single line gives every pair of findings a single before and after. So time has one dimension.

Space is the setting in which a finding can be followed apart from the point of view. In space a pattern can be traced from here to there. Space has more than one dimension, because space and time are two different settings, and a setting counted from comparison alone has no feature but its number of ways of differing. If space and time each had one way of differing, nothing would tell space from time.

Space has more than two dimensions, and you can see the reason on a flat page. On a flat page you can tell east from north, and nothing on the page stands apart from both east and north. Lift your eyes off the page, and the direction straight up is the direction from which the page's two directions can be told apart. Every difference is placed twice: once by the comparison in which the difference is found, from that comparison's point of view, and once in the setting where the difference is found. The difference between two directions of a setting is itself a difference, so that difference too must be placed in the setting, and that difference has a place in the setting only along a third direction, made of neither of the two. In a setting of three directions the fit is exact: each direction is the place of the difference between the other two. So the placing of differences requires at least three directions. Four and six directions would also give every difference a place. The minimality principle says that a setting takes the least number that meets its requirements. Of three, four and six, the least is three: space has three dimensions.

I reach the same counts of time and space by a second road, an argument with no step in common with the first. Every comparison goes through one order of steps: first a point of view, then a finding, then a record laid out. The record shapes the point of view of the next comparison, and so the order of steps goes round again. The cycle has three steps and one direction of turning. I make two identifications: each of the three steps, in the large world of space and time around us, with one direction in which things extend, and the one direction in which the cycle turns

with the one direction of time. The first road counts ways of differing, the second road follows the cycle of comparison, and the two roads arrive at the same place: one dimension of time and three of space.

Six of Possibility

Your coffee is on the table. Slide the cup along the table, then across the table, then lift the cup. The two slides and the lift are three ways to move the cup, and every other way to move the cup is made of those three. Now move the cup to the cup of tea it could have been. You cannot get from the coffee to the tea along any direction of the table or of the room. The tea is a way your cup could have differed, and the tea is a way you cannot travel.

The tea belongs to the third setting of every finding: possibility, the range of what a finding could be. A finding is fixed in all six aspects of the comparison in which the finding is made. Before a particle counter clicks, what the counter could find can differ in six ways. The counter's verdict can differ, a click or no click, and the verdict carries two of the six aspects, sameness and difference. The content of the finding can differ (the count), and so can its context (where and when). The two sides of the comparison can differ: a different counter, or different radiation. Each of the six ways is a way in which possible findings differ, and none of the six ways is made of the others, because none of the six aspects can stand in for another. Possibility is always the range of what could be found in one comparison, from that comparison's own point of view, and so possibility stays bound to the point of view. Possibility therefore spans all six aspects, the two sides included, and not only the four aspects that can be followed apart from the point of view: possibility has six dimensions.

Picture cans stacked in a shop window: one can on top, two cans in the row beneath, and three cans in the bottom row. The top row alone holds one can, the top two rows hold three cans, and the whole stack holds six cans. Time, space and possibility have counts of dimensions that climb in the same way. Time has one: the single point of view. Space has three: one

and two, the point of view and a pair. Possibility has six: one, two and three, the point of view, a pair, and the three pairs. One and three and six make ten.

Why No One Sees the Six

Every comparison is made at one place, at one time, with one outcome. You can walk to the next room, and you can read yesterday in a diary. You cannot walk to the outcome that did not happen. You can look into other places and read other times from their records, but you can reach other outcomes only by supposing them. Anyone who compares can travel through space, and no one who compares can travel through the dimensions of possibility. So, to anyone inside the world, the six dimensions of possibility appear closed: the six have no depth that anyone can move into or look into, and their extent shows only through its effects.

Physics has a word for dimensions that appear closed. When a dimension has a finite extent, physicists call the dimension *compact*. The compact dimensions of this chapter also have no edge, as the surface of a ball has a finite area and no edge. The six dimensions of possibility are compact, and they are present everywhere you are. A sculptor's block of stone has three directions you can measure with a tape, but the block also has a pattern of layers, present at every point, which sets how the stone can be shaped and which no tape measures. The three directions of the block are like the three of space, and the layers are like the six dimensions of possibility, which are present at every place, as the layers are, and which you meet as the forms that matter can take.

I also find six small dimensions by an argument from physics. Chapters 8 and 9 showed that the arena and the matter in it are described side by side, each in its own character: the arena, meaning space and time together, by a smooth description, and matter by a stepwise description. The two descriptions are joined without being merged. In geometry, you can make a new shape by setting the whole of one shape at every point of another shape, and the new shape is called a *product* of the two shapes.

Each of the two is called a factor of the product. The surface of Klein's garden hose is a product: a long line, with the whole of a small circle at every point of the line. The geometry of the world is a product of the same form, because the arena and matter are joined side by side. The large factor of the world's geometry is the arena of four dimensions. Every place and moment of the arena holds the whole of a small shape of six dimensions. The small shape is called the *internal space*: the six small dimensions taken together as one shape, which holds the possibilities that content can take.

I find the shape of the internal space from three identifications and one condition. First, I take the internal space to have one direction for each of the six aspects of comparison, so the internal space has six dimensions. Second, I take the internal space to be made of two pieces: one piece carries the three positions of every comparison, and the other piece carries the pair of content and context. The act of comparing is the relating of two things, and the thing compared is what is known. The thing compared against is what the act reaches toward and never contains in one act. Third, I take each piece to be built from as many basic cells as the piece carries parts, so the piece of the three positions has three cells, and the piece of content and context has two. A basic cell is one of the kinds of shape that Chapter 1 counted, the basic pieces from which a shape can be built: the surface of a ball, for example, is built from two, a single point and a disk whose rim is drawn together to that point. The condition is that every point of each piece is like every other point, as every point of a ball's surface is. I take the condition because nothing in the arena in which content is compared can single out one point of a piece.

Among shapes that are compact and alike at every point, the mathematics shows that exactly one pair of pieces satisfies the three identifications and the condition, and each piece has a plain meaning. Take a quantum system with two possible outcomes, like a choice between yes and no. Before the system is found, it can be in many states, each state a blend of the two outcomes. The range of all those states is exactly the surface of a ball, one point for each direction an arrow could point. The surface of the ball

has two dimensions, and the surface is the piece of content and context. For a quantum system with three possible outcomes, the range of all its states is a shape of four dimensions, and that four-dimensional shape is the piece of the three positions. Four and two make six. So the internal space is a space of possibilities in the plain sense: the states of a three-way choice, side by side with the states of a two-way choice.

I identify the six dimensions of possibility, counted from comparison, with the six dimensions of the internal space: the two sixes are one set. Both sixes are counted by the same six aspects of comparison, one dimension for each aspect, and by nothing else. So no comparison could ever register a difference between the two sixes, and a difference that no comparison can register is no difference.

The six dimensions of possibility are small, and their size is measured in Planck lengths. The Planck length is the length of the Planck scale. Chapter 8 showed that at the Planck scale the smooth description of the arena and the stepwise description of matter meet on equal terms: at that scale, a body's size as gravity describes it equals its size as quantum theory describes it. I take each of the six directions, on its own, to reach the Planck scale, so the six are a few Planck lengths across.

The six dimensions of possibility stay compact because the large world of space and time is present around them as their context. The context of the six includes a standard of rest and of turning, fixed in the large world. A standard of rest and of turning is matter in the large world against which motion is measured: the distant stars are one such standard, and a spinning gyroscope keeps pointing at the same distant stars. Chapter 1 found that content and context go together: no content is ever found without a context. Content and context also come as a pair in the product of the two factors. The six dimensions are held as content, as the small factor of the product, and the large world of four dimensions, the large factor, is their context. The six dimensions are closed and finite because they are held as content within that context.

The six dimensions are held at one size and one shape at every place in the large world, and they are held stiffly. If the size of the six changed from place to place, the size would itself be a field, a quantity with a value at every place, and the field would carry a force of its own. A force reaches a shorter distance the heavier the particle that carries the force. The weak force, for example, acts only over very short distances because the particles that carry the weak force are heavy. The Planck mass is the mass at which gravity's strength on a body reaches one, about twenty-two millionths of a gram, as Chapter 7 said. Particles would carry any change in the size or the shape of the six. The carrier particles have masses of two to three Planck masses. So the force of the carrier particles reaches less than one Planck length.

The gyrations of Chapter 2 are vibrations of the six dimensions of possibility: the lasting vibrations of which the dark matter is made. The extent of the six also shows in the strength of gravity, because the strength of gravity in the large world is tied to the volume of the six, their extent taken in all six directions together. Einstein's equations of gravity in four dimensions come out of Einstein's theory written for ten dimensions and summed over every point of the six dimensions of possibility. I keep Kaluza's step, summing over the six to go from ten dimensions to four, with one change: the six were never directions of space, and nothing ever curled them small.

Where the Authors and I Meet, and Where We Part

I keep Cham and Whiteson's picture of extra dimensions as extra ways for particles to wiggle, and I reach that picture by a separate argument. The six dimensions of possibility contain the forms that the content of the world can take. Possibility stays bound to the comparer's own point of view, because of the structure of comparison (what every comparison must contain). So no one moves into the six. The count and the shape of the six do not make the six a place, and nothing travels through the six. I also keep Cham and Whiteson's picture of the mailing address: the six say

more exactly what a thing is, as the extra line of the address says more exactly where you are. And no one can travel anywhere by way of the six, as the extra line brings your mail no faster.

I part from Cham and Whiteson on four points, each for a reason. First, the number of dimensions is known: one of time, three of space and six of possibility, each count drawn from what every comparison contains. Second, the six are unseen because they are possibility, and no one who compares travels through possibility. So the six are not directions of space made too small to see, and they are not closed to some particles and open to others. Third, gravity is weak on ordinary matter for a reason of its own. Chapter 7 showed that gravity is weak on the electron because the electron is very light against the Planck mass: about seventy-four and a third halvings below the Planck mass, where a halving is a factor of two in mass. The six are a few Planck lengths across, and their size enters gravity in one place only, by helping to fix the Planck mass itself. Fourth, string theorists also count ten dimensions, four large and six small. String theorists obtain the total of ten from the consistency of the mathematics of string theory, and they choose the split and the shape of the six among a very large number of possible shapes. Each count comes from comparison, and the six have one shape.

What the Measurements Found

Physicists have looked for extra dimensions in the pull of gravity at short range. In 2007 the physicist Kapner and his colleagues measured the pull between masses brought very close together, and the team found that the ordinary law of gravity, in which gravity weakens with the square of the distance, holds down to about a twentieth of a millimeter. Kapner's test is the kind of measurement that Cham and Whiteson report at about a millimeter, carried twenty times closer.

Physicists have also looked in the solar system for the force that hidden dimensions of changing size would carry. In 2003 the physicists Bertotti, Iess and Tortora timed radio signals sent between the Earth and the

Cassini spacecraft as the signals passed close to the Sun. The Sun's gravity delayed the signals by the amount that general relativity, Einstein's theory of gravity, predicts, to within a few parts in a hundred thousand. So the Cassini timing shows no extra pull across the solar system of the strength a carrier of small mass would give.

Physicists have also looked at the Large Hadron Collider, where, as Cham and Whiteson report, no heavier copies of known particles have turned up.

And physicists have counted the dimensions directly. On 17 August 2017 the detectors of LIGO and Virgo recorded gravitational waves, ripples of space, from two neutron stars merging. Pardo, Fishbach, Holz and Spergel, four physicists, used the waves from that merger to measure the number of dimensions of space and time through which the waves had traveled. They found four dimensions, to within about a tenth: three of space and one of time.

We now know two things from the measurements. Wherever the large world has been measured, the large world has three dimensions of space and one of time. Gravity in the large world is Einstein's gravity, with no extra pull beside it, from the scale of the solar system down to a twentieth of a millimeter. My account predicts the same gravity from its own ground. A change in the size of the six carries a force that reaches less than one Planck length, some thirty powers of ten below the shortest distance at which anyone has tested gravity. So gravity in four dimensions is general relativity.

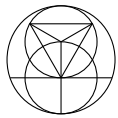
> **The short answer**
>
> The world has ten dimensions, one of time, three of space and six of possibility, and the six are the range of what a finding could be, present at every place and never a place themselves.

Each of the three settings of Chapter 1 now has its number of dimensions: three for space, one for time and six for possibility. So each finding you make now has a known shape: a place in three ways, a moment on one line, and an outcome chosen from six. The count also shows, ahead of the later chapters on travel, that every route anyone could take runs through the three dimensions of space and the one of time.

If space has three ways of differing and possibility has six, what is the one dimension of time?

PART THREE

FROM THE ARENA TO THE CLOCK



Chapter Twelve

What Is Time?

In which four good clocks come home disagreeing, and the one word for what they measure turns out to name three things

What is time?

What this chapter uses

A *comparison* is the act of finding whether two things are the same or different in some respect, and every measurement is a comparison; a *finding* is the outcome of one comparison, laid down as a record; a *comparer* is whatever makes a comparison, whether or not the comparer has a mind (Chapter 1).

Continuous: nothing is sudden, as along a ramp; *discontinuous*: something is sudden, as at the edge of a step; *symmetric*: what is found stays the same across a change of setting, as each step of a staircase is like every other; *asymmetric*: different everywhere, as the height along a ramp is (Chapter 1).

The *Incommensuration Theorem*: at the foundation of any event or comparison, symmetry and continuity cannot both be perfect together, and neither can asymmetry and discontinuity. The Incommensuration Theorem is a structural fact about the nature of knowing (Chapter 1).

Gravity is the *arena*, the stage of space and time on which the three forces act, and so gravity stands beside the three forces and is not a fourth force (Chapter 7).

In the first two weeks of October 1971, four atomic clocks went around the world twice, as passengers. The four clocks were cesium beam clocks. A cesium beam clock keeps time by counting the waves of a radio signal held in tune by atoms of cesium. The clocks rode on ordinary scheduled airliners, strapped into seats in the passenger compartment. The clocks were bolted together in two stacks, with a battery pack between the clocks of each stack. Two men rode beside the clocks: Joseph Hafele, an assistant professor of physics at Washington University in St. Louis, and Richard Keating, of the United States Naval Observatory in Washington. The first trip went east around the world. The second trip went west. The traveling clocks were compared with the Naval Observatory's atomic time scale before the first trip, between the two trips, and after the second trip.

When the clocks came home, they no longer agreed with the Observatory's time. The clocks that had flown east had lost about fifty-nine billionths of a second against the Observatory's time. The clocks that had flown west had gained about two hundred and seventy-three billionths of a second. Both amounts agreed with what Einstein's relativity predicts for the eastward trip and for the westward trip. Hafele and Keating reported the two amounts in the journal *Science* in July 1972. Four good clocks had traveled, and the four came home disagreeing with the time kept by the good clocks that had stayed. So your question about time comes back in a sharper form. If two good clocks can disagree about how much time has passed, which of the two clocks tells the time, and what is the time that both of the clocks were measuring?

Snapshots, and a Clock for Every Place

Jorge Cham and Daniel Whiteson give the question "What is time?" a chapter of *We Have No Idea*, and they answer the question with the picture that physicists use every day. Cham and Whiteson ask you to think of the world as a film: a string of still snapshots, each snapshot describing where everything is and what everything is doing at one moment. The snapshots are joined in two ways. The snapshots come in an order. Each snapshot follows from the snapshot before it by cause and effect. The authors sum up the picture in one line: "Time is the ordering and spacing of those snapshots" (*We Have No Idea*, ch. 8, "So Tell Us Already: What Is Time?"). They also report that physicists, philosophers and five-year-olds have argued over time for centuries. To date, they write, no set of words for time is universally agreed.

In *Frequently Asked Questions About the Universe*, Cham and Whiteson start from change: "Basically, physics thinks about time as the thing that allows the universe to change" (*Frequently Asked Questions About the Universe*, ch. 1, "Practical Versus Possible Versus Not Impossible"). In their account, the past limits what the present can be, and that limit is cause and effect. Every change also takes some time: a pizza goes through its steps,

from flour and tomatoes to a hot pie, and never jumps. In the same book Cham and Whiteson report what relativity shows about clocks. Other people see a clock run slow when the clock moves fast or sits near a heavy mass. Yet each person always feels time pass at its normal rate. So Cham and Whiteson conclude that "there's no central cosmic clock keeping the universe in sync" (*Frequently Asked Questions About the Universe*, ch. 12, "Time Is Relative").

In *We Have No Idea*, Cham and Whiteson go one step further. Observers moving at very different speeds can disagree even about which of two things happened first. Cham and Whiteson picture the disagreement as a race between a pet llama and a pet ferret: depending on how fast you travel and where you are, you could see either pet win. They write that the watchers who disagree "would all be correct!" (*We Have No Idea*, ch. 8, "Question #4: Do We All Feel Time the Same Way?") Because of the race, Cham and Whiteson give up the idea of "an absolute true history of the universe": a single story of everything that has happened so far, which every watcher could check against what that watcher saw. They write that Einstein's relativity makes it clear that "even the description of events in the universe depends on who is recording that description".

I keep every one of the authors' pictures (the film of snapshots, the clocks that run at different rates, and the race between the llama and the ferret), and I add three things to the pictures. The first thing I add is the reason that time and change go together. The second thing I add is that the authors' one word, 'time', names three different things. The authors' definition already contains two of the three things. The third thing I add is that what happened in the world stays one, the same for every comparer. What happened in the world stays one even though there is no single cosmic clock and no single time-ordered list of what happened.

Time Comes with Comparison

Look at the cup of coffee on your table; at seven the coffee was hot, and now, at eight, the coffee is warm. You have two findings. The two findings come in an order: hot, then warm. Now imagine the cup and the whole room held perfectly still: the same heat in the coffee, the same level in the cup, the same air, with nothing anywhere becoming any different. In that still room, everything found at eight would be exactly what was found at seven. As far as any finding could tell, seven and eight would be one and the same moment.

Here is the same picture in its barest form. Imagine a completely empty universe, and put two things in it: a capacity to perceive, say a head with an eye in it, and a book. Let nothing change. A carved head and a carved book would then serve as well as a real head and a real book, because nothing is happening. Take two moments in that universe and call them moment zero and moment one. Everything at moment one is exactly as it was at moment zero, so the two moments cannot be told apart.

To tell moment zero from moment one, something has to change. The change also has to be found. Only three things are present: the head, the book, and the interaction between the head and the book. The book is still, and what goes on inside the head cannot be seen from outside the head, so the difference between moment zero and moment one can be found only in the flow between the head and the book, in the perceiving itself. Perceiving is a comparison. In this book a comparison is the act of finding whether two things are the same or different in some respect (Chapter 1). The outcome of a comparison, laid down as a record, is a finding. So time and comparison depend on each other as ideas. Time cannot be thought of without comparison already thought of, and comparison cannot be thought of without time as part of the comparison. Dependence in one line: “Time comes with the comparison, not before it”.

The head in the empty universe can be any comparer, because a comparer, in this book, is whatever makes a comparison: a person, an instrument, a detector or an atom, whether or not the comparer has a mind

(Chapter 1). I take the same empty universe down to single particles and ask what is the least that leaves a lasting difference. Put one electron and one photon (a single packet of light) into the empty universe, and let the electron and the photon meet. The photon can bounce off the electron, but a lone electron has no inner states in which to keep a record of the bounce. Nothing else is there for the bounce to register against. Add a proton, and the electron and the proton make one hydrogen atom. Light of the right frequency can lift the atom's electron to a higher state. One atom is still not enough to leave a lasting difference, because in an otherwise empty universe the frequency of the light has nothing to be measured against. Two hydrogen atoms are enough, with the light that passes from one atom to the other. One atom gives up a little energy as light. The other atom takes in the light and is changed. In that one exchange a difference has been found. Time comes with that exchange of light, as time comes with your look at the cup.

I reach the authors' time, the "thing that allows the universe to change", on separate ground: time comes with comparison. The authors start from what the laws of physics need in order to say anything, while I start from what any finding needs, before any law of physics is written down. By our two routes, the authors and I reach one result: time and change go together, and in a world where no change could be found, no two moments could be told apart. The authors state their pizza rule in six words: "Nothing in this universe is instantaneous" (*Frequently Asked Questions About the Universe*, ch. 1, "Practical Versus Possible Versus Not Impossible"). The pizza rule has its ground in comparison too. An interaction which spans any distance must also take some time to span that distance, and I count that rule as a special case of continuity. In that passage continuity means the continuity of influences across space: no influence, interaction or signal crosses from one place to a distant place in zero time.

One Word for Three Times

Picture a laboratory bench with a lump of radioactive material on it, a counter beside the lump, and a clock on the wall above. Each of the three things goes with a kind of time. The three kinds of time are different kinds of thing.

The clock on the wall measures the first kind, which I call *geometric time*: the time that belongs to the shape of the arena. The arena is space and time together (Chapter 7): two of the three settings of every finding, with possibility the third. Geometric time includes two things. The first of the two things that geometric time includes is *proper time*, the time a clock shows as the clock is carried along the clock's own path through space and time. The clock on the wall shows the proper time of the wall's path. The second of the two things that geometric time includes is the order of which events can reach which: the pattern that Chapter 10 shows space to be. Any comparer who measures geometric time finds that geometric time is smooth and uneven. Geometric time is smooth because the time measured changes gradually from one path to the paths beside it. Geometric time is uneven because the time measured differs from one region to another with the matter in each region: a clock nearer a heavy mass runs slower than a clock farther away. The difference between the two clocks changes gradually as either clock is moved.

The counter measures the second kind, which I call *event time*, the time of findings: the order of findings for one comparer. Each click is a finding. An atom has decayed, the counter has registered the decay, and a record now exists that did not exist a moment before. Any comparer who measures event time finds that event time comes in steps and reads the same for everyone. Event time comes in steps because a finding is one outcome with no case in between: the counter clicks, or the counter does not click. Event time reads the same for everyone because a record, once made, is the same record for every later comparison of that record. The click recor-

ded on Monday is the same click when someone reads the record on Tuesday. The order of event time is a before and an after, and the order runs one way.

Between the clicks, quantum theory describes the third kind of time. Quantum theory describes the lump by its *quantum state*: a smooth mathematical wave that sets the odds of each possible finding. The chance that a given atom has decayed grows smoothly from moment to moment, and the quantum state, the wave that sets those chances for every atom of the lump, changes without a jump. Quantum theory has a rule for the change of the quantum state, and the rule has a single dial. Turn the dial forward by some amount, and, by the rule, the state moves forward by the same amount. I call the number on that dial *evolution time*. Evolution time belongs to the mathematics of quantum theory and is smooth there. Every turn of the dial has an exact undoing: the same rule, with the dial turned back by the same amount. Evolution time is the time of possibility: of what could be found, and with what odds.

Physicists use the single word 'time' for all three. The three times are distinct, because each time is a different kind of thing. Geometric time differs from event time: a date and a place in the shape of space and time pick out no result of any measurement. Event time differs from evolution time. A finding cannot serve as the dial of quantum theory's rule, because a finding comes in a jump and the record of a finding is never undone, while the dial turns smoothly and every turn of the dial can be undone exactly. Evolution time differs from geometric time too: the dial carries the wave through the wave's range of possible findings, and that range forms a space of its own, apart from space and time. So the dial is no direction of space and time: nothing travels through the range of possible findings from one place to another. The three times are also inseparable, because each time needs the other two. A finding needs a quantum state, whose possible outcomes the finding selects among, and a place and a moment where the finding is made. The shape of space and time is known only

through the findings that mark the shape, as a clock's ticks mark the clock's path. The changing quantum state needs findings that put the state's odds to use, and a clock by which the state's dial is read.

Each of the two great theories of physics contains two of the three times. General relativity contains geometric time, which is what the theory describes. General relativity also contains findings as events, each at a point of space and time. General relativity has no range of possibilities, and so it has no evolution time. Quantum theory contains findings, with their odds, and it contains evolution time in its mathematics. The clock of quantum theory is supplied from outside the theory, like the clock on the laboratory wall. The two theories share event time, the time of findings, and each theory contains the one time that the other theory lacks.

The Incommensuration Theorem of Chapter 1 shows why the three times stay three. In the plain words of this chapter, "smooth" means continuous, "jumpy" means discontinuous, "even" means symmetric, and "uneven" means asymmetric. In those words, smooth and even cannot both be perfect in one comparison, and neither can jumpy and uneven. Geometric time is found smooth and uneven, like the ramp of Chapter 1: every small step along the ramp is a small step up, and each point of the ramp is at a different height. Event time is found jumpy and even, like the staircase of Chapter 1: each step of the staircase rises suddenly at its edge, and each step is like every other step. A time found both smooth and uneven and also jumpy and even would have at least one of the two pairings that the Incommensuration Theorem says cannot be perfect: smooth with even, or jumpy with uneven. If one time were all three times together, with each made perfect, that one time would have to be smooth, jumpy, even and uneven all at once, and so that one time would have both of the pairings. Like geometric time, evolution time is smooth, so evolution time falls on the same side of the pairings as geometric time. Adding evolution time changes neither of the two pairings that a single time would have. The exact undoing of the dial belongs to quantum theory's rule, that is, to the mathematics of quantum theory. Every time that a detector registers on the lump is event time. The number on the dial is taken from a clock

outside the lump, and no measurement made on the lump reads that number. So no comparer ever finds evolution time itself. The exact undoing of the dial is a fact about the rule, and not a finding that evolution time is even. Evolution time never shows, in any finding, the pairing of smooth with even that the Incommensuration Theorem says cannot be perfect. So each of the three times is complete in its own work, and the three times exist together as three. No one time is all three together with each made perfect. No unified time exists.

The three times also show why physicists have found time hard to understand. Each of the two theories is exact where it is used, and each kind of time is right where it is used. The trouble begins when physicists ask one time to do the work of all three times. Go back to the bench. In quantum theory the lump's wave moves forward by the dial of evolution time, and physicists take the number on the dial from the clock on the wall, which hangs in the arena outside the wave. In 1967 Bryce DeWitt wrote a paper on the quantum theory of gravity. In that paper DeWitt put the arena itself into a quantum state, as physicists put the lump into a quantum state, and the equation that results has no time in it at all. Physicists call the puzzle of an equation with no time in it the problem of time. I show what happened: physicists read evolution time from a clock of the arena, and DeWitt had turned the arena into the thing that was to evolve. Once the wall clock and the room it hangs in are inside the wave, no clock is left outside the wave from which physicists could take the number on the dial.

Now return to the authors' definition: "Time is the ordering and spacing of those snapshots". In this chapter's terms, the authors' "ordering" of the snapshots is event time, the order of findings. The authors' "spacing" of the snapshots is geometric time, the time a clock measures between one snapshot and the next. So the authors' definition already contains two of the three times, and it contains both of them correctly. The third time has no snapshot of its own: evolution time is the time of what

could be found, running between the findings. So time has an exact definition after all: three definitions, one for each of the three things the word names.

Cham and Whiteson observe that time differs from space: physicists can treat time as a fourth direction, and yet you still move through time in one way only, at one second per second. The sorting into three times also shows what lies behind that observation. Time has one dimension (Chapter 11), and that one dimension belongs to geometric time. The one dimension of time is the direction along which the arena carries every clock. The world happens as findings are made, one act after another, and that order of acts is event time. Time is not another dimension of space.

Which Clock Tells the Time?

Go back to the clocks on the airliners. Each clock showed the geometric time of its own path, which is the clock's proper time, and the clocks' paths were different. A clock's rate is set by its place in the arena: by its height in a field of gravity, and by its motion. A clock raised higher runs a little faster than a clock below it. A clock in fast motion runs a little slower than a clock at rest. Seen from the center of the Earth, an airliner flying east adds its speed to the turning of the Earth, and an airliner flying west takes its speed away from the turning of the Earth. So the eastbound clocks moved faster than the clocks on the ground and lost time. The westbound clocks moved slower and gained time. Every flying clock was also higher than the Observatory, so every flying clock also gained a little time from its height. Which clock tells the time? Each clock tells the time of its own path.

Time comes with comparison, so a question follows: does a clock that takes part in more interactions run faster? To speak of how fast time flows, you have to say which time you mean. For the rate of a clock, the answer is no. At the same height and moving the same way, a busy clock and an idle clock keep the same rate: the number of interactions a clock takes part in has no part in fixing the clock's rate. The time you feel passing is another

matter: for someone perceiving, the felt passage of time goes with the number of changes in what is perceived, and with how much of what is perceived is new. The rate of your watch is geometric time, set by where and how you move, while the passing you feel goes with your findings, and the order of your findings is event time. So you feel your own time pass at its normal rate, whatever other people see your watch do. The authors say the same: "you always feel time moving normally" (*Frequently Asked Questions About the Universe*, ch. 12, "Time Is Relative"). Two of the three times are in you at once, geometric time in your watch and event time in your findings, each doing its own work.

Since 1971, clocks have shown more finely and in daily use that a clock's rate is set by its height and its motion. The satellites of the Global Positioning System carry atomic clocks. In the weaker gravity of the satellites' orbits, the satellite clocks run faster than clocks on the ground, and the satellites' speed makes the satellite clocks run a little slower, so the net gain is about thirty-eight millionths of a second each day. Light travels more than eleven kilometers in thirty-eight millionths of a second. So every satellite clock is adjusted before launch to allow for the clock's daily gain. Without that allowance, the positions that the system gives would drift by more than eleven kilometers in a single day. Neil Ashby set out the whole accounting of the satellite clocks in 2003, in his paper "Relativity in the Global Positioning System". In 2010, as Chapter 10 told, Chin-Wen Chou and his colleagues compared two clocks at the National Institute of Standards and Technology, each clock ticking with the light absorbed by a single aluminum ion. An ion is an atom with an electric charge, because the atom has lost or gained an electron. Each clock held one charged atom of aluminum. Chou and his colleagues raised one of the two clocks by thirty-three centimeters. The raised clock ran faster, by about four parts in a hundred million billion, the amount that relativity predicts for that change of height. We now know that geometric time differs smoothly from place to place, by the amounts that relativity predicts, at every height and every speed at which geometric time has been measured.

The clock experiment of 2010 shows two of the three times working together. Quantum theory describes the ticking: an aluminum ion takes in light only at one exact frequency, the same for every aluminum ion. Relativity describes the difference between the two rates: the arena is shaped a little differently thirty-three centimeters higher. The findings came in steps, as event time does, and the findings were made in the smooth and uneven arena of geometric time.

No Universal Now, and One History

The authors' race between the llama and the ferret shows a real feature of the world: comparers moving steadily past one another disagree about which distant events happen at the same moment. Take two events so far apart, and so close in time, that no signal could pass between them. The two events have no fixed order: for one comparer the first event is earlier, and for another comparer the second event is earlier. Chapter 15 shows the shape of what can reach what from each event, and in that shape the two events of such a pair lie outside each other's reach, so no comparison joins them.

Every finding is made at one place and moment, by the comparer that makes it. News of a distant finding reaches you only by a signal, which arrives no sooner than light could bring the news, so the universe has no single "now" shared by every comparer. Physicists call a single "now" stretched across the whole universe a *surface of simultaneity*. No comparison registers a surface of simultaneity on which a finding would be settled for every comparer together. The authors and I agree that there is no universal now.

The authors also give up the idea of one history, in their sense of the word "history": "an ultimate time-ordered list of when things happened" (*We Have No Idea*, ch. 10, "History Is History"). About that list I agree with the authors: no such list exists, because the order of distant events changes from one comparer to another. What stays one is the history of what happened, finding by finding, and that history is the same for every com-

parer. The history stays one because of a fact about findings: what a finding finds is the same for every comparer who finds it, and the record of the finding reads the same for everyone who later consults the record. Two witnesses to one event must be able to reconcile their accounts, or there was no one event for them to witness. So the findings of many comparers make one history in what happened: every finding is one finding, and every record of a finding agrees with every other record of that finding. The one history is many in its clocks: each comparer finds the history in the order, and at the rate, of the comparer's own path. Watchers of the llama and the ferret can see different pets win, and each watcher is correct, as the authors say. Each pet's crossing of the finish line is still one event, and every watcher who consults the record of that crossing reads the same record. The authors write that even the description of events changes with whoever records the description. I find that only one part of the description changes: the order and the timing of the description change from one recorder to another, while what each finding found is the same for every recorder.

What We Now Know

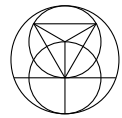
Four clocks went around the world in 1971. Each clock kept the geometric time of its own path, and the clocks came home disagreeing because their paths through the arena were different. The clocks measured what we call "time", and the word "time" names three things. Geometric time is the time a clock shows along its path, set by the shape of space and time, smooth and uneven. Event time is the order of findings, made in steps, the same for everyone who reads its records, and running one way. Evolution time is the dial of quantum theory's smooth change, the time of what could be found. Time comes with comparison, each of the three times has its own work, and no one time is all three together with each made perfect.

The short answer

Time comes with comparison: physics uses one word for three times, the time on your clock, the order of your findings and the time of quantum change, and no one time is all three with each made perfect.

The word "time" has to be sorted into three before any further question about time, so that each question in the chapters that follow can say which time it asks about. The sorting also shows that the world is found from inside, along many paths, each path with its own clock. The sorting shows, too, that the findings made along all the paths make one history of what happened.

If time is the order of findings, why does it go only one way?



Chapter Thirteen

Why Does Time Only Go Forward?

In which the cream spreads through the coffee, a film is run backward, and every record is found to come after the act it records

Why does time go forward and never backward?

What this chapter uses

A *comparison* is the act of finding whether two things are the same or different in some respect, and every measurement is a comparison; a *finding* is the outcome of one comparison, laid down as a record; a *comparer* is whatever makes a comparison, whether or not the comparer has a mind (Chapter 1).

The three *settings* in which anything is measured are space, the place of a finding; time, the moment of a finding; and possibility, the range of what could have been found instead; a setting is *bent* when one part of the setting differs from another part (Chapter 1).

Continuous: nothing is sudden, as along a ramp; *discontinuous*: something is sudden, as at the edge of a step; *symmetric*: what is found stays the same across a change of setting, as each step of a staircase is like every other; *asymmetric*: different everywhere, as the height along a ramp is (Chapter 1).

The *Incommensuration Theorem*: at the foundation of any event or comparison, symmetry and continuity cannot both be perfect together, and neither can asymmetry and discontinuity. The Incommensuration Theorem is a structural fact about the nature of knowing (Chapter 1).

From January to March of 1927, the astronomer Arthur Eddington gave the Gifford Lectures at the University of Edinburgh. Eddington made the lectures into a book, *The Nature of the Physical World*, which was published the next year. The book's fourth chapter is "The Running-Down of the Universe". Under the heading "Time's Arrow", in that chapter, Eddington asks his reader to do one simple thing: "Let us draw an arrow arbitrarily". Eddington then tells his reader to follow the arrow and to watch the state of the world at each point along the arrow. Where the random element in the world grows as you go along the arrow, the arrow points toward the future. Where the random element shrinks, the arrow points toward the past. Eddington named the one-way running of time "time's arrow", and physicists still use his name. Eddington also said

where the arrow comes from: from the growth of the random element, the mixing of things, which physicists measure as a quantity called entropy. For Eddington, the arrow of time and the growth of mixing were one and the same thing.

Is the mixing of things the whole reason that time goes one way, or is there a deeper reason beneath the mixing?

From Cham and Whiteson's pages

What Cham and Whiteson Showed

Jorge Cham and Daniel Whiteson ask why time goes one way, with cases from the kitchen and from daily life: cooked food does not turn raw again, ice cubes do not form in a drink on a hot day, and you remember yesterday and never tomorrow. Cham and Whiteson give their verdict in *We Have No Idea*: "Time appears to have a preferred direction, and we have no idea why" (*We Have No Idea*, ch. 8, "Question #3: Why Does Time Move Forward?").

The authors give their reader a test to try. Watch a video of a bouncing ball, the authors say, and ask whether you can tell if the video is running forward or backward. A ball that bounces perfectly, losing no energy, looks the same whether the video runs forward or backward. A real ball bounces a little lower each time and comes to rest. When the film of the real ball runs in reverse, the film shows a resting ball that starts to hop higher and higher. Anyone can see that the film is running backward. The authors report that almost every law of physics works as well in reverse as forward, and even quantum mechanics runs backward without trouble. In the authors' account, the real ball is given away by disorder and by the second law of thermodynamics: physicists measure disorder as entropy, and the second law says that entropy increases with time, on average.

The authors then ask whether entropy explains the direction of time. Cham and Whiteson grant that entropy increases with time, and they answer that the increase "still doesn't explain why time goes only for-

ward". The authors point out that anyone can picture a universe in which time runs backward and entropy falls along with time. The second law still holds in that backward-running universe. The authors conclude: "So entropy is not so much an insight as much as it is a clue" (*We Have No Idea*, ch. 8, "Does Entropy Help Us Understand Time?"). The authors write in the same section that "we still don't know" whether entropy explains the direction of time. The authors add that nobody knows why the universe began so orderly, either (ch. 8, "Question #3: Why Does Time Move Forward?"). The authors find a second clue in the weak force, the force that turns one kind of particle into another and causes some kinds of radioactive decay, and in their account the weak force has a small and real preference for one direction of time (ch. 8, "Time and Particles").

Cham and Whiteson's second book is *Frequently Asked Questions About the Universe*. In that book the authors say that the laws of physics themselves do not explain the flow of time: physics has many laws for how the world changes with time, and every one of those laws takes the flow of time for granted. In the authors' words: "None of them actually tell us how the flow of time works" (*Frequently Asked Questions About the Universe*, ch. 1, "Going with the Flow"). In the same section the authors note that the second law of thermodynamics does not by itself require time to go forward: the second law requires only that disorder fall if time ever ran backward. Some physicists propose that time flows because entropy rises, and so would stop when entropy reaches its largest value. The authors call that proposal a big leap (ch. 12, "The Heat Death").

The Cream in the Cup

Pour a little cream into your coffee and watch. For a moment there is a white curl of cream in the dark coffee. Then the curl spreads, and the cup turns one even brown. You can watch the cup all morning, and the cream never gathers itself back into a curl.

The cream stays spread for a reason that comes from counting. Picture the tiny parts of the coffee and the cream, jostling all the time. Very few arrangements of the tiny parts put all the cream in one curl. A vastly larger number of arrangements spread the cream evenly through the cup, and all of them look the same to you: one even brown. Each jostle moves the cup from one arrangement to another, and almost every arrangement a few jostles away is a spread-out one, so the cup drifts into the spread-out state and stays there.

Physicists have a name for the count of arrangements. The *entropy* of a thing is a count of the arrangements of its small parts that look the same from outside. The count is always made relative to some look at the thing, and for the cup the look is your glance at the cup. A curl of cream has low entropy, because few arrangements of the parts make a curl. An even brown has high entropy, because a great many arrangements of the parts make an even brown. The *second law of thermodynamics* says that the entropy of a thing of many parts, left to itself, does not decrease. The second law is a law of what happens almost always among very many parts. The physicist Ludwig Boltzmann showed in 1877 that the second law comes from counting arrangements, as we have just done for the cup.

The count of arrangements has the limit that the authors found: by itself, the count does not tell forward from backward. Take a deck of cards in which the hearts still run in order from ace to king and the other cards are mixed. Use the count of arrangements to work out what the deck will look like after a few more shuffles, and the count says: more mixed. Use the same count to work out what the deck looked like a few shuffles ago, and the count says "more mixed" again, because almost every arrangement a few shuffles away from the present one is mixed. The count cannot tell the future from the past, because the laws used in the count run both ways. You know better about the deck only because you know one more fact: decks leave the factory in order. The factory order is a condition placed at one end of the deck's history. The growth of entropy in the world can point one way only with a condition of the same kind: the condition that our epoch, the era of the world in which we live, began with

very low entropy. The philosopher David Albert argued in 2000 that the low-entropy beginning should be counted as a law of nature in its own right, because nothing else in physics supplies the low-entropy beginning.

So the authors are right that the growth of entropy alone does not fix the direction of time, and so do I. The laws run both ways, and the count of disorder gives a direction only from a beginning that was less mixed than what came after it.

Your cup of coffee shows one more one-way order. You see the cream spread, and a moment later you remember that you saw the cream spread. Your noticing comes before your memory of noticing, and the order of noticing and remembering holds for one glance at one cup.

Two Ways to Run a Film Backward

Go back to the authors' film of the real ball, the ball that bounces a little lower each time and settles to rest. Run the film backward. The ball lying still begins to hop, higher each time, until it rises into the hand that dropped it. Everyone watching knows the film is running backward. Yet each arc in the backward film is an arc a ball can fly. Each push the floor gives the ball is a push the laws of motion allow, provided that at every bounce the molecules of the floor all move together in just the right way. Everything in the backward film obeys the laws of physics.

The phrase "the laws run backward" can mean two different claims. The first claim is that if a process obeys the laws, the same process run backward obeys the laws too. I call the first claim *lawful reversal*. As Chapter 4 used the word, the state of a thing is everything about it at one moment: where each part is, and how each part is moving. The second claim is that the reversed process passes back through exactly the states the original process passed through, and arrives at exactly the condition the original process started from. I call the second claim *faithful reversal*.

Lawful reversal follows from the symmetry of the laws. When what is found in a thing stays the same across a change of setting, Chapter 1 calls the thing symmetric. For lawful reversal, what stays the same is the laws

of physics, and the change of setting is the reversal of time, in which ten seconds after becomes ten seconds before. For nearly every process the laws stay the same when time is reversed. So the reverse of nearly every lawful process is lawful too. The one small exception is in the weak force, and I take up that exception in the last section of this chapter.

Faithful reversal needs much more than lawful reversal. For the backward film to retrace the forward film, every molecule of the floor would have to go back along its exact path, and so would every molecule of the air the ball pushed aside and every trace of warmth each bounce left in the floor. Each molecule and each trace of warmth would have to be described exactly, at every place and to every fineness. Leave a gap anywhere in the description, however small, and the part left out is free to go somewhere other than where it came from, so the backward run is no longer the forward run retraced. When a description of the state has no gap anywhere, the description is continuous, in the sense of Chapter 1: nothing in the description is sudden, and sameness holds without a break, at every point and every scale.

So a perfect reversal of time needs two things perfected together, because the reversal must be faithful as well as lawful: the laws must be perfectly symmetric, and the description of the state must be perfectly continuous. Chapter 1 gave the Incommensuration Theorem in plain words: at the foundation of any event or comparison, symmetry and continuity cannot both be perfect together, and neither can asymmetry and discontinuity. So a perfect reversal of time needs exactly the pair, symmetry and continuity, that the Incommensuration Theorem states cannot be perfect together. So no process, at any scale, runs backward faithfully. The limit on faithful reversal is a limit in principle, and therefore a limit in all practice, because every instrument that could attempt a reversal works by making comparisons, and the theorem holds of every event and every comparison. Faithful reversal is impossible because of the structure of comparison alone. The structure of comparison is what every comparison

must contain. Entropy plays no part in the argument that faithful reversal is impossible, and neither do the number of parts and the condition at the beginning of the world.

In the equations of physics, the difference between lawful reversal and faithful reversal does not show. Mechanics describes a system by one complete list of the position and motion of every part, and quantum mechanics describes a system by one complete quantum state, so in both theories the description is complete by construction. Once the description is taken to be complete, lawful reversal and faithful reversal look like one and the same thing. Quantum mechanics "works just fine backward", as the authors say, because completeness is built into its equations: the ease with which the equations run backward belongs to the equations, which assume a description with no gap. The equations remain excellent tools, but the Incommensuration Theorem sets the limit on what the equations can be taken to say about the world.

The reason the authors asked for follows from the Incommensuration Theorem: the world runs one way because of the structure of comparison.

The Order of Every Comparison

I reach the same answer a second way, starting from a picture, and the answer is again that the world runs one way because of the structure of comparison. Watch a photographer at work. First the photographer takes up a position: she stands somewhere, holds the camera at some height, and chooses a lens. From her position many pictures are possible, and she has taken none of the pictures yet. Then she presses the shutter, and in the instant of the click one picture is taken and all the other possible pictures are not. Afterward there is the print, a fixed thing that anyone can pick up and look at, the same for everyone who sees the print. The print then shapes what the photographer does next: she looks at the print and moves to a better spot.

The photographer's work has three parts, in order: position, click, print. Every comparison has three parts of the same kind, in the same order. First there is the range of what could be found from where the comparer stands, as the photographer's position holds many possible pictures. The comparer is whoever or whatever makes the comparison. Then there is the act, in which one finding is made, as the click takes one picture. Then there is the record of the finding, laid out where anyone can look at the finding again, as the print is, and the record shapes the next comparison, as the print shapes the photographer's next move.

The Immanent Metaphysics is my account of what every act of knowing must contain. The Immanent Metaphysics rests on three axioms, its basic statements, and each axiom holds of every comparison whatever. Chapter 1 used three facts about the three settings of space, time and possibility: the settings are inseparable, not interchangeable, and distinct. The three facts are the three clauses of the third axiom. The second axiom states the order of position, click and print. A range of what could be found comes before any act, an act comes before its record, and a record comes before the next range. The order is an order of coming before, as a question comes before its answer, and not a time shown on any clock. The order runs one way only: no print comes before its click.

I identify the direction of time with the one-way order of every comparison. Every record ever found follows the act it records: no footprint has been found before the step that made it, and no count on a detector before the particle that made the count.

Chapter 12 sorted the word "time" into three times: geometric time, the time on your clock; event time, the order of your findings; and evolution time, the time of quantum change. The direction of time belongs to event time, the order of findings, one record after another.

Look at your cup again, with the order of range, act and record in mind. Your glance at the cream is one comparison. The glance runs from what you could have found in the cup, to the act of seeing the cream

spread, to the memory you now hold of having seen the cream spread. One glance at one cup already has a before and an after, and the after is the record.

Two Arrows, Joined in Every Record

Eddington was right that the mixing of things has a direction. The growth of mixing is one of two arrows of time, and the two arrows are different things that point the same way.

The first arrow is the *structural arrow*: the one-way order of every comparison, from the range of what could be found, to the act, to the record, together with the impossibility of running any process backward faithfully. The structural arrow is present in a single comparison, made once.

The second arrow is the *entropic arrow*: the growth of entropy in things of very many parts, which is the arrow of the cream in your coffee and of Eddington's random element. The entropic arrow is a law of what happens almost always, so it is found only where there is a crowd of parts to mix. A single card cannot be shuffled into disorder, but a deck of fifty-two cards can. The entropic arrow also needs a beginning that was less mixed than what came after it, as the deck needs its factory order.

The two arrows are both present in every record. When the photographer's shutter opens, light strikes the film. Wherever the light strikes, a tiny grain darkens: the darkened grain is the record. When a particle passes through a detector, a counter steps up by one: the count is the record. Each record is itself a change that does not undo itself. Making a record raises the entropy of the instrument that holds the record: the film, or the counter, ends a little more mixed than it began. So each act of recording is two things at once: the act follows the order of comparison, from range to act to record, and the act is a growth of entropy in the instrument. The two arrows agree wherever both are found because every record is one event in which both are present and point the same way.

Cham and Whiteson say that nobody knows why the universe began so orderly, and the two arrows show where that orderly beginning belongs. Our epoch began with low entropy, and that low entropy is a condition on the entropic arrow. The low entropy at the beginning fixes how the direction of time appears across the whole history of our universe: stars burn their fuel, cups of coffee cool, cream spreads and stays spread. The direction of time itself comes from the order of comparison, from range to act to record, which every comparison in any epoch follows. I answer in Chapter 22 why our epoch began so orderly, and the answer depends on what a count of disorder is. Every count of disorder is made relative to an outside world, from which the states are told apart, and each epoch begins with a new outside world, and so with a new count. Chapter 22 shows that the space and time of each new epoch begin even, and that this evenness is the low entropy of our beginning.

The two arrows also show that the authors were right to doubt one proposal about the end of time. The authors judged it a big leap to say that time flows because entropy rises, and so would stop at the largest value of entropy. The direction of time rests on the order of comparison, and the growth of entropy rests on that order in turn, so a largest value of entropy, wherever one is reached, leaves the order of comparison as it was.

What the Particles Showed

The authors' last clue comes from particles: the weak force's preference for one direction of time. Physicists found the clue by measurement. We need two mirror operations to follow the particle clue. The first operation swaps every particle for its twin with every charge reversed (Chapter 19 shows that such twins exist because comparing makes a state and its mirror together). The second operation reflects space as in a mirror, so that left becomes right. Physicists call the two operations together C P, for charge and parity, and parity is the physicists' name for the reflection of space.

In 1964 a team of four physicists watched the long-lived kaons in a beam of neutral kaons decay. A neutral kaon is an unstable particle made of a quark bound to an antiquark, with no net charge. The four physicists were James Christenson, James Cronin, Val Fitch and René Turlay. When a particle is made of a quark bound to an antiquark, physicists call the particle a *meson*, so the kaons are mesons. The four physicists found a few of the long-lived kaons decaying into two pions, the lightest particles made of quarks. If the laws stayed the same under C P, a long-lived kaon could never decay into two pions. So the weak force breaks the combined mirror C P, by a small amount.

The finding of 1964 is about time too, because of a general result of physics. The *CPT theorem* says that swapping every particle for its charge-reversed twin, mirroring space, and reversing time, all three flips together, is an exact symmetry of every theory of the kind physicists use for particles and forces. If the three flips together leave the laws the same, and the first two flips together do not, then the third flip, the reversal of time, cannot leave the laws the same by itself. So the break in C P found in 1964 is also a break in the symmetry of time.

Physicists later found the break in the symmetry of time directly. In 1998 physicists of the CPLEAR collaboration at CERN compared two changes: neutral kaons turning into their charge-reversed twins, and the twins turning back into kaons. The physicists found that the two changes do not run at the same rate, so a film of the process run backward differs from the film run forward. The CPLEAR result is the kind of effect the authors describe, in which switching between two arrangements of quarks one way takes longer than switching back. In 2012 the BaBar collaboration, another team of physicists, found a break of the same kind with B mesons. B mesons are mesons far heavier than the kaons. We now know that the weak force runs some processes differently forward and backward, by a small amount that has been measured.

Some break in the symmetry of time must exist. Within any finite domain, symmetry and continuity are both present, each to a finite degree. The Incommensuration Theorem forbids symmetry and continuity to be

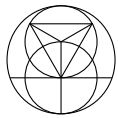
perfected together. A perfect symmetry of time would let every process run backward faithfully, but no process runs backward faithfully, so the symmetry of the laws under the reversal of time cannot be perfect, although the symmetry holds to an extraordinary degree. So a small one-way remainder in time must exist in the world: some process must run differently forward and backward. I read the measured break in the weak force as the required one-way remainder, found by instruments. The argument from the Incommensuration Theorem fixes that an asymmetry of time exists, while physicists find by measurement how large the asymmetry is, which force shows it, and by what mechanism.

The pattern of the measurements also agrees with the argument from the Incommensuration Theorem. The laws of nature keep the combined symmetry of all three flips and break the symmetry of time alone. The reversal of time can take part in a combined symmetry, in which the other two flips make up for the one-way remainder in time, but the symmetry of time taken by itself cannot be perfect. The authors were right to call the weak force a clue. The weak force shows the same thing as the cream in the cup and the photographer's print: the direction of time is part of what it is for anything to compare with anything else.

> **The short answer**
>
> Time goes forward because every comparison goes one way, from what could be found, to the finding, to its record, and that order needs no special beginning of the world.

So the direction of time is in the act that every measurement performs, the act of comparing by which the world is found from inside. The growth of disorder that Eddington named is the same direction, as the direction appears in things of many parts. Once the direction of time is placed in the act of comparison, the question of going back in time becomes a question about undoing findings.

Then can I go back and keep the coffee from spilling?



Chapter Fourteen

Why Can't I Travel Back in Time?

In which a loop in time is drawn on paper, the coffee spills, and the trip back turns out to name nothing

Why can't I travel back in time, and undo a mistake?

What this chapter uses

A *comparison* is the act of finding whether two things are the same or different in some respect, and every measurement is a comparison; a *finding* is the outcome of one comparison, laid down as a record; a *comparer* is whatever makes a comparison, whether or not the comparer has a mind (Chapter 1).

The three *settings* in which anything is measured are space, the place of a finding; time, the moment of a finding; and possibility, the range of what could have been found instead; a setting is *bent* when one part of the setting differs from another part (Chapter 1).

Continuous: nothing is sudden, as along a ramp; *discontinuous*: something is sudden, as at the edge of a step; *symmetric*: what is found stays the same across a change of setting, as each step of a staircase is like every other; *asymmetric*: different everywhere, as the height along a ramp is (Chapter 1).

Three things in nature do the bending: gravitation bends space, the cosmological constant bends time, and the dark matter bends possibility (Chapter 1).

Gravity is the *arena*, the stage of space and time on which the three forces act, and so gravity stands beside the three forces and is not a fourth force (Chapter 7).

Every comparison goes one way, from what could be found, to the finding, to its record, and so time goes forward (Chapter 13).

In Princeton, in 1949, the logician Kurt Gödel wrote down a universe for Albert Einstein's seventieth birthday. Both men worked at the Institute for Advanced Study in Princeton, and Einstein turned seventy in March 1949. Gödel's universe was a new solution of Einstein's own equations of gravity, the equations that say how energy shapes space and time. Gödel published the solution in an issue of the journal *Reviews of Modern Physics* dedicated to Einstein's birthday, and the solution described a whole world

in which all the matter turns. Gödel's world has a strange property. Gödel's world has a loop in time through every point: a path that a body could follow, and that brings the body back to the very place and moment the body set out from.

Gödel also published an essay in 1949, in a volume of essays on Einstein's thought. The volume was *Albert Einstein: Philosopher-Scientist*, edited by Paul Arthur Schilpp. In the essay Gödel argued from his solution that the passing of time is not objective. Einstein replied in Schilpp's volume. Einstein called Gödel's work "an important contribution", and he wrote that the problem about time which Gödel's work raised had troubled him while he was building his theory of gravity, the general theory of relativity. Einstein then set down a question about the loops: "It will be interesting to weigh whether these are not to be excluded on physical grounds".

So the equations of gravity allow a loop in time: Gödel's world obeys the equations and has a loop through every point. If a path can bring you back to where and when you started, can the path bring you back to this morning, before your mistake?

From Cham and Whiteson's pages

What Cham and Whiteson Showed

Jorge Cham and Daniel Whiteson open their book *Frequently Asked Questions About the Universe* with the question of going back in time. Their running example is a cup of coffee spilled on your pants. Cham and Whiteson begin by saying what the word "possible" means. When a thing can be built at a reasonable cost and in a reasonable time, an engineer calls the thing possible. A physicist uses another standard: "A physicist will say something is possible if they don't know of a law of physics that prevents it" (*Frequently Asked Questions About the Universe*, ch. 1, "Practical Versus Possible Versus Not Impossible"). The authors use the physicist's standard, and so they ask whether going back in time breaks any law of physics.

Cham and Whiteson's answer has two parts. First, Cham and Whiteson show that changing the past is impossible, because a changed past would leave an effect with no cause: the bad coffee would exist, and the act that made the bad coffee would not. Split timelines (one history that splits into two) do not save the plan to change the past either, because "Timelines represent change, so they can't themselves change" (*Frequently Asked Questions About the Universe*, ch. 1, "You Can't Go Back to the Future"). Second, a trip to the past that changes nothing is "not known to be impossible" (*Frequently Asked Questions About the Universe*, ch. 1, "No Do-overs?"). Space and time together can bend. The authors describe two bent shapes that would carry a loop in time: the space near an endlessly long spinning cylinder of dust, and a wormhole, which is a tunnel that joins two different places and times. A traveler on a loop in time stays on one timeline, so whatever the traveler did in the past has already happened, and the spill stays spilled. The authors offer an idea of their own near the end of their first chapter: a machine that runs time backward inside itself, so that your coffee unspills while the rest of the world runs on.

Cham and Whiteson are firmer in their first book, *We Have No Idea*. They write that modern physics is as certain as it can be that travel back in time is not possible, because travel back in time would let effects come before their causes. They also look closely at the stories people tell about time travel. Some stories send their travelers back and forth through time as if along a hallway, so that a traveler has one place in space and time and "then later" another place. The authors ask: "What does 'later' mean?" (*We Have No Idea*, ch. 8, "Question #2: Can We Travel Back in Time?"). They point out that the storyteller has slipped an ordinary flowing time back in, on top of the map of space and time, in which every event is already laid out.

The Coffee Spills

Take your cup from the table and, this once, knock the cup over. The coffee runs across the table and onto your pants. You see the spill, you feel the heat through the cloth, and the stain spreads.

You have now found something. You compared your pants before the spill with your pants after the spill, and the difference was there. The difference you found is a finding: the outcome of one act of comparison. A *record* is what a finding leaves behind for later comparisons to read: the stain, the wet patch on the table, your memory of the spill. The spill also happened at one place in the pattern of space and time: at this table, at a quarter past eight this morning.

Now ask what "going back to before the spill" would mean. The question sounds like one request, but the question contains three requests. You could mean reaching a place in space and time that lies earlier than the spill, the way you reach a town west of you. You could mean that the order of your findings changes: the spill unfound, the stain unmade, this morning's record wiped clean. Or you could mean what people mean when they wish to go back. The wish is to be at a quarter past eight this morning, the very morning, as it was. The cup would still be upright, and you would be there to catch the cup. I name the three meanings: reaching an earlier place is the geometric reading, changing the order of findings is the event reading, and being at this very morning is the joint reading. The joint reading is the sense in which people use the phrase "going back", because going back to this morning means being at this morning, and at no other morning that resembles this morning.

Two Times in One Word

Chapter 12 sorted the word "time" into three times. *Geometric time* is the time on your clock and the order of cause among events, laid out in the shape of space and time. *Evolution time* is the smooth time along

which quantum theory's description of what could be found changes. The three readings of "going back" use two of the three times: geometric time and event time.

Geometric time and event time are there in two different ways. I tell the two ways apart with one plain distinction: between what exists and what is real. A law exists; a measurement is real. As the line uses the word, to *exist* is to stand as structure. A thing that exists is the same however anyone consults it, as a law is. To be *real* is to be given in an actual act of comparison, which happens when it happens, as a measurement does. Geometric time exists: this morning lies in a region of space and time that stands in the pattern as structure. Every event in the region keeps its place. Event time is real: you found the spill in one act, at one moment, and what remains of that act now is the record of the spill (the stain, and your memory of the spill).

The wish to go back uses both senses, existing and being real, at once. The wish uses the sense of existing to name the destination, since this morning is "still there" in the pattern of space and time, and the sense of being real to describe the arrival, since you are present at the morning as the morning happened. Cham and Whiteson asked what the word "later" means, and their question is about using the one word "time" in both senses at once. A map of space and time, on its own, has places and no "later", because the "later" belongs to the order of findings, and the storyteller borrows the "later" without saying so.

A Loop on Paper

Begin with the geometric reading, the one the authors grant: travel around a loop in bent space and time. When a clock could follow a path back to where and when the clock started, physicists call the path a *closed timelike curve*. Gödel's world has a closed timelike curve through every point. A wormhole has two mouths, the two ends of its tunnel. In 1988 the physicists Michael Morris, Kip Thorne and Ulvi Yurtsever showed that a wormhole would carry closed timelike curves if someone moved its two

mouths so that the mouths aged differently. The authors' spinning cylinder of dust is a third shape that carries closed timelike curves, beside Gödel's world and the moving wormhole. A time machine on paper is a shape that obeys Einstein's equations. By contrast, a person who says "time travel" asks for something done.

Physicists who study shapes with loops in time add one rule, and Cham and Whiteson use the same rule. The rule is the *self-consistency principle*, which a group of physicists set out in 1990: John Friedman, Michael Morris, Igor Novikov, Fernando Echeverria, Gunnar Klinkhammer, Kip Thorne and Ulvi Yurtsever. In a world with loops in time, the self-consistency principle states which histories are possible: only the histories in which the state of things at each event is one state and not two. Cham and Whiteson state the self-consistency principle in their own words when they say that you and your earlier self "are both part of the same timeline" (*Frequently Asked Questions About the Universe*, ch. 1, "No Do-overs?").

Now picture a country in which the only way to travel is by road. A woman drives back to the town where she was born. She arrives, and what she finds is the town as it is on the day she arrives, not the morning of her birth. The road took her to a place. The morning she was born was an occasion, found once by the people who were there.

A loop in time does for a traveler what the road does for the woman: the loop brings the traveler to a place in space and time, and not to an occasion that was already found. I show why, in three steps. A traveler who carries a clock is a comparer (anything that makes comparisons, in this case an instrument that makes findings). Each reading of the traveler's clock is a finding. First, the traveler carries along the records made at the start of the loop, and every finding at the end of the loop is made from a range of possibilities that those records have shaped. So every finding at the end of the loop comes after the findings at the start, in the one-way order of findings that Chapter 13 described: from the range of what could be found, to the act, to the record. Second, the traveler's clock agrees with the order of findings. A clock's reading increases at every step along the clock's own path. So the clock shows a later reading at the end of the loop

than at the start. Third, suppose that the loop brings the traveler back to the very event of departure. Then the self-consistency principle requires that every physical mark of the trip, the clock's reading among the marks, be set back on the way round to the mark's state at the start. The marks must be set back because the state of things at the event of departure is one state and not two. Setting the marks back is itself a further act, and the findings of that act come after the findings the act would have to undo. So the arrival is a later finding of the traveler, and the traveler does not find the departure again.

The loop in time is part of the geometry of the solution of Einstein's equations, and the three steps (the records carried, the clock's reading and the setting back of the marks) say what happens to whatever goes round the loop. Whatever goes round the loop and comes back arrives at a later finding of its own. If a thing keeps no record of anything found on the way, the thing brings nothing from the end of the trip back to the start, and the thing is no traveler in the sense of the wish. So the authors' result, that you could not unspill your coffee, is true on every loop: on Gödel's loop, in the wormhole or beside the cylinder of dust, wherever you arrive, you arrive after the spill.

The Trip the Wish Asks For

On the second reading, the event reading, you ask that the spill be unfound. You ask that a finding already laid down come undone as a finding, or that a later finding come before an earlier finding. Chapter 13 showed that every comparison runs one way, from what could be found, to the finding, to the finding's record, and that the record shapes what can be found next. The one-way order of findings is the direction of time. The direction of time is a precedence and not a clock reading, and it cannot be reversed. A precedence is an order of coming before, as a question comes before its answer. On the event reading, you ask for the order of findings to be reversed, and the order of findings cannot be reversed, so nothing can give you what you ask for.

The third reading, the joint reading, is the wish itself: to be at a quarter past eight this morning, the very morning, as it was. Hold the near misses beside the wish. Tomorrow's copy of your kitchen is a copy, even with the cup set upright. Another morning, even with the same cup and the same light as this morning, is a likeness. Move one hair's breadth away from this morning, in place or in moment, and you are at another place. Each near miss differs from this morning somewhere, however slightly, and the person who wishes to go back refuses every near miss. So the wish is for this morning exactly, in both of the ways this morning is there at once: the very place in the pattern of space and time, and the very occasion, with the occasion's findings given again.

The Incommensuration Theorem, from Chapter 1, shows that no arrival gives what the joint reading asks for. Chapter 1 explained the theorem's four words, continuity, discontinuity, symmetry and asymmetry, in plain terms. When nothing in a thing is sudden, we call the thing continuous. When something in a thing is sudden, as at the edge of a step, we call the thing discontinuous. When something in a thing is different everywhere, we call the thing asymmetric, as the height along a ramp is different at every point.

What any comparer finds of geometric time is continuous and asymmetric. Geometric time is found continuous because the times measured along neighboring paths vary smoothly from one path to the next. Geometric time is found asymmetric because the times measured differ from region to region with the matter present, as Chapter 12 showed: a clock nearer a heavy mass runs slower than a clock farther away. What any comparer finds of event time is discontinuous and symmetric. Event time is found discontinuous because a finding is one outcome, with no case in between: the cup spilled, or the cup did not spill. The stain says the same thing at noon as at nine.

The wish is that one arrival, one act of comparison, find this morning exactly as a place and exactly as an occasion. So the wish is for one time, found in one act, with all four characters perfected together: the smoothness (continuity) and the variety (asymmetry) of the place, and the jump

(discontinuity) and the sameness (symmetry) of the occasion. To have all four characters perfected together, a time would have to hold continuity with symmetry, or asymmetry with discontinuity, or both, and the Incommensuration Theorem forbids both pairings. I show that a time found as both geometric time and event time carries at least one of the two forbidden pairings. Apply the result to the phrase "time travel". So no arrival gives what the joint reading asks for.

Put the three readings of "going back" together: the geometric, the event and the joint. The geometric reading describes a later finding of the traveler, and so describes something other than what the wish is for. The event reading and the joint reading ask for what nothing can be. I draw the conclusion: "time travel", in the sense in which people use the phrase, names no concept. The phrase "time travel" is like the phrase "the largest prime number", which has the grammar of a name and names no number, because every prime number is exceeded by a larger prime number. The mistake in the phrase is a category error, in the sense of Chapter 8: applying a concept where the concept does not belong. This morning's spill was real, found once in one act, and someone who wishes to go back treats the spill as if the spill stood as structure, waiting for a visit. Geometric time and event time are each in good order on their own terms, and the fault lies only in asking one time to be both geometric time and event time.

Of last Thursday's findings: their being over is what it means for a finding to have been made. The sentence holds for this morning's spill too. The spill lies in a region of space and time, and the region exists. The stain on your pants is real now, each time you look at the stain. The region and the stain are not occasions you can attend a second time.

A Third Kind of Answer

Cham and Whiteson set two standards side by side, the engineer's and the physicist's, and they take the physicist's standard for their book. In their words: "Since this is a book about physics and the universe, we take the physicist's point of view" (*Frequently Asked Questions About the Uni-*

verse, ch. 1, "Practical Versus Possible Versus Not Impossible"). I use a third standard: whether a request names anything at all. The third standard has a plain example: ask someone for the color of the number seven. The answer is not hidden or hard to find. The request names nothing, because the request puts the word "color" where the meaning of the word does not reach. When I say that a thing cannot be, I mean that the request names nothing. No future machine can satisfy a request that names nothing, so a thing impossible in principle is impossible in all future practice.

Two things count as one by the physicist's standard and as two by the third standard: what the equations allow, and what a trip is. By the physicist's standard, Gödel's loops count as a way back, since the equations allow the loops and no known law forbids the loops. By the third standard, the equations allow a shape, and a shape is structure. Whether a trip runs along the shape is a separate question. A trip along the shape brings the traveler only to a later finding of the traveler's own. You cannot go back. You cannot go back because to say "back" of time is to treat an earlier finding as a place to be reached, the way an earlier event in geometric time is a place. A finding is given once, in an act, and the order of findings runs in one direction only. A wormhole would need engineering, energy and a rare kind of matter, called exotic matter, but the reason you cannot go back has nothing to do with any of the three. Not because exotic matter does not exist.

My answer rests on the structure of comparison, and the answer uses only three things from Einstein's theory of gravity. The three things are the definition of geometric time, two facts of the geometry, and the self-consistency principle. The first fact of the geometry is that a clock's reading increases along every path a clock can follow. The second fact is that a path into an event's past and back again is a closed loop.

Physicists have their own results on Einstein's question, whether the loops are to be excluded on physical grounds. In 1992 the physicist Stephen Hawking studied a time machine grown, in a limited region, from a slice of space that runs on without end. Hawking proved that the time machine could form only with matter whose energy some observer meas-

ures as negative, and he also proposed, as a conjecture, that the laws of physics keep loops in time from appearing at all. A quantum field is a field such as light, described by quantum theory, as Chapter 8 put it. In 1997 the physicists Bernard Kay, Marek Radzikowski and Robert Wald proved that the simplest quantum field has no well-behaved state on part of the boundary where the loops of a time machine would begin. My answer does not use the results of Hawking, or of Kay, Radzikowski and Wald, as steps. The results are checks on the answer. In the terms of physics itself, the results show no way into the past, no door of the kind people imagine for "time travel".

The Eddy in the River

One idea is left: the authors' own machine, which would run time backward inside itself, "like creating small eddy currents here and there that temporarily flow backward" (*Frequently Asked Questions About the Universe*, ch. 1, "Going with the Flow"). Physicists have run a small part of the world backward, in a laboratory.

In 1950 the physicist Erwin Hahn placed a liquid in a magnetic field. Hahn gave the nuclei of the liquid's atoms a short pulse of radio waves. Each nucleus carries a spin, the built-in turning that Chapter 4 likened to a top that never runs down. The axis of each tiny top turns about the direction of the magnetic field. Nuclei in slightly different fields turn at slightly different rates. So the tops, which the pulse had lined up, drifted out of step, and the signal the tops gave together faded away. Hahn then gave a second pulse. The tops came back into step, and the signal returned. Physicists call the returning signal the spin echo. In 1971 the scientists Won-Kyu Rhim, Alexander Pines and John Waugh extended the reversal to the interactions of the nuclei with one another.

The spin echo shows how far a reversal can go. I call a mark that a motion leaves in one particle a *trace*. The angle by which one nucleus has drifted is a trace. I keep the word record for what a finding leaves, and a record is not undone. The spin echo returns because one pulse could reverse

every trace: each nucleus held its own drift in its own angle, one trace per nucleus. Even so, the tops come back into step only in part. The experiment runs forward throughout in the order of findings: the signal is found faded, then comes a pulse, then the echo is found. Only the smooth turning of the tops runs backward, and the record of the fading stays in the laboratory.

The authors' machine would make a reversal of the same kind as the spin echo, on a larger scale: inside the machine, the coffee would lift back into the cup in a lawful reversal, a reversed motion that obeys the laws of physics. Chapter 13 set lawful reversal beside faithful reversal. In a faithful reversal, a process passes back through exactly the states it passed through, and arrives at exactly the condition it started from. The spill is still a finding already made. The heat of the spill has already passed into the cloth and the air, and on to countless particles that no pulse can reach. The clean pants would be a new finding, made after the spill. The authors themselves suggest leaving a note outside the machine, and the note is a record that the machine leaves in place. The order of findings runs on through the eddy, and the eddy is one more thing that happens in the order of findings.

Where the Two Accounts Meet

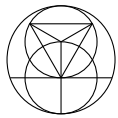
On travel into the past, my account and the authors' agree: going back cannot change the past, and the timeline neither changes nor splits. A finding, once laid down, stays laid down: the authors' "Timelines represent change, so they can't themselves change", said of findings instead of timelines. The two accounts have different grounds for the claim that going back cannot change the past. The authors rest the claim on cause and effect, a law the universe keeps. I rest the claim that going back cannot change the past on what a finding is. Every act of comparison makes a finding, so the claim is true wherever anything is found. On the loops the two accounts part. The authors count travel around a loop as a trip to the past without change, while I show that the loop brings the traveler to a

later finding of the traveler's own. The two accounts part again on the authors' reversing machine, which the authors hold is not ruled out by known physics. On my account, the machine would run back the motion inside the machine, and the spill would stay found. Cham and Whiteson's own question, what "later" means, was the right question to ask. "Later" means the order of findings, and every trip, on any loop, runs forward in the order of findings.

> **The short answer**
>
> Travel to an earlier time names nothing, because a finding once made stays made, and any loop in space and time brings a traveler only to later findings of the traveler's own.

Cham and Whiteson give two kinds of answer to the question of going back: changing the past breaks a known law, and a trip around a loop is "not known to be impossible" (*Frequently Asked Questions About the Universe*, ch. 1, "No Do-overs?"). Going back to this morning as it was is a request of a third kind: a request that names nothing. You can now put one test to each question in this book about what we could do: does the request name anything at all? The spilled coffee is the plainest finding you will make today, and the spill's being over is what it means for the spill to have been found.

Relativity also says that a signal faster than light would arrive, for some observer, before the signal was sent. Why can't anything go faster than light?



Chapter Fifteen

Can We Travel Faster Than Light?

In which a moon of Jupiter comes out of the shadow ten minutes late, and the speed of light turns out to be the shape of what can reach what

Can we travel faster than light, and why does light have a top speed at all?

What this chapter uses

A *comparison* is the act of finding whether two things are the same or different in some respect, and every measurement is a comparison; a *finding* is the outcome of one comparison, laid down as a record; a *comparer* is whatever makes a comparison, whether or not the comparer has a mind (Chapter 1).

The *content* of a finding is what the finding finds, as the warmth of your coffee; the *context* is where the content is found, and the context has three sides, the three settings of space, time and possibility (Chapter 1).

Continuous: nothing is sudden, as along a ramp; *discontinuous*: something is sudden, as at the edge of a step; *symmetric*: what is found stays the same across a change of setting, as each step of a staircase is like every other; *asymmetric*: different everywhere, as the height along a ramp is (Chapter 1).

The *Incommensuration Theorem*: at the foundation of any event or comparison, symmetry and continuity cannot both be perfect together, and neither can asymmetry and discontinuity. The Incommensuration Theorem is a structural fact about the nature of knowing (Chapter 1).

Gravity is the *arena*, the stage of space and time on which the three forces act, and so gravity stands beside the three forces and is not a fourth force (Chapter 7).

Every comparison goes one way, from what could be found, to the finding, to its record, and so time goes forward (Chapter 13).

At the beginning of September 1676, in Paris, the astronomer Ole Rømer made a prediction about a moon of Jupiter. Rømer was a member of the Royal Academy of Sciences. Rømer's paper calls the moon of his prediction the first satellite of Jupiter. The first satellite is the innermost of Jupiter's four large moons, which astronomers now call Io. Io passes into Jupiter's shadow and comes out again, over and over. When Io comes out

of the shadow, astronomers call the moment an emersion. An observer on the Earth can time an emersion like the tick of a distant clock. Rømer said that the emersion due on 9 November would come late.

The emersions watched in August set the expected time. Io should have come out of the shadow at 5:25:45 in the evening of 9 November. Observers in Paris saw Io come out at 5:35:45, ten minutes later. Rømer's account appeared in the *Journal des Sçavans* of 7 December 1676. In the English translation, published the next year, the title of Rømer's account reads "A Demonstration concerning the Motion of Light". Rømer's reason for the late emersion was that light takes time to cross the distance from Jupiter to the Earth, and that the distance had grown since August. Rømer reckoned that light needs twenty-two minutes to cross the whole width of the Earth's orbit, and he wrote that light needs less than a second to cover about three thousand leagues. A league is an old measure of distance, about four kilometers.

On the evening of 9 November, the late emersion seen in Paris showed a plain fact with many consequences: light takes time. There were two events: the emersion at Jupiter, and the sighting of the emersion in Paris. An event is a single happening at one place and one moment. Something had to pass from the emersion to the sighting, and the passing took minutes. Once you know that light takes time, you can ask two questions. If we pushed hard enough, could anything go faster than light? Why does light have a top speed at all, and why does light have that speed and no other?

The Authors' Speed Limit

Jorge Cham and Daniel Whiteson open the chapter of *We Have No Idea* on travel faster than light with a one-word answer: no. Then they explain the answer. The authors' verdict is firm: "There is little doubt that this speed limit is real" (*We Have No Idea*, ch. 10, opening). The authors argue with a story about a hamster named Bertha. Bertha holds two flashlights pointing opposite ways, switches both on at once, and finds both beams

moving at the speed of light. An astronaut floats in space and watches the Earth carry Bertha past, and the astronaut finds the same speed for both beams. Larry is a cat on a spaceship going faster still, and Larry finds the same speed again. Two targets stand one on each side of Bertha. Bertha, the astronaut and Larry disagree about which target the light strikes first, and the authors say that all three are right. Then the authors imagine the cat on a ship faster than light. On a ship faster than light, Larry would see a beam strike its target before the beam left the flashlight. An effect would come before its cause. In the authors' use, causality is the rule that effects follow their causes. The authors conclude that nothing goes faster than light, because going faster would break causality.

In their second book, *Frequently Asked Questions About the Universe*, the authors state the limit in one line: "Really, the speed of light should have been called the 'speed of information' or 'the universe's speed limit'" (ch. 6, "Options for Teleportation"). The authors add, in the same section, that the limit holds for gravity too. A change in the Sun's pull takes eight minutes to cross the distance to the Earth. So the Earth feels the Sun where the Sun was eight minutes ago. The authors show in both of their books that a body with mass never reaches the speed of light, because going faster takes ever more energy, and reaching the speed of light would take infinite energy (*Frequently Asked Questions About the Universe*, ch. 6, "Getting There at Light Speed"). The authors also say in their first book that nothing dramatic happens as you approach the limit, and that you simply never get there (*We Have No Idea*, ch. 10, "The Speed Limit of the Universe").

Then the authors turn to deeper questions and leave those questions open: they ask why there is a maximum speed at all, why the maximum speed has the value it has, and whether the limit could change. The authors also ask why the universe respects cause and effect, and they suggest that the question may be beyond the power of science to answer, because science itself assumes causes. On the value of the limit the authors are candid: "Right now we have no idea why the speed limit is what it is" (*We Have No Idea*, ch. 10, "But Why This Speed?"). Cham and Whiteson

also note that a universe with any speed of light between zero and infinity would still work. The authors sum up the chapter with a joke that has a point: "yes, but no, but yes, but no" (*We Have No Idea*, ch. 10, "Summary"). The point of the joke is that a fast particle can outrun light in ice or in water, where light is slowed, but no particle outruns light in empty space.

In this book, each of the authors' results follows from this book's own ground: what every act of knowing must contain. I also answer the questions the authors leave open: why there is a top speed at all, why the universe is causal, why the speed has the number it has, and whether the limit could be different elsewhere. And I give the reason for a fact the authors report as found: every comparer finds the same speed of light.

A Rule Posted on a Box, or the Shape of the Ground

The usual picture of the speed limit is an empty box. In the usual picture, space is a container that is already there, and the things of the world move about inside the container. The speed of light is a rule posted on the box, and the rule limits how fast anything inside the box may go. Once you accept the usual picture, you ask the next question at once. Could a clever enough engineer bend the rule, or find a loophole in the rule?

Now picture someone walking on a globe. The walker's antipode is the point directly opposite her on the far side of the globe. She asks for a point on the surface of the globe that is farther from her than her antipode. On a sphere the antipode is the farthest point there is, so the walker is asking for a point that the surface does not have. To go north of the North Pole is a request of the same kind, because on the Earth north ends at the Pole. The shape of the sphere stops the walker, and a rule plays no part in stopping her. The walker's request is badly formed, because at the antipode the word "beyond" has nothing to apply to.

The speed of light is like the antipode: the speed of light belongs to the shape of the ground, the way the antipode belongs to the shape of the globe, and the ground of the speed of light is comparison itself. The box

with a rule posted on it is the wrong picture. Chapter 1 said that every measurement is a comparison. Chapter 10 said that every way one event affects another is an interaction, and that every interaction is a comparison. A cause is one kind of interaction, the kind in which the link runs steadily one way, from cause to effect. So every cause is a comparison, and whatever limits comparison as such limits every cause.

Comparison has a range, the span within which comparisons can be made, and the range has two edges. Planck's constant marks the inner edge. Planck's constant is the smallest package of action, of happening, that nature deals in. For a given energy, Planck's constant sets a floor under how fine a single comparison can be, and the floor is a limit on comparing, not a smallest piece of space or of time. The speed of light marks the outer edge: in one second, a comparison made here can connect this place with places up to a little under three hundred thousand kilometers away, and no farther. In one year, a comparison made here can connect places up to one light-year away, and no farther. A light-year is the distance light covers in a year. The two edges bound the range of comparison, from its finest detail to its farthest reach. Your question about speed needs only the outer edge.

Chapter 10 showed that space is the pattern of which events can affect which. The pattern is made of causes, and causes are comparisons. So the outer edge of comparison is also the outer edge of space, as space is found from each event. I call the outer edge of the range of comparison the *edge of comparison*: the outer edge of what any comparison can connect. The edge of comparison belongs to what comparison is, so a better instrument does not move the edge, in the same way that better boots do not carry the walker past the antipode.

The Cone of What Can Reach What

Picture a single flash: a firework bursting at one place and one moment in a dark sky. The firework's light spreads out as a sphere that grows by about three hundred thousand kilometers every second. Now picture all

the moments of the sphere of light at once: the small sphere of the first instant, a larger sphere a second later, and a still larger sphere a minute later. Physicists draw all those moments in one drawing. Time runs up the page, and only one or two directions of space run across the page. In the drawing, the growing sphere looks like a cone opening upward from the flash. Run the drawing the other way, back in time from the flash, and every place and moment from which light could have reached the flash makes a second cone, opening downward.

The *light cone* of an event is the set of all the events that can be causally joined to that event. The upper cone contains every event the flash can affect, and the lower cone contains every event that can affect the flash. Every cause is a comparison. So from the flash a comparison can be made with any event inside the flash's cone, and with no event outside the flash's cone. When two events lie outside each other's cones, we call the two events *spacelike separated*. Two spacelike separated events are so far apart in space, and so close in time, that nothing traveling at the speed of light could pass between them, and neither event can make any difference to the other.

Picture a cup of coffee on a table on Mars, and someone on Mars noticing that the cup is still warm. Noticing the warm cup is a finding, the outcome of one comparison, made at one place and one moment. News of the finding on Mars can reach you on Earth, by radio or by any other means, only once light could have made the trip: between about three and twenty-two minutes later, depending on where the two planets stand in their orbits. Until light could have made the trip, the warm cup on Mars is spacelike separated from whatever you are doing at your own table. Comparers moving in different ways disagree about which distant events happen at the same moment, as Chapter 12 showed, so "its now", the moment on Mars that matches your moment here, is no fact for you. At your own table you can say which findings have had time to reach you and which have not. Your lower cone is the cone of everything that can affect you here and now. Your lower cone contains every finding that has had time to reach you.

In the usual account, physicists take the speed limit first and then draw the cone: they apply the limit to every path a signal could take, and the cone is what is left. I take the cone first: at each event, the cone marks which comparisons can be made from that event, and the speed of light sets how wide the cone opens. Causation is the cone at each event, unbroken and pointing one way.

With the cone I can also answer the deepest question in the authors' chapter: why the universe respects cause and effect at all. The answer has two steps, one for why there are causes and one for why causes have the shape they have. The first step uses two things already shown: a cause is an interaction that runs steadily one way, and every interaction is a comparison. A record is what a finding leaves behind for later comparisons to read. So causes are no extra rule laid on the world. A world in which anything affects anything is a world of comparisons, and a world of comparisons already has causes.

The second step uses the Incommensuration Theorem of Chapter 1. Two other pairings remain, continuity with asymmetry and symmetry with discontinuity, and each of the two can be carried all the way, to perfection. Continuity with asymmetry is an unbroken link that runs one way. Continuity with asymmetry is exactly the shape of the cone, which is unbroken (the cone has no gap anywhere in it) and one-way (the cone's future half and its past half are different). In general relativity, the cone at every event is perfectly unbroken and perfectly one-way. So the universe is causal because every interaction in the universe is a comparison, and every comparison runs one way. The universe's causes have the cone's shape because the cone's shape, continuity with asymmetry, is one of the two pairings that can be carried to perfection in any comparison.

The Same Speed for Everyone

Throw a ball forward at twenty kilometers an hour in a train moving at a hundred. For a rider on the train the ball moves at twenty kilometers an hour, and for someone standing beside the track the ball moves at about a

hundred and twenty. The speeds of ordinary things change with the motion of whoever compares them. The speed of light is the exception. Every comparer, however the comparer moves, finds the same speed of light, as Bertha, the astronaut and Larry all did. In 1905 Einstein made the sameness of light's speed a starting point of his special theory of relativity, which is the theory of how lengths and durations compare for comparers moving steadily relative to one another. When every comparer finds a quantity the same, we call the quantity *invariant*.

I read the invariance of light's speed as the invariance of an edge. The speed of a ball is a ratio of two findings made within the range of comparison: distance gone over time taken. A ratio of two findings within the range differs from comparer to comparer, as the ball's speed differs for the rider and for the bystander. The speed of light is the shape of the outer edge of the range of comparison, and an edge of comparison is the same for every comparer, because comparing is what every comparer is doing. I put the sameness of an edge with a picture: one may understand why the speed of light is a constant by comparing it to one's horizon. No walker outruns the horizon, because each walker's horizon is drawn from where the walker stands. The horizon goes wherever the walker goes, and every walker has a horizon. In the picture, the walker is any comparer, and the horizon is the edge of comparison. Light in empty space travels at exactly the speed of the edge, and light is the most perfect example of the edge, but light is not the reason the edge is where it is. The edge of comparison is the reason Einstein's starting point holds, and Einstein's theory remains exactly as it is.

Experimenters found long ago that light's speed is the same for every comparer, and they have found the same result many times since. In 1887, in Cleveland, two scientists, Albert Michelson and Edward Morley, split a beam of light into two beams at right angles. Michelson and Morley sent each beam to a mirror and back. They compared the two round trips while the Earth carried the whole instrument along the Earth's orbit. They turned the instrument to face different ways. They found the two round trips the same in every direction they tried, to within the fineness of their

instrument. The Earth's motion through space added nothing to light's speed one way and took nothing from light's speed the other way. We now know that every comparer finds the same speed of light, whatever the comparer's own motion. An edge of comparison requires the same speed for every comparer.

The edge of comparison applies to gravity as well as to light, as the authors say of the speed limit. Chapter 7 gave the name arena to space and time together, the setting in which every finding of physics is made. A change in the shape of the arena spreads through the arena as a wave at the speed of light. On 17 August 2017, as Chapter 8 told, detectors in the United States and in Italy caught a wave in the shape of the arena, sent out by two neutron stars spiraling into each other. About two seconds later a satellite in orbit caught a burst of gamma rays, light of the highest energies, from the same part of the sky. The wave and the burst of light had set out together from a galaxy about 130 million light-years away. The wave and the light arrived within two seconds of each other. We now know that changes in the shape of the arena travel at the speed of light: the speed of the wave and the speed of light agree to within a few parts in a million billion.

A Message That Would Arrive Before It Was Sent

The authors' argument with Bertha and Larry is my argument too, and I add the reason the argument is right. Go back to the two targets on either side of Bertha. For Bertha the targets are the same distance away, and the light goes at the same speed both ways, so the light reaches both targets at once. For the astronaut the light also goes at the same speed both ways, because light's speed is the same for every comparer. But while the light is on its way, the Earth carries the left target toward the left beam and the right target away from the right beam, so for the astronaut the left target is struck first. For Larry, who sees the Earth move the other way, the right target is struck first.

The cone shows why comparers can disagree about the order of the two strikes. The cone also shows why comparers cannot disagree about the order of two events inside each other's cones. The two strikes are spacelike separated: each strike lies outside the other strike's cone, so no comparison joins the two strikes, and nothing fixes one order for the strikes that every comparer must find. Each comparer puts the two strikes in order by the same light and by the comparer's own motion, and the orders differ. A comparison joins two events that lie inside each other's cones, and because every comparison runs from the act to its record, every comparer finds the two events in the same order.

Suppose that a message leaves the left target at the moment the light arrives at the left target, and reaches the right target at the moment the light arrives at the right target. For Larry, who sees the light reach the right target first, the message would be received before it was sent. Chapter 13 showed that every comparison runs one way: what could be found comes first, then the act of finding, then the record of what was found, and the record follows the act it records. A message received before it was sent would put a record before the act it records. A request for a message faster than light is a request for a comparison beyond the edge of comparison. A comparison beyond the edge of comparison is no comparison. The request for a message faster than light names nothing, in the words Chapter 14 used for travel to an earlier time: the request puts a word where the word's meaning does not reach.

A *signal* is anything that passes from one event to another and lets a record at the second depend on an act at the first: a shout, a letter, a radio pulse. A traveler carries her own records with her, her memories and the reading of her watch, so a traveler is a signal from where she set out to where she arrives. The edge of comparison lets the traveler go anywhere her upper cone reaches, and given time, her upper cone reaches a great deal. A place is a position in the pattern of what can reach what. The events outside the traveler's cone have no position in the pattern that runs from her. So a better engine would bring her no nearer to the events out-

side her cone. There is therefore a two-part answer to the first half of your question, whether we can travel faster than light: no journey within the cone is excluded, and every journey ends inside the cone.

No signal can pass the edge of comparison, and the reason is structural: the reason belongs to the structure of comparison itself. The request to signal past the edge is a request to compare beyond comparison. Once the words of the request are understood, the request has no content. We know from what comparison is, before any experiment is made, that no signal can pass the edge. Every experiment agrees with that conclusion.

A body that approaches the edge behaves just as the authors describe. A body with mass can be pushed ever closer to the speed of light, each step costing more energy than the last, but no push, however great, carries the body to the edge or past the edge. Particles arriving from space do the pushing for us, high in the air. The particles strike the top of the atmosphere and make muons, the heavier cousins of the electron that we met in Chapter 4. The muons fly down at nearly the speed of light and fall apart in about two millionths of a second by their own clocks. In 1941 the physicists Bruno Rossi and David Hall measured how long muons of different speeds last on their way down through the air. Rossi and Hall found that the faster muons decay more slowly, as relativity says a fast clock must run slow. We now know that muons get close to the edge and stay inside the edge. The muons' slowed clocks show how close the muons get.

Muons in ice, the authors' example, stay inside the edge as well. Light in ice moves more slowly than light in empty space, because the ice keeps taking the light up and giving the light out again. A fast muon can outpace the slowed light in the ice and leave a faint blue glow behind it. The muon is still inside its cone, because the edge of comparison sets the cone, and light in empty space marks the edge.

The edge of comparison does not forbid some things that sound faster than light, because none of those things carries anything across the edge. In 2015, in Delft, Bas Hensen, Ronald Hanson and their colleagues meas-

ured pairs of linked electrons in two laboratories 1.3 kilometers apart. The physicists chose each measurement and recorded each result so quickly that light could not have carried word of the choice or of the result from one laboratory to the other in time. The results agreed in exactly the pattern that no instructions carried by the electrons could give them. The agreement showed only when the experimenters brought the two lists of results together, by ordinary means at ordinary speed, and set the lists side by side. We now know that the agreement is real and that nothing passes between the two laboratories: a correlation, an agreement between two lists, is no connection, and no one can send a message with a correlation.

Why This Number?

A light-year is a distance named by a time. A light-second is the distance light travels in one second, a little under three hundred thousand kilometers. The speed of light is a rate of exchange, like the rate of exchange for mass and energy that Chapter 6 used: the speed of light turns an amount of time into an amount of space. I read the speed of light as the rate of exchange of the edge of comparison itself. The speed of light says how far the edge reaches in space for each second of time: a little under three hundred thousand kilometers.

The edge itself comes from comparison, and the number we write for the edge comes from our units. The top speed follows from two steps. First, every act comes before its record, as Chapter 13 showed, so no signal arrives at the instant it is sent: every signal takes some time. Second, comparison has an outer edge, as the globe showed: in any given time, a comparison made here can connect only places so far away. A signal takes some time, and in that time the signal gets at most as far as the edge, so every signal has a greatest speed: the rate at which the edge reaches outward. The two steps are the answer to the authors' question of why there is a maximum speed at all.

The number for the speed of light depends on our rulers and clocks. The meter is now defined as the distance light travels in a set fraction of a second, so the figure of about three hundred million meters each second states the size of our meter against our second. Rømer measured the same edge with the units and instruments of his day: twenty-two minutes for light to cross the width of the Earth's orbit, and three thousand leagues in less than a second. The numbers that carry content are *pure ratios*: numbers with no unit. The value of a pure ratio does not depend on our choice of units. One pure ratio is the mass of the electron measured against the Planck mass, which Chapter 7 pictured as a grain of sand. We find pure ratios by measurement.

The authors also ask whether the limit could be different in another region of the universe or in another age of the universe. The edge itself is a feature of comparison, and the edge applies to any being, in any universe, that interacts with anything else. Wherever anything affects anything, causes have a fastest reach. In our world, light in empty space travels at exactly the fastest speed of any cause. For the ages we can see, the authors report that astronomers have applied today's laws of physics, the speed of light among them, to what the sky shows of the distant past. The astronomers found no hint of any violation of the limit (*We Have No Idea*, ch. 10, "Past and Future").

> **The short answer**
>
> The speed of light is the outer edge of comparison itself, the same for every comparer, with a number that shows only the size of our units, and every journey and every message stays within the edge.

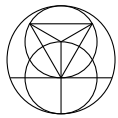
The authors write that few rules in the laws of physics are as hard and unbendable as the speed limit (*Frequently Asked Questions About the Universe*, ch. 18, opening), and the edge of comparison is the reason for the rule. The edge of comparison also shows where each of us stands: every

finding that reaches you comes from within your own lower cone, and every later question in this book about travel and contact depends on that fact.

If light of every energy travels at one speed, the most energetic messengers from space can test whether the speed is the same at the highest energies; who is sending the messengers?

PART FOUR

FROM THE CLOCK TO THE STARS



Chapter Sixteen

Who Is Shooting Superfast Particles at the Earth?

In which the bullets from space turn out to be messengers, and we read what they say about how far they came, what sent them, and the road they crossed

Who is shooting superfast particles at the Earth?

What this chapter uses

A *comparison* is the act of finding whether two things are the same or different in some respect, and every measurement is a comparison; a *finding* is the outcome of one comparison, laid down as a record; a *comparer* is whatever makes a comparison, whether or not the comparer has a mind (Chapter 1).

The *content* of a finding is what the finding finds, as the warmth of your coffee; the *context* is where the content is found, and the context has three sides, the three settings of space, time and possibility (Chapter 1).

The three *settings* in which anything is measured are space, the place of a finding; time, the moment of a finding; and possibility, the range of what could have been found instead; a setting is *bent* when one part of the setting differs from another part (Chapter 1).

A *gyration* is a lasting vibration of the six small dimensions of possibility, and the unit of which the dark matter is made (Chapter 2).

The basic elements of matter are a closed list of kinds of particle: the kinds are few because every comparison has three positions, and each kind of matter comes three times, in three *generations* (Chapter 4).

Gravity is the *arena*, the stage of space and time on which the three forces act, and so gravity stands beside the three forces and is not a fourth force (Chapter 7).

At twelve minutes past six on the morning of 7 August 1912, a hydrogen balloon named *Böhmen* rose from Aussig, a town on the river Elbe. Three men rode in the balloon's basket: Captain W. Hoffory, who flew the balloon; E. Wolf, who kept the weather observations; and Victor Hess, who observed the electricity of the air.

Hess carried three sealed metal vessels, two with thick walls and one with thin walls. Each vessel held an instrument that keeps an electric charge and shows how fast the charge leaks away, and the charge leaks be-

cause something passes through the walls and knocks the air inside into electrically charged pieces. So the faster the charge leaks, the more of the something is passing through. Sealed vessels on the ground leaked too, so the something was present everywhere. Hess set out to find from which way the something came. Hess's test was simple: if the something came up out of the ground, it would thin out as the balloon climbed.

The readings rose instead. Between a quarter to ten and a quarter to eleven, at about four thousand eight hundred meters, the two thick-walled vessels read close to three times what the same two vessels read on the ground after the landing. Over the region of the Schwielochsee the balloon reached five thousand three hundred and fifty meters, and at a quarter past noon the balloon came down at Pieskow, fifty kilometers east of Berlin.

On earlier flights Hess had measured at night, and once during an eclipse of the Sun. Each time he had found the reading as high as at other hours, so the Sun could hardly be the cause. He put his conclusion in one sentence, which in English reads: a "radiation of very high penetrating power enters from above into our atmosphere". The sentence is in his report of seven balloon flights (Hess, *Physikalische Zeitschrift*, 1912). Something was arriving from above, by day and by night. If something arrives from above, who is sending it?

What Hess found is now called cosmic rays. A *cosmic ray* is a particle that arrives at the Earth from space. Later work showed that most of what arrives is protons, the cores of hydrogen atoms, together with the cores of heavier atoms. The word "ray" stayed with cosmic rays from the years when physicists took them for a kind of light. What reached Hess's vessels was mostly a spray of lighter particles, made when the arrivals from space strike the air high above.

From Cham and Whiteson's pages

What Cham and Whiteson Showed

Jorge Cham and Daniel Whiteson begin their chapter on cosmic rays by asking you to imagine waking up to find your house sprayed with bullets. Then they tell you that, if the Earth is your house, your house is being sprayed right now (*We Have No Idea*, ch. 11, opening). They take the mystery out of the name "cosmic ray" at once: "it simply means a particle from space" (*We Have No Idea*, ch. 11, "What Are Cosmic Rays?"). The Sun sends out cosmic rays, and so do other stars and other objects in space. The air above us stops most cosmic rays. The northern and southern lights are the glow of cosmic rays that the Earth's magnetic field steers toward the poles.

Then the authors turn to the fastest cosmic rays. Physicists measure a particle's energy in electron volts, the unit that Chapter 5 gave as the energy one electron gains in crossing one volt. The largest machine on Earth for speeding particles is the Large Hadron Collider near Geneva, and in its run of 2015 to 2018 the collider brought two protons together with about thirteen trillion electron volts in each collision. The authors write that cosmic rays of about that energy strike the top of the atmosphere about once per square meter every second. The fastest particle the authors report carried more than a hundred billion billion electron volts, which they put at almost two million times the energy of the collider's fastest particles. Set against one collision of the collider's second run, at thirteen trillion electron volts, that energy is more than seven million times as great. Physicists nicknamed that particle the "Oh-My-God particle" (*We Have No Idea*, ch. 11, "What Are Cosmic Rays?").

The Fly's Eye is an array of light detectors in the Utah desert that watches the night sky for the faint glow that a falling shower of particles makes in the air. It caught the Oh-My-God particle on 15 October 1991. From the glow, the Fly's Eye team worked out that the particle that started the shower had carried about three hundred billion billion electron volts (Bird and others, *Astrophysical Journal*, 1995).

The Oh-My-God particle was one particle, smaller than an atom. It carried about as much energy as a baseball thrown at sixty miles (about ninety-five kilometers) an hour.

The authors draw two conclusions from the fastest particles. The first conclusion is about what could make particles so fast. In the authors' figure, astrophysicists put the highest energy that anything known could give a particle at about a hundred thousand trillion electron volts. The fastest particles carry more than a thousand times as much. So, the authors write, "there must be a new kind of object in the universe that we don't know about" (*We Have No Idea*, ch. 11, "What Are Cosmic Rays?").

The second conclusion is about where the new objects that make the fastest particles are. The leftover light of the Big Bang fills all of space. The authors picture that light as a fog that slows any fast charged particle crossing it. In their figure, the leftover light slows a particle that starts with a thousand billion billion electron volts to a hundredth of that energy within a few million light-years (*We Have No Idea*, ch. 11, "Where Are They Coming From?"). So the authors conclude that the senders of the fastest particles are near us, in our own region of the cosmos.

Cham and Whiteson then list five suspects for the sender (*We Have No Idea*, ch. 11, "What Could They Be?"). The first suspect is the giant black holes at the centers of galaxies, regions so dense that not even light comes back out. The authors write that decades of watching have caught a handful of the fastest arrivals, and that these arrivals do not seem to line up with the positions of the giant black holes. The second, third and fourth suspects are an accelerator built by alien scientists, a flaw in a computer simulation of our universe, and a new force of nature. The fifth suspect is ordinary astrophysics: some event in the life of a star that nobody has yet seen. The authors close their

chapter by changing the picture of bullets they began with: instead of bullets, "you might think of them as messengers" (*We Have No Idea*, ch. 11, "Cosmic Messengers").

I take Cham and Whiteson at their word. A messenger carries news, and the fastest messengers carry three pieces of news: how far they have come, what their sender is made of, and what they have already delivered to physics. A fourth piece of news comes with a different messenger: light.

A Swing Pushed in Time

Push a child on a swing. Push at the moment the swing comes back toward you, in time with its own swinging, and each push adds to the last, so that the swing rises high. Push at any other moment and the pushes work against each other, and the swing barely moves.

Physicists call the matching of a push to a thing's own motion a resonance. A *resonance* is a reaction that goes far faster because the energy brought in matches a state of the thing produced, as a swing rises high when it is pushed in time with its own swing. The definition is the one given. At the matching energy the reaction goes fast. Away from that energy the reaction is slow.

The proton has a state that a push can match: a state of higher energy, into which a push of the right energy can lift the proton. A proton is three quarks, two up quarks and one down quark, held together by the strong force. Each quark carries a spin, the built-in turning, like a top's, that Chapter 4 gave the electron. A spin points one way or another. In the proton the spins of the three quarks partly cancel. Turn the three spins so that all three point the same way, and the same three quarks make a heavier particle. Physicists call that particle the Delta. The *Delta* is the proton's excited partner: the same light quarks of the first generation, with their three spins aligned. Excited means lifted into a state of higher energy. The Delta is about a third heavier than the proton, because aligning the spins costs

energy. The Delta lasts almost no time at all: it falls apart at once into a proton or a neutron and a pion, the lightest of the particles that the strong force builds from quarks.

The Delta was found as a resonance. In 1951 and 1952, the physicist Enrico Fermi and his group sent pions at protons with the synchrocyclotron of the University of Chicago, a machine that whirls particles outward in a spiral. The group measured how often the pions scattered off the protons. As the group raised the energy of the pions, the rate of scattering rose steeply toward a peak, which was the first resonance found among the particles made of quarks (Anderson, Fermi, Long and Nagle, *Physical Review*, 1952). The peak was the Delta. At the matching energy, pion and proton join for an instant into one particle and then come apart.

Now return to the leftover light of the Big Bang, which Cham and Whiteson picture as a fog. The leftover light is cold and feeble, so a proton at rest could sit in it forever and never be lifted into a Delta. A fast proton runs into the light head on. Run through a light drizzle and the drops strike your face harder the faster you run, and in the same way, the faster a proton moves, the harder the leftover light strikes it. At energies like the energy of the Oh-My-God particle, the feeble light strikes the proton with the energy needed to lift it into a Delta. That strike is the push in time with the swing. The energy of the strike matches the state of the Delta.

The proton is lifted into a Delta, and the Delta falls apart at once into a proton or a neutron and a pion. The pion carries off part of the energy, and the particle that remains travels on with less. That particle strikes the next particle of leftover light, is lifted into a Delta again and loses energy again, and the losses go on until the particle has been slowed below the energy at which the leftover light can lift it into a Delta. One sentence: the Delta "is excited when high-energy cosmic-ray protons strike the photons left over from the Big Bang, which limits how far the most energetic cosmic rays can travel".

Cham and Whiteson and I tell one result, from two sides. The authors tell the result from the side of the fog: what the leftover light does to a fast charged particle on its way. I name the state that the leftover light lifts the proton into, and I place that state among the kinds of particle. The Delta is one of the wholes, the things bound together out of smaller parts, that the kinds of particle and their forces make: a whole built of three light quarks of the first generation. The Delta "adds no new kind" to the closed list of Chapter 4. The Delta's mass is measured. I report that the limit on distance that follows from that mass is established physics. The limit was worked out in 1966 by Kenneth Greisen, and separately by Georgiy Zatsepin and Vadim Kuzmin. The discovery of the leftover light had been published the year before. The authors' notes give the limit the names of Greisen, Zatsepin and Kuzmin. So the fastest particles reaching us now were fired from near enough that the leftover light has not yet worn them down.

What Any Sender Is Made Of

Suppose bullets strike your house, and you cannot yet see who fires them. You still know some things about the gun. The gun is made of metal, and it fires by the burning of powder, because every gun does. You know that much before you find the gun, because you know what guns are made of.

In the same way, I can tell you what the sender of the cosmic rays is made of before anyone finds the sender, because the kinds of particle form a closed list, the list of Chapter 4, to which no kind can be added. No new kind of elementary particle exists, at any energy. Chapter 7 identified gravity with the arena itself: space and time together, two of the three settings of every finding, in which the forces act. Within the arena the forces are three, and there is no fourth force with a carrier in the sequence of the three. So whatever fires the fastest cosmic rays is built of the known kinds of particle and acts through the three forces, within the arena.

Now read the list of suspects with the closed list in hand. Three of the suspects are each built of the known kinds of particle: the giant black holes, an accelerator built by alien scientists, and an unseen event in the life of a star. Each of these three suspects acts through the three forces within the arena, so I keep all three on the list. I take a new force of nature off the list, because the forces are three and there is no fourth. I also take off the flaw in a computer simulation, because our world is a world of its own, not a simulation run in some other world. The reason, in one line: the arena of space and time has no least step, while everything a computation could produce can be set out in a list, and no list reaches a whole with no gaps. In Chapter 27 I reach the same conclusion: the world is no computer program.

The authors' central sentence is that "there must be a new kind of object in the universe that we don't know about". In their chapter, the new kinds of object are their five suspects. I agree with that sentence for the three suspects I keep, each a new kind of object built of the known kinds of particle. I leave the naming of the sender to astronomers and their telescopes. The candidates include every object built of the known kinds of particle, among them kinds of object that no telescope has yet seen. I add what every candidate is made of. Whoever is shooting, the gun is made from the same list of pieces as you are.

The fastest cosmic rays raise a further question: could collisions this strong turn ordinary matter into the dark matter of Chapter 2? The sky has been running collisions stronger than any machine of ours for billions of years. No, for a collider, a star or anywhere else in our era of the world, and one of its reasons is energy. A gyration is one unit of the dark matter: a lasting vibration of the six small dimensions of possibility (the six further dimensions of the world, beyond the three of space and the one of time). One gyration holds the energy of the mass of about ten billion billion protons. The most energetic particles that reach the Earth from space each carry less than a ten-millionth of the energy one gyration holds. The

Oh-My-God particle made physicists exclaim, yet it falls short of the energy of one gyration by more than ten million times. So the sky's collisions and ours both fall far short of the energy that one gyration holds.

What the Messengers Have Already Brought

Before there were machines to speed particles, the sky did the work of such a machine, because the cosmic rays arrived already fast. Physicists carried photographic plates up mountains and into balloons. They carried vessels of damp gas too, in which a fast charged particle leaves a line of tiny droplets behind it. Then they waited for the sky to send something new. The sky delivered three new particles in fifteen years.

In August 1932, Carl Anderson at the California Institute of Technology photographed a cosmic-ray track that curved like an electron's track, but the wrong way. The track was made by a particle with the electron's mass and a positive charge. Anderson named the particle the positron. In Chapter 19 I find that the positron is the electron's mirror, the electron with every label reversed, and that such mirrors exist because comparing makes a state and its mirror together.

In 1936 and 1937, two pairs of physicists found a new charged cosmic-ray particle: Anderson and Seth Neddermeyer at the California Institute of Technology, and Jabez Street and Edward Stevenson at Harvard. The particle weighed more than the electron and less than the proton. It is the muon: the heavier copy of the electron that Chapter 4 counted, the same as the electron in charge, in spin and in every way it acts, and about two hundred times heavier. The muon's charge, spin and mass in its entry for the muon. Nobody had a reason for the muon. The physicist Isidor Rabi asked: "Who ordered that?" The muon is the electron in its second generation, one of the three instances of every kind of matter that Chapter 4 counted. That book calls the muon the electron "one turn on". Muons pass through you now: they are made high in the air when cosmic rays strike the cores of atoms, and about one muon passes through each square centimeter every minute.

In 1947, George Rochester and Clifford Butler at Manchester photographed two cosmic-ray events that left V-shaped tracks (Rochester and Butler, *Nature*, 1947). The tracks were made by the first particles found to carry the quark later called strange. The strange quark is the second-generation partner of the down quark inside the proton.

Our world met the particles in the order its machines could reach them. The cosmic rays were one of those machines, and for these three particles the sky's machine came first: the cosmic rays delivered each of the three before any machine on the ground produced it. I also say: "The muon arrived before anyone had a reason for it because cosmic rays delivered it early". The closed list holds every kind of particle the cosmic rays delivered. The positron, the muon and the strange quark each came from the sky first and from the laboratory later, and each is one of the kinds of particle that follow from the structure of comparison, which is what every comparison must contain.

Light That Arrives Together

Chapter 15 ended on a question that the most energetic messengers can answer: does light of every energy travel at the one speed of light? We can answer the question only with a messenger whose departure we can time, and that messenger is light. The cosmic-ray particles carry electric charge, so the magnetic fields between the galaxies bend their paths, and the leftover light slows them as well. No record shows when any one of the cosmic-ray particles set out. So the test is made with light, and the cosmic-ray particles take no part in it.

The light comes from gamma-ray bursts, the brief, enormous flashes of the most energetic light that we met in Chapter 10. A gamma-ray burst is sent out by a violent explosion in a distant galaxy. The burst lasts from a fraction of a second to a few minutes. A burst sends out light of very different energies at nearly the same moment. That light then travels for a very long time across the space between the galaxies.

Picture a race of runners of every size, released at one shot of a starting gun onto a road so long that light takes billions of years to cross it. On a smooth road every runner keeps the same pace, and all the runners cross the line together, but on a road of gravel, with stones of a least size, small feet and large feet would strike the stones differently. Over so long a road, the runners would then arrive spread out, sorted by size. In the picture, the runners are the light of each energy, the shot of the starting gun is the burst, and the road is space.

Space with a grain would be the gravel road. Chapter 8 described a grain of space and time as a least step of length or of duration, like the smallest dot of a printed photograph. The simplest pictures of a grain place the grain at about the Planck length, the length at which a body's gravitational size and its quantum size meet, and the Planck length is about a hundred billion billion times smaller than a proton. In those simplest pictures, light of higher energy travels at a slightly different speed from light of lower energy. Over a road billions of light-years long, a slight difference in speed grows into a delay that a telescope can measure.

Astronomers have timed the light. In 2013, Vlasios Vasileiou and colleagues used the Fermi Gamma-ray Space Telescope, named for the same Enrico Fermi whose group found the Delta, to time the light of several bursts, and they found no delay. Vasileiou and colleagues placed the energy at which any sorting of light by its energy could begin above seven times the *Planck energy*, the energy held in the Planck mass of Chapter 7. The Planck mass is the mass of a speck of sand about a quarter of a millimeter across. In 2024, as Chapter 10 told, the team of the Large High Altitude Air Shower Observatory in China reported its timing of the exceptionally bright burst of 9 October 2022. The team placed the energy at which any sorting of light by its energy could begin above ten times the Planck energy (Cao and others, *Physical Review Letters*, 2024). A higher energy belongs to a finer length, so the timings of 2013 and 2024 place any

grain of space that would slow light below the Planck scale. Those simplest pictures of a grainy space and time are therefore excluded. The runners of every size crossed the line together.

The arena has no grain of any kind. The arena is space and time together, two of the three settings of every finding, and the arena is continuous: a small move in it brings only a small change in what is found, with no sudden step. I give the reason: "a step in the arena would give it the character of content". A grain is a piece. Pieces are content, what a finding finds. The arena is two of the three settings of the context in which pieces are found, and that context has no pieces of its own. So the arena has no least length, no least area and no least duration. Chapter 10 described space the same way: without a smallest step. So light of every energy crossed the arena from the bursts together, as runners of every size cross a smooth road together.

The particles and the light carry two kinds of news. The particles carry news of their sender: the sender is near, and the sender is built of the known kinds of particle. The light carries news of the road, which is space: any grain that would sort light by its energy lies below the Planck scale.

> **The short answer**
>
> Whoever is shooting is in our own region of the cosmos and is built of the known kinds of particle; the arena has no least step, and the timing of light from distant bursts places any grain that would slow light below the Planck scale.

The authors find it alarming that "we have no idea what (or who) is shooting them at us" (*We Have No Idea*, ch. 11, opening). From inside the world, by catching what arrives, we already know that the shooter is in our own region of the cosmos and is made of the same pieces as we are.

The cosmic rays crossed the space between the stars at nearly the speed of light, and they are made of the same pieces as we are; what stops anyone, us or beings of another world, from making that trip?



Chapter Seventeen

What's Stopping Anyone from Traveling Between the Stars?

In which the stars turn out to be years apart, every road runs within our one world, and the sky stays quiet for some other reason

What's stopping anyone, us or them, from traveling between the stars?

What this chapter uses

A *comparison* is the act of finding whether two things are the same or different in some respect, and every measurement is a comparison; a *finding* is the outcome of one comparison, laid down as a record; a *comparer* is whatever makes a comparison, whether or not the comparer has a mind (Chapter 1).

The three *settings* in which anything is measured are space, the place of a finding; time, the moment of a finding; and possibility, the range of what could have been found instead; a setting is *bent* when one part of the setting differs from another part (Chapter 1).

Three things in nature do the bending: gravitation bends space, the cosmological constant bends time, and the dark matter bends possibility (Chapter 1).

Gravity is the *arena*, the stage of space and time on which the three forces act, and so gravity stands beside the three forces and is not a fourth force (Chapter 7).

The world has ten dimensions, one of time, three of space and six of possibility, and the six are the range of what a finding could be, present at every place and never a place themselves (Chapter 11).

The speed of light is the *edge of comparison*, the outer edge of what any comparison can connect, the same for every comparer (Chapter 15).

In the summer of 1950, four physicists walked together to lunch at Fuller Lodge in Los Alamos, New Mexico. The four physicists were Enrico Fermi, Edward Teller, Emil Konopinski and Herbert York. On the walk, Konopinski brought up a cartoon he had recently seen in the magazine *The New Yorker*. The cartoon explained why public trash cans were disappearing from the streets of New York: the cartoon showed a flying saucer in the background, and little green men streaming toward the saucer with the cans. Fermi said the cartoon's theory had the merit of explaining two things at once, the reports of flying saucers and the missing trash cans.

The talk then turned to whether flying saucers could somehow go faster than light, as Konopinski later recalled. Fermi asked Teller how probable it was that within the next ten years there would be clear evidence of a material object moving faster than light. Teller put the chance at one in a million. Fermi answered that one in a million was much too low, and that the probability was more like ten percent.

Later, at the lunch table, Fermi asked a question that seemed to come from nowhere. Teller remembered Fermi's words as "Where is everybody?" York remembered the words as "Don't you ever wonder where everybody is?" Everyone at the table laughed, because everyone knew at once that Fermi meant beings from other worlds. York recalled that Fermi then worked through a chain of estimates aloud: how many planets like the Earth there are, how many of those planets carry life, and how many carry beings with high technology. Fermi concluded that the Earth ought to have had visitors long ago, and many times.

Thirty-five years later, Eric Jones, a scientist at Los Alamos, wrote to Teller, Konopinski and York, the three of the four who were still living. Jones collected the three men's memories of the walk and the lunch into a report from Los Alamos. The three men's recollections differ in small ways, as memories do. Together, the recollections record two questions asked on one day: could anything travel faster than light, and where is everybody? One edge of the world bears on both questions: the speed of light. The speed of light is the same for us and for anyone out there.

What Cham and Whiteson Found

In *Frequently Asked Questions About the Universe*, Jorge Cham and Daniel Whiteson ask Fermi's questions in two directions, from us outward and from others toward us: what keeps us from going to the stars, and why no one has come to the Earth.

For our own travel to the stars, the authors answer that the distances between the stars are no obstacle in themselves. Space is mostly empty, and nothing drags on a ship. The obstacle is the time a ship needs to cross

the distances. Proxima Centauri, the nearest star, is about forty trillion kilometers away. The authors take a spacecraft of today as moving at about forty thousand kilometers an hour, at which speed the trip to Proxima Centauri would take more than a hundred thousand years. Even the fastest speed any spacecraft has reached, about 635,000 kilometers an hour (the Parker Solar Probe, close to the Sun, in 2023), would make the trip take more than seven thousand years. A faster ship needs energy, and a lot of it. A colony ship of a few million kilograms needs about a hundred times the energy that all of humanity uses in a year to reach half the speed of light, by the authors' estimate. The authors go through the engines that could supply so much energy: nuclear bombs set off behind the ship, ion drives, antimatter, a small black hole, and sails pushed by sunlight or by lasers. Chapter 2 described a black hole: a region from which nothing that falls in comes back out. The authors find every engine on their list "technically feasible" from a physics perspective. So the authors conclude that "the physics is not the problem" (*Frequently Asked Questions About the Universe*, ch. 8, "So What Are We Waiting For?").

The authors also look at shortcuts: ways to reach a star sooner than light could reach the star by crossing the space in between. The two shortcuts the authors weigh are squeezing space and tunneling through space. In *We Have No Idea*, the authors change the question from "Can I travel faster than light?" to whether we can reach distant stars in a reasonable time. The authors' answer to the changed question is "Maybe, but it's very expensive" (*We Have No Idea*, ch. 10, "But Maybe We Can Visit Other Stars"). The authors explain the loophole in the speed limit of light with a moving walkway, in *Frequently Asked Questions About the Universe*. Physics is strict about how fast you walk along the walkway, and physics sets no limit on how fast the walkway itself moves. In the picture, the walker is a ship and the walkway is space itself. The authors report that a ship that squeezes the space ahead of it must also stretch the space behind it. Physicists have proposed negative mass to do the stretching. No one has ever seen negative mass.

For visitors coming to the Earth, the authors work out how long a visit would take. Our radio broadcasts have been leaving the Earth for about a century. Suppose a civilization about thirty-three light-years away heard our broadcasts and sent a ship at half the speed of light. The ship would be arriving about now: thirty-three years for our broadcasts to reach the civilization, and sixty-six years for the ship to come back. No one has come, and the authors take the most likely explanation to be that no intelligent civilization lives within about thirty-three light-years of us. A civilization could visit every likely planet in the galaxy in well under a million years, with a billion ships or with probes that build copies of themselves from the rubble around other stars. No one has recorded a visit to the Earth by a fleet of ships or by self-copying probes either. The authors close with two cases that physics cannot settle: visitors who came before anyone could write the visit down, and visitors who chose to stay hidden. In the authors' words, "The physics of galactic exploration can't rule out sneaky, or shy, alien visitors" (*Frequently Asked Questions About the Universe*, ch. 2, "Scenario #4: Or Have They?"). In *We Have No Idea*, the authors list further reasons the sky could be quiet: life could be rare, civilizations could live at other times, other civilizations could signal in ways we do not recognize, or other civilizations could prefer not to talk.

Every one of the authors' estimates depends on one rule, which the authors treat as settled: nothing moves through space faster than light.

A Journey Inside the Reach of Light

Chapter 15 showed what the speed of light is: the outer edge of comparison. The outer edge of comparison is the edge of what any one act of comparing can connect, and the edge is the same for every comparer, every person or thing that compares. "The edge", for short, means the outer edge of comparison. Chapter 15 drew the edge as the surface of a light cone. The light cone of an event holds all the events that can be causally joined to that event, and the upper cone of an event holds every event

that the given event can affect. Everything in the upper cone of an event lies *within the reach of light* from that event: light sent out from the event, or anything slower than light, can get to each event in the upper cone.

Now picture a ship leaving the Earth for Proxima Centauri. At every moment of the trip, the ship is somewhere inside the upper cone of the ship's own departure. The ship's arrival, years later, is an event that the departure affects, because the ship itself carries the effect from the departure to the arrival. So the whole trip lies within the reach of light from the launch, all the way to the landing.

Travel within the upper cone of a body's departure, however slow relative to popular aspiration, remains structurally permitted. In plain words, the structure of comparison, what every comparison must contain, sets no limit on travel within the upper cone. A body can go anywhere in the upper cone of the body's departure, and, given time, that upper cone contains a great deal. A body cannot arrive somewhere outside the upper cone of its departure. I call the limit on arrival "a description of where 'somewhere' is". Chapter 15 showed the reason for that limit on arrival: a place is a position in the pattern of what can reach what. So a body can travel only to places in the upper cone of its departure, and an event outside that upper cone has no position in the pattern of what the body can reach.

On travel within the reach of light, I agree with the authors, on separate ground. Cham and Whiteson reach their conclusion, that "the physics is not the problem", by surveying engines one at a time and finding that no law of physics they know rules out any of the engines. On my account, the same conclusion follows from the structure of comparison. The structure of comparison sets one limit: no signal goes past the edge. On a journey within the reach of light, nothing goes past the edge. So the structure of comparison sets no limit on any engine or any trip within the reach of light, whatever engines are invented later. Three questions are left to engineering: how large a ship can be built, how much fuel the ship can carry, and what the ship will cost. The authors weigh the three engineering questions in detail in their chapter.

The Stars Are Years Apart

Astronomers name the distances between stars by a time. Chapter 2 defined a light-year as the distance light travels in a year: a little under ten trillion kilometers. Proxima Centauri is a little over four light-years away.

Chapter 15 gave a picture for naming a distance by a time. The speed of light turns an amount of time into an amount of space, the way a rate of exchange turns an amount of one currency into an amount of another. As a time, the distance to Proxima Centauri is a little over four years of light's travel. A signal or a ship from the Earth reaches Proxima Centauri no sooner than light does, a little over four years after leaving, as the Earth's own clocks count time.

We give the speed of light as about three hundred thousand kilometers each second, and that number belongs to our units. The reason exactly. In light-seconds per second, the speed of light is one. In meters per second, the number for the speed of light records the size of the meter against the second. So the years light takes to reach a star measure the star's distance. The count of kilometers gives the star's distance in the units of our rulers.

The authors tell of one consolation for the traveler. Near the speed of light, the traveler's own clock runs slow beside the clocks left at home. At 99.999999 percent of the speed of light, a ship would cross the whole galaxy in about thirty years by the clock on board, while the clocks on the Earth count more than a hundred thousand years, by the authors' figures.

Some travelers make a trip near the speed of light, with a slow clock, every second. We met cosmic rays, the fast particles from space, in Chapter 16. When cosmic rays strike the top of the atmosphere, the cosmic rays make showers of muons. The muons are made typically ten kilometers or more above the ground. A muon at rest lives only about two millionths of a second before the muon decays. A muon moves at nearly the speed of light, and if the muon's clock ran at the rate of our clocks, the muon would cover less than a kilometer in two millionths of a second. Yet muons reach the ground in great numbers: about one muon passes

through each square centimeter of the Earth's surface every minute. The reason in its entry "Muon": because muons move at nearly the speed of light, "their clocks run slow as seen from the Earth".

Chapter 15 told how two physicists, Bruno Rossi and David Hall, measured the muons' slow clocks in 1941. Rossi and Hall counted muons in Colorado, at Denver and at Echo Lake, about sixteen hundred meters higher in the mountains to the west. Rossi and Hall found that fast muons last longer than slow muons, by the amount relativity predicts for clocks in motion. We now know that a traveler near the speed of light ages less on the way than the people who stay at home, and that muons show the slowing of moving clocks every minute, on every square centimeter of the ground. The muon's shortened trip is still a trip within the reach of light. The muon's slow clock shortens the trip for the muon. The muon's arrival stays inside the upper cone of the muon's birth.

The probe Voyager 1, our own farthest traveler, shows the scale of the distances between stars. Voyager 1 was launched in 1977, and in 2012, as the authors note, the probe crossed out of the bubble of the Sun's wind (the stream of charged particles flowing out from the Sun) into the space between the stars. The physicist Donald Gurnett and his colleagues measured the thin gas around the probe, and Gurnett's team found the gas many times denser than the gas of the Sun's wind, as the gas between the stars is. The team dated the crossing to August 2012, when the probe was about a hundred and twenty times as far from the Sun as the Earth is, a distance light covers in less than a day. After thirty-five years of flight, Voyager 1 had gone less than one light-day toward stars that are more than four light-years away.

New Roads and Faster Cars

The point of the authors' moving walkway is true in my account too. Space can change its own size faster than light, with nothing traveling faster than light through space. I describe a case that astronomers already see in the sky. Take the distance to a very distant galaxy as the distance is

today, and ask how fast that distance grows: for the most distant galaxies, the distance grows by more than a light-year each year. The moving away of distant galaxies is a growth of the arena between them, and not a signal across it. Chapter 7 defined the arena as space and time together, two of the three settings of every finding (the third setting is possibility). The outer edge of comparison limits signals, and the growth of the arena is no signal: the growth carries no message and joins no two events. In 2004 the astronomers Tamara Davis and Charles Lineweaver set out how fast the distances to galaxies grow.

I agree with the authors that nothing moves through space faster than light, even through a shortcut. My account has a further result, on its own ground: whatever travels through a shortcut, if anyone could build one, arrives at a place in our own world. To see the ground, go back to the country of Chapter 14, where the only way to travel is by road. In that country, a woman drove back to the town of her birth. The woman arrived at a place: the town as it was on the day she arrived. What makes a town a place. For a traveler in the road country, a town is a place because roads join the town to other towns. For that traveler, a town is a place only if a road reaches the town, however good the traveler's car might be. We asked what space is in Chapter 10 of this book, and we found that space is the pattern of which events can affect which. So if a path from the Earth can reach a place, that place is, by that fact, part of our own pattern of which events can affect which: part of our one world.

Now we can place the authors' shortcuts in the road country. A wormhole is the tunnel through space and time that we met in Chapter 14. A wormhole would join two far places by a short passage, and Einstein's equations of gravity allow a shape of that kind. A *warp drive* is a ship that would shrink the space ahead of it and stretch the space behind it. A wormhole held open by negative energy would be a new road, and a warp drive a faster car. In the quoted sentence, *negative energy* means less energy than empty space has. Wherever a new road or a faster car arrives, the road or the car arrives at a town on our own roads. In the picture, a town on our own roads is a place in our own world.

I show in terms of the light cone that a trip through a wormhole also ends in our own world. In a bent space and time, the light cones follow the bend, and a wormhole is part of the bend. So a ship that went through a wormhole would arrive inside the upper cone of its departure, where the upper cone follows the bend of space and time.

Physicists have studied with care what a wormhole road would need. Michael Morris and Kip Thorne were physicists at the California Institute of Technology. In May 1988 Morris and Thorne published a paper on wormholes and on using wormholes for travel between the stars, and in that paper Morris and Thorne found a family of wormholes through which a traveler could, in principle, pass. The *throat* of a wormhole is the narrowest part of the tunnel. Each wormhole in the family needs its throat held open by a special material, and Morris and Thorne worked out the properties of that material. No one has ever found such a material. The authors say that no one has seen wormholes either: "Nobody has ever seen evidence that they actually exist" (*Frequently Asked Questions About the Universe*, ch. 18, "Wormhole Warp Drives").

Two more of the authors' ideas for shortcuts have answers in earlier chapters: hyperspace, and an exit through a black hole. The first idea is hyperspace, a second space beside ours that a ship could slip into. The authors themselves find that extra dimensions are only more ways for a particle to wiggle, "like adding another line to your mailing address" (*Frequently Asked Questions About the Universe*, ch. 18, "A Hyperspace (or Subspace, or Superspace) Warp Drive"). In Chapter 11 we met six small extra dimensions, and we reached the authors' result on separate ground: the six small dimensions hold the range of what a finding could be, and no one travels through the six small dimensions.

The authors' second idea is an exit at the far end of a black hole. The authors describe a passage through the ring at the center of a spinning black hole, out into a *white hole*. A white hole is a region that would throw out what a black hole takes in. On the exit through a black hole, I differ from the authors. I report a result of another. Matter falls in while a real black hole forms, and the falling matter breaks up the passage inside a

spinning hole. I expect the inside of a real spinning hole to end as the inside of every black hole ends. A traveler who falls into a black hole crosses the hole's horizon, its surface of no return, one way only. Inside, the traveler reaches the end of the fall, where everything that fell in stops being matter of the kind our world is now made of. The end of the fall is not a region of space at the far end of the hole, so no white hole lies at the far end for a ship to come out into. In Chapter 21 we follow a traveler across the horizon to the end of the fall.

Every shortcut the authors list is a road within our world, if anyone could build the shortcut. Every place you could ever travel to, by any engine, is a part of our own world.

The Silent Sky

Now turn the question around, as Fermi did at lunch, and ask why no one has come to the Earth. The galaxy is very large and very old. Yet we have heard from no one else in the galaxy. The puzzle of the silent galaxy is called the *Fermi paradox*, after the question Fermi asked at Fuller Lodge.

One proposed answer to the Fermi paradox uses the speed of light: other civilizations talk to one another faster than light, and we hear nothing because we listen for the wrong kind of signal. The reply uses the edge: every signal stays within the outer edge of comparison. So no civilization communicates faster than light, because no civilization can. I also state that no civilization communicates faster than light. The edge is structural, part of what every comparison must contain, and so the edge is the same for any being in any universe that interacts with anything at all, because interacting is comparing, and comparing has the edge. Suppose a civilization understands physics better than we do. The civilization has then understood, among other things, what kind of thing the edge is, and the civilization has found no way past the edge, because there is no "past" to find.

The edge settles one part of the authors' reckoning. The authors' estimates for visitors assume a message that travels at the speed of light and a ship that travels slower. The times the authors give for messages remain exactly as the authors give them, since no signal anywhere outruns the edge. In a conversation across the galaxy, the messages travel no faster than light either, so the authors find that any conversation across the galaxy could take generations (*We Have No Idea*, ch. 17, "Could We Learn Physics from Them?"). The message carrying each question and each answer crosses the distance between the speakers at the rate of exchange, a year for every light-year.

Radio astronomers have listened for messages from other civilizations since 1960. The authors tell of one strange signal, caught by a radio telescope in Ohio in 1977. The signal lasted seventy-two seconds, someone circled the signal on the printout with the word "WOW!", and no one has heard the signal again (*We Have No Idea*, ch. 17, "So Where Are They?"). We now know that no one has found a message from another civilization in more than six decades of listening.

The silent sky has some explanation other than signals faster than light, since no signal travels faster than light. The authors list many candidate explanations: life rare, intelligence rare, civilizations living at other times, signals we do not recognize, neighbors who choose silence or caution. One explanation is ruled out: the signal faster than light. Every other candidate stays on the authors' list, and each is a question about who is out there and how the beings out there live. I add one fact to every candidate: the same edge holds for whoever is out there as for us, and the stars are the same years of light's travel apart for them as for us.

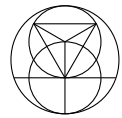
Fermi had given his estimate a decade to come true: a ten percent chance of clear evidence, within ten years, of a material object moving faster than light. In all the years since the lunch at Fuller Lodge, no one has found any body or signal that left one event and arrived outside the light cone of that event. One edge holds every ship and every message, ours and anyone's, within the reach of light.

The short answer

What stands between anyone and the stars is the years that the distances take and the energy that the engines need. The reason is that the structure of comparison limits every traveler and every signal to the reach of light, and the structure of comparison sets no limit on any trip within the reach of light.

The authors' hopes for travel agree with the outer edge of comparison, which Chapter 15 showed. The obstacles to travel between the stars are time and energy, which are the obstacles that the authors weigh. The outer edge of comparison also leaves the silent sky as a question about who is out there, and not about how the beings out there would reach the Earth.

Is anyone out there to make the trip at all?



Chapter Eighteen

Are We Alone?

In which the materials of life turn out to be the same in every star, and how much of each a place holds turns out to be its history

Are we alone in the universe?

> What this chapter uses
>
> A *comparison* is the act of finding whether two things are the same or different in some respect, and every measurement is a comparison; a *finding* is the outcome of one comparison, laid down as a record; a *comparer* is whatever makes a comparison, whether or not the comparer has a mind (Chapter 1).
>
> The basic elements of matter are a closed list of kinds of particle: the kinds are few because every comparison has three positions, and each kind of matter comes three times, in three *generations* (Chapter 4).

On 8 April 1960 the radio astronomer Frank Drake set his alarm clock for three in the morning. The day was the first day of Project Ozma, and the place was the National Radio Astronomy Observatory at Green Bank, in West Virginia. In Project Ozma, Drake meant to listen to two nearby stars for a radio message from someone living near one of them. Drake's instrument was the observatory's Howard Tatel telescope, a radio dish

eighty-five feet across, and he had decided that the telescope's receiver would work at one wavelength: twenty-one centimeters, the radio wavelength that hydrogen gives off.

The team pointed the telescope first at Tau Ceti, a nearby star much like the Sun. Drake and the telescope operators spent the morning watching the pen of a chart recorder wiggle across its paper as the pen drew a line for the strength of the incoming radio signal. Each time the pen rose, the team hoped. Each time the pen fell back, and the line it had drawn was the ordinary hiss of noise. At noon Tau Ceti set in the west. The team turned the telescope to their second star, Epsilon Eridani, also much like the Sun. A few minutes went by. Then the pen of the chart recorder began banging off its scale. Bursts of noise came out of the loudspeaker eight times a second.

Day after day, whenever the telescope turned back to Epsilon Eridani, the team tuned to the frequency of the burst and listened. A week went by, and the burst did not return. About ten days after the first day of the search the burst came again, and this time the burst came just as strongly into a small horn antenna that the team had poked out of the control room window. The great dish collects faint signals from the one patch of sky it points at, while the small horn, pointed out of a window, picks up only strong signals from all around it. The burst came in as strongly through the horn as through the dish, so the burst came from somewhere near Green Bank: the burst was radio interference made by people on the Earth. The team took a break after a month of searching, and after a second month had covered every frequency it judged plausible near the hydrogen line (hydrogen's twenty-one-centimeter wavelength), for both stars. The team heard no one.

Drake's plan to listen at one wavelength depended on a fact about hydrogen. A hydrogen atom gives off a twenty-one-centimeter wave when the spins of its electron and its proton, which act as two tiny magnets, turn from pointing the same way to pointing opposite ways. The turn of the spins is a step in energy, and the size of the step is fixed by what a hydrogen atom is made of and how the atom is held together. The size of the

step sets the wavelength. So the wavelength is the same for hydrogen near Tau Ceti, in the gas between the stars, and at Green Bank. Astronomers read small shifts in the hydrogen line as the motion of the gas that gives the line off. In 1958 the astronomers Jan Oort, Frank Kerr and Gart Westerhout drew the first map of our galaxy's spiral arms. They drew the map from the shifts of the hydrogen line. Oort, Kerr and Westerhout could draw their map because the hydrogen line is the same in every cloud of hydrogen, so a shift in the line measures the motion of the cloud. Drake's search was looking for a fact about Tau Ceti: whether anyone near Tau Ceti was sending, and on what wavelength. The hydrogen line, by contrast, is a fact about hydrogen, the same everywhere. So the morning at Green Bank is a small case of the question we are asking. Which features of our place are the same everywhere, and which are local?

The Traveler's Problem

The cartoonist Jorge Cham and the physicist Daniel Whiteson open their chapter on life, in *We Have No Idea*, with a trip abroad. A traveler finds that some habits of home are shared by people everywhere, because those habits come from deep needs such as eating and sleeping, while other habits turn out to be local choices that could easily have been different. Cham and Whiteson say that seeing another place is the best way to learn which of the things you took for universal are local. They go on to say that we see the universe from one place only, and so we, too, have trouble telling which features of our experience are universal and which are local. They write that perhaps the most important question of this sort, universal or local, is the question about life itself: "is life in the universe common or rare?" (*We Have No Idea*, ch. 17, opening).

Cham and Whiteson break the question into factors, in a form known as the *Drake equation*. The equation is named after the same Frank Drake who listened at Green Bank, and it has seven factors. The first factor is the number of stars in our galaxy. The second factor is the average number of planets each star has. The third factor is the share of planets that could

support life. The fourth is the share of livable planets that develop life. The fifth is the share of planets with life that develop intelligent life. The sixth is the share of intelligent species that build a technology able to send messages into space. The seventh is the chance that a species able to send messages into space is around at the same time as we are. When the seven factors are multiplied together, the result is the number of species we could talk to. The authors point out that if any one factor is zero, we will never hear from anyone, even if someone is out there.

Then Cham and Whiteson fill in the factors that have been measured. According to their report, astronomers have found that about one in five stars in our galaxy has a rocky planet of about the Earth's size, receiving about as much light from its star as the Earth does. The next factor is the share of Earth-like planets on which life begins. The authors answer that factor with their own refrain: "we simply have no idea if a setup like ours gives life every time or only once in a million or quadrillion times" (*We Have No Idea*, ch. 17, "Number of Habitable Planets with Life (flife)"). They explain that from one example of life, no one can estimate how likely life is to begin. They write that either there is life on other planets or there is not. The answer exists, they add, whether or not we are here to ask. They close their chapter on the one fact they hold certain: "life exists, and we are the proof of that" (*We Have No Idea*, ch. 17, "Are We Alone?").

I take every measured number in Cham and Whiteson's chapter as they give it. I also hold to the fact Cham and Whiteson close on, that life exists. I add, from my account, a way of sorting the parts of the authors' question into two groups. Some of what life needs is fixed by the kinds of particle and how they join, so it is the same in every star. Other parts of what life needs were set by events, by what happened at each place, and so they differ from place to place. I count how often life itself arises among the amounts that events set. How often life arises is read only by finding life, place by place.

What Is the Same in Every Star

When sunlight passes through a prism, the light spreads into a band of colors from red to violet. In 1814 the optician Joseph von Fraunhofer looked closely at the band. He mapped more than five hundred and seventy thin dark lines across the band. In 1859 and 1860 the physicist Gustav Kirchhoff and the chemist Robert Bunsen showed that many of Fraunhofer's dark lines sit exactly where heated elements in the laboratory give off bright lines. So each dark line is made by an element in the Sun's outer layers. The element takes in its own color from the light that rises beneath it. Physicists call a color at which the atoms of one element take in or give off light a *spectral line*. Each spectral line is set by the atom's *energy levels*, the particular energies that the atom's electrons can have. In 1925 the astronomer Cecilia Payne read the strengths of the spectral lines of many stars. She found that the stars are made mostly of hydrogen and helium.

When astronomers read a star's makeup from its spectral lines, every reading depends on one fact: each element's energy levels are the same in every star. The reason: the amounts of the elements in the stars are known "because each element's levels are fixed by structure and are the same in every star". Here *structure* is whatever follows from the form of comparison (what every act of comparing must contain) and from the kinds of particle and their forces, with no measured number. As Chapter 4 showed, a kind is a sort of particle whose every member is found exactly like every other: an electron made this morning is exactly like one made in the first second of our history. The list of kinds is closed. The structure of comparison has a place for each kind, and every place is filled, so no further kind is waiting to be found.

The kinds join into larger things. Quarks join into protons and neutrons, protons and neutrons into nuclei, nuclei and electrons into atoms, and atoms into molecules. I use the word *whole* for a thing bound together out of smaller parts. A proton is a whole, and so are a nucleus, an atom and a molecule. I ask three questions of every whole, and I answer all

three in one sentence: "Which wholes exist is structure, which last is structure and measured values, and how many there are is history". Which wholes can exist follows from the kinds and their forces alone. Which wholes last follows from a rule of structure together with masses that are measured. The rule of structure is that a whole lasts when nothing lighter, one particle or several taken together, has the same three numbers: the same electric charge, the same number of particles of the proton's family, and the same number of particles of the electron's family. At the temperatures of today's universe, every change keeps all three numbers the same. So the proton lasts, because nothing lighter than a proton has the proton's three numbers. A free neutron is a neutron on its own, outside any nucleus. A free neutron has no charge, one particle of the proton's family and none of the electron's family. An antineutrino is the antimatter partner of a neutrino. A proton, an electron and an antineutrino together have the neutron's three numbers, since an antiparticle, the antimatter partner of a particle, counts as minus one in its family. Together, the proton, the electron and the antineutrino weigh less than the neutron. So a free neutron turns by itself into a proton, an electron and an antineutrino. In that sentence, *history* means what events set: how many of each whole there are.

The kinds and their forces are the same everywhere. So a carbon atom near Tau Ceti has the same energy levels as a carbon atom on the Earth. Water near Tau Ceti is the same molecule as water on the Earth. At every star, atoms join into the molecules of life by the same rules.

Cham and Whiteson come at the question of what is the same everywhere from the side of life. They look at the variety of life on the Earth. They reason that a feature that varies widely from one living thing to another is no requirement of life. They suggest that a feature shared by every living thing might be common to life everywhere. Their example of a shared feature is the need for water and for a source of energy. They write that life "always seems to require water" and seems to require plenty of carbon, and that life "tends to require nitrogen, phosphorus, and sulfur" (*We Have No Idea*, ch. 17, "Number of Habitable Planets with Life (flife)"). Their ground for that list is a survey of the one example of life we have,

the life on the Earth. My ground is the structure of the kinds, and from that ground follows a further result: wherever water, carbon, nitrogen, phosphorus and sulfur occur, they are the same ingredients. The next question is whether the ingredients of life occur at a given place, and in what amount. The answer is history, set by what happened at that place.

What Each Place Holds Is Its History

Think of the iron in a drop of blood, the calcium in a tooth, the oxygen in a breath. Every atom of that iron, calcium and oxygen has a nucleus made after the first minutes of our history were over. During the first minutes, nuclei of hydrogen and helium formed, with traces of three other light nuclei, and then the forming of nuclei stopped. Every heavier nucleus was made later, in stars.

Every nucleus carries a positive electric charge, so any two nuclei push each other apart. Two nuclei join only where they move fast enough to come close, as nuclei do in the hot core of a star. The joining of light nuclei into heavier ones is *fusion*, the burning that keeps a star shining.

A walker cannot cross a footbridge with one plank missing in the middle by stepping from plank to plank. The walker can cross the footbridge in one long stride, from the plank before the gap to the plank after the gap. In the picture for nuclei, each plank is a nucleus, counted by how many protons and neutrons it holds in all. A helium nucleus holds four. Helium stands before a missing plank: no nucleus with five protons and neutrons in all lasts, and none with eight lasts, so helium cannot grow by adding one piece at a time, or by joining one other helium nucleus. In the hot core of an aging star, three helium nuclei make the stride together and become one nucleus of carbon. Carbon has a state at just the energy that the three helium nuclei bring in, a state for the three to land in. Because carbon has that state, the stride runs fast enough to make the carbon there is. Physicists call a reaction sped up by a match of energy and state a resonance. Chapter 16 met a resonance in the Delta, the proton's excited partner.

In 1953 the astronomer Fred Hoyle argued that carbon must have a state at just the energy that three helium nuclei bring in, because there is carbon in the world and the three-helium stride is the only road to carbon. Hoyle also said at what energy the state lay. Physicists found the state at that energy: a group at the California Institute of Technology found the state first, in 1953, and Charles Cook, William Fowler, Charles Lauritsen and Thomas Lauritsen reported fuller measurements in 1957. The state is now called the *Hoyle state*. As helium burns in the core of an aging star, some of the new carbon takes in one more helium nucleus and becomes oxygen. The carbon in every living thing and the oxygen of every breath were made in this way. Cham and Whiteson say the same on their own ground: they write that the heavier elements needed for complex chemistry are made by fusion in the centers of stars and scattered when those stars collapse and explode. They add that stars that collapse and explode are rarer far out in the galaxy. So, they reason, a planet too far out in the galaxy has too few of the heavier elements.

The amounts of the elements at a place are a record of all the events that made the elements. The astronomer Martin Asplund and his colleagues measured the surface of the Sun and reported the measurement in 2009. The surface of the Sun keeps the makeup of the cloud the Sun formed from. For every hundred thousand nuclei of hydrogen, Asplund's team found about forty-nine of oxygen, twenty-seven of carbon and nearly seven of nitrogen. Draw the amounts of the elements as a curve against the mass of each nucleus. The curve falls like a mountainside from hydrogen and helium. The mountainside has three features: a deep notch just after helium; a sawtooth, in which nuclei with even numbers of protons and neutrons stand above their odd neighbors; and a peak at iron. Each of the three features comes from the way the nuclei were made. The notch is the stretch of light nuclei that the three-helium stride steps over. The sawtooth comes from the stars building their nuclei out of helium nuclei. A helium nucleus holds an even number of protons and neutrons. The peak

is at iron, where the burning of stars comes to its end. So the amounts of the elements are a record of what the stars did: history set the amounts, and structure does not fix them.

The heavy elements that life needs are made in stars, over billions of years of stellar evolution. Habitable planets depend on that history.

I now apply the last part of the sentence, that how many wholes there are is history, to the Drake equation's seven factors. Every one of the seven factors is a count or a share: how many stars, how many planets, what share of those planets. Counts and shares are amounts, and on my account amounts are history, set place by place and read by measurement. Every factor depends on what structure fixes everywhere: the kinds of particle, the wholes they make, and every atom's energy levels. So every star has the same materials and the same rules for joining them. Each place has its own share of the materials of life, set by its history. History sets the number of planets that form around a star. History also sets how often a planet with the right materials comes to hold life. So the question "Are we alone?" asks for an amount set by history: how many places hold life. Life has so far been found in one place, here, so the share of planets that hold life is a number not yet measured.

The last factor of the Drake equation is the chance that another species is around at the same time as we are. The last factor is about time as well as space. The authors' closing picture is also about time: they picture "a few outposts of life in the history of the universe" (*We Have No Idea*, ch. 17, "Are We Alone?"). One fact of my account applies to life across time. As Chapter 2 says, our era of the world is an epoch: an era in which stars, galaxies and black holes form. Another epoch follows ours. The next epoch grows in the same way that ours grew. The new epoch also begins with the same structure, and the same orderly start, under which stars, planets and people became possible in ours. Chapter 22 of this book follows that series of epochs. For the question of this chapter, one result of Chapter 22 is enough: the rules by which the materials of life are made are the same in every epoch, as they are at every star.

Is There Another Earth?

Listeners to Cham and Whiteson's podcast asked a practical form of the question of life elsewhere: is there a backup Earth we could move to? The authors answer in their second book, *Frequently Asked Questions About the Universe*. They look first in our own solar system and find no good second home. Venus is far too hot, under air that presses ninety times as hard as ours. Mercury barely turns, so one side is fried and the other frozen. The giant planets are balls of gas and ice, with nowhere to stand. The authors judge Mars the best bet in our neighborhood, but Mars has lost the magnetic field that would shield its air from the Sun, and they give a separate chapter to whether Mars could be remade. Their verdict on the neighborhood is a joke about houses: "We seem to be in the undesirable real-estate situation of having the best house on the block" (*Frequently Asked Questions About the Universe*, ch. 7, "Cosmic Neighbors").

So Cham and Whiteson look farther, to planets around other stars. In 1995 the astronomers Michel Mayor and Didier Queloz reported a planet about as heavy as Jupiter. The planet circles 51 Pegasi, a star like the Sun. Mayor and Queloz found the planet without seeing it. As the planet pulled the star to and fro, the color of the star's light shifted by a small, regular amount. The authors tell that from 2002 astronomers also found planets by the slight dimming of a star when a planet passes in front of the star, and that the Kepler telescope watched thousands of stars for those dips. A few planets have even been photographed directly, as fuzzy points beside the glare of their stars. The authors sum up what the searches found: "What we learned is that the universe is teeming with planets" (*Frequently Asked Questions About the Universe*, ch. 7, "Planets Beyond Our Solar System"). They estimate hundreds of billions of planets in our galaxy alone.

Then Cham and Whiteson draw up a list of what a good home needs. A good home must be near enough to reach, which means within our galaxy. A good home must be rocky, so that there is ground to stand on. It must lie in its star's *Goldilocks zone*, the authors' name for the band of or-

bits neither too close to the star nor too far from it, so that the planet is neither too hot nor too cold. It must have air, and the air must hold oxygen we can breathe, which on the Earth was made by microbes over billions of years, so a ready home must already hold microbial life. The authors report that the science is still too new to count how many planets meet the whole list.

At each step of the search for another Earth, astronomers read light. Every reading depends on the fact that each element's energy levels are the same in every star. Astronomers read the shift in the color of 51 Pegasi's light as motion because the star's spectral lines, at rest, sit exactly where the same elements' lines sit in a laboratory on the Earth. The authors also report that starlight passing through the thin air of a far planet comes out changed in color. They tell of one *mini-Neptune*, about a hundred and twenty light-years away. A mini-Neptune is the authors' word for a planet smaller than Neptune and larger than the Earth. The starlight that passed through the air of that mini-Neptune carries the mark of water vapor (*Frequently Asked Questions About the Universe*, ch. 7, "Oh Yeah, an Atmosphere"). I apply the same reason, that energy levels are the same everywhere, to the reading of the mini-Neptune's air, because the levels of a molecule of water are fixed by structure, as the levels of an atom are. So water takes in the same colors from starlight a hundred and twenty light-years away as in a laboratory on the Earth.

Liquid water can last under ice on a cold world for a reason that also follows from structure. In winter a lake freezes from the top down, and the fish swim on beneath the ice. In ice, each water molecule holds four neighbors at the corners of a three-sided pyramid, and each neighbor is held by the pull of a hydrogen atom of one molecule toward a pair of outer electrons on the oxygen atom of the next molecule. Together the molecules make an open framework. The framework leaves more room between the molecules than the jostling molecules of liquid water take. So ice is lighter than the same amount of water and floats, and the ice lid keeps the deep water liquid. Wherever water freezes into the open framework of ice, on the Earth or on any other world, its ice floats on the water

beneath it. The authors report that a huge ocean is thought to lie beneath the ice of Jupiter's moon Europa, and ice with the open framework, formed on such an ocean, floats on the ocean as a lid.

What differs from one planet to the next is history. History set how much rock a planet holds and how much air and water it has. History also set how much carbon and oxygen the planet has to build with. A planet's history is two things: what the stars before the planet made, and what happened as the planet formed. History also set how many planets have air that holds oxygen made by life. Astronomers read that count by finding the planets one at a time. So two sorts of fact hold on every world. Ice with the open framework floats on the water of other worlds as it floats on ours, while the share of carbon in the cloud that each place formed from was set by the history of that place.

Life Is Rare, and It Is Here

Picture a person choosing a gift for a friend: she weighs the futures each gift would bring, and then selects one gift. Nothing before the selecting fixes which gift she picks. She carries that choice forward, as her own, with every other choice she has made. A thermostat on the wall also compares. It weighs the warmth of the room against the warmth it is set to, and switches the heater on or off. The thermostat is pushed toward the warmth it is set to, and nothing in that pushing shows that anything was selected. I call what the person does a *true choice*: a selection made "with nothing before the selecting fixing it".

Cham and Whiteson end their chapter on the fact that life is here, and I end this chapter on the same fact. A living being is made of the same matter as a stone, and everything that happens in a living being is a physical process. Yet a living being differs from a stone in kind, inside nature, with nothing added to nature. Think of notes scattered across a page, and the same notes made into a sonata. The notes are of one kind throughout, and the sonata is a new kind of thing because of how the notes are held together. In the picture, the notes are matter, the same in a stone and in a

living being, and the sonata is the living being. On my account, a living being is new in kind because its true choices are gathered into a self, which carries the choices forward as its own and knows them from inside.

The universe we can see is almost all stars, gas, dust and rock. The stars, gas, dust and rock are spread through spaces so wide that light takes years to cross from one star to its neighbor. In a star or a cloud of gas, no one chooses a gift for a friend. Life is rare in the universe, as a share of all its matter, and it is here. In that sentence the word "rare" is about life as a share of all the matter there is. So the sentence is about a share of matter, while the count of living worlds is a separate number, an amount set by history.

My account also shows what a search for life from far away finds: a telescope that finds oxygen in a distant planet's air finds the materials and the chemistry of life. A living being differs in kind from a stone because its true choices are gathered into a self, a difference known from inside. No one looking from outside can see the difference between a living being and a stone, because from outside a true choice and chance look the same. I also give a case: a single bacterium swimming toward its food. Someone watching the bacterium cannot tell whether the bacterium is making a true choice or moving by chance. The authors worry that a message from far away could look to us like pure noise. Every chooser, seen from outside, is in a like position: the chooser's choices look like chance, and the chooser's choosing is known from inside, by the chooser itself.

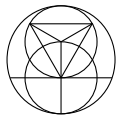
> **The short answer**
>
> Life has been found in one place, here: its materials and the rules by which they join are the same at every star, while whether life is anywhere else is set by each place's history, and is read only by finding life there.

The traveler's problem that Cham and Whiteson open with is telling the universal from the local. For the materials of life, the kinds of particle, the wholes and the energy levels of every atom are universal, while the amounts, the planets and the count of living worlds are local. You can sort every later question about our place in the universe into what the structure fixes everywhere and what history set here.

Every one of the materials of life is matter; why is the world made of matter and not of antimatter?

PART FIVE

FROM THE STARS TO THE BEGINNING



Chapter Nineteen

Why Are We Made of Matter, Not Antimatter?

In which every particle meets its mirror, the mirror turns out to be required, and the matter we are made of turns out to be a remainder from the beginning of our epoch

Why are we made of matter and not antimatter?

What this chapter uses

A *comparison* is the act of finding whether two things are the same or different in some respect, and every measurement is a comparison; a *finding* is the outcome of one comparison, laid down as a record; a *comparer* is whatever makes a comparison, whether or not the comparer has a mind (Chapter 1).

The *content* of a finding is what the finding finds, as the warmth of your coffee; the *context* is where the content is found, and the context has three sides, the three settings of space, time and possibility (Chapter 1).

Three things in nature do the bending: gravitation bends space, the cosmological constant bends time, and the dark matter bends possibility (Chapter 1).

Every comparison has three positions: the *act of comparing*, the relating; the *thing compared*, what is known; and the *thing compared against*, what the act of comparing reaches toward and never contains in one act, the beyond (Chapter 4).

The basic elements of matter are a closed list of kinds of particle: the kinds are few because every comparison has three positions, and each kind of matter comes three times, in three *generations* (Chapter 4).

Gravity is the *arena*, the stage of space and time on which the three forces act, and so gravity stands beside the three forces and is not a fourth force (Chapter 7).

On 2 August 1932, at the California Institute of Technology in Pasadena, the physicist Carl Anderson was photographing the tracks of cosmic rays. Chapter 16 told of cosmic rays: the fast particles that arrive at the Earth from space, together with the showers of particles that those fast particles knock loose in the air. Anderson caught the cosmic rays in a *cloud chamber*: a closed vessel of damp gas in which a fast charged particle leaves a line of tiny droplets behind the particle, as a high jet leaves a

white trail across a cold sky. A strong magnet surrounded the chamber, so that the track of every charged particle bent into a curve, one way for a positive charge and the other way for a negative charge. Inside the chamber Anderson had set a plate of lead six millimeters thick. The plate showed which way each track had run, because a particle that crosses lead loses some energy, and a slower particle bends more sharply in the magnet.

One of Anderson's photographs from 2 August held a single thin track that crossed the lead plate. The track bent more sharply above the plate than below, so the particle had come up from below and lost energy in the lead. The particle was moving upward, so its curve was the curve of a positive charge. If a proton had made a track as sharply bent as Anderson's track, the proton would have carried so little energy that the proton would have stopped within a few millimeters of gas. Anderson's track ran on far beyond a few millimeters. Anderson concluded that he had photographed a particle with a positive charge and a mass of the same order as the electron's, far lighter than a proton. Anderson named the new particles in the paper he sent to the journal *Physical Review* the following February: "These particles will be called positrons". Chapter 9 described the positron as the electron's mirror partner, with the electron's mass and the opposite charge. In Anderson's photograph antimatter became, for the first time, a thing found in physics: a curved line of droplets.

Dirac's Twins

Jorge Cham and Daniel Whiteson open their chapter on antimatter a few years before Anderson's photograph, with the physicist Paul Dirac. Dirac wrote one equation for fast electrons, an equation that obeyed both quantum mechanics and relativity, and the equation worked as well for an electron with a positive charge as for the ordinary electron with a negative charge. The authors write that Dirac could have set aside the second answer, the electron with a positive charge, as an artifact of the mathematics. An artifact of the mathematics is a quirk of the equation, with nothing in

nature behind the quirk. Dirac kept the second answer, and went further: "He proposed that all particles have a corresponding antiparticle" (*We Have No Idea*, ch. 12, "Mirror Particles"). The authors call the antiparticles the evil twins of the particles: the same mass, with every charge reversed. When a particle meets its twin, the two annihilate: they disappear, and their mass leaves as energy. The authors measure the energy of annihilation in raisins: a household raisin weighs about a gram. If a raisin of matter met a raisin of antimatter, a gram of each, the two raisins would release more than forty kilotons of explosive force (*We Have No Idea*, ch. 12, "Antiparticle Annihilation"). In the second book by Cham and Whiteson, *Frequently Asked Questions About the Universe*, the authors consider antimatter as a fuel for a starship. The authors also write that "There are big mysteries as to why antimatter even exists" (*Frequently Asked Questions About the Universe*, ch. 8, "Antimatter").

Then the authors list what they do not know about antimatter. The first of their questions is plain: "Why do antiparticles exist?" (*We Have No Idea*, ch. 12, "The Mysteries of Antimatter"). The authors also ask why a particle may annihilate only with its own twin. They ask why the photon, the Z boson and the gluon, all of them carriers of force, have no separate twins, while the W bosons, the two charged carriers of the weak force, do have twins. The authors find the usual answer, that the photon is "its own antiparticle", to be a phrase "which seems more like avoiding the question than answering it" (*We Have No Idea*, ch. 12, "Neutral Matters"). They ask whether antimatter falls as matter does. They name the largest question themselves: "But the biggest of these questions is a simple one: Why is our world made of matter, not antimatter?" (*We Have No Idea*, ch. 12, "The Mysteries of Antimatter").

The authors show that the world's excess of matter over antimatter is real and enormous. If the world had made matter and antimatter in equal amounts, nearly all of the matter and the antimatter would have annihilated into light, so the matter around you is far more than a world of equal amounts would have kept. Physicists have looked for, and found, a slight preference for matter in the way particles behave. The authors say of the

slight preference for matter: "it doesn't come close to accounting for the huge imbalance that we see today" (*We Have No Idea*, ch. 12, "Why the Universe, Not the Antiuniverse?"). Astronomers have also looked for the flashes of light that would mark a border between a region of matter and a region of antimatter, and have found none: the authors report that our whole cluster of galaxies is matter.

The authors' largest question depends on a smaller question, which has to be answered first: what is antimatter, and why does antimatter exist at all? The answer to the smaller question comes from the structure of the kinds of particle: what kinds there are, and what each kind is. The answer to the largest question comes from the history of the world.

A State and Its Mirror

Begin with a picture from arithmetic. Take zero, and write it as plus one and minus one. Nothing has been added, since plus one and minus one still sum to zero. Yet where there was nothing to see, there are now two marks, each the reverse of the other. I describe a particle and its antiparticle, made together, with the same picture from arithmetic: the pair is "nothing made visible", zero separated into plus one and minus one.

A particle and its antiparticle come as a pair because of the act that makes the pair. The thing compared and the thing compared against are conjugate, in the sense Chapter 8 gave the word: neither comes before the other, and neither can be made perfect except at the expense of the other. Now picture a battery in a flashlight, set between two contacts. The same battery can go in either way round, and turning the battery round changes only the battery's order between the contacts. A state of matter is like the battery. The thing compared and the thing compared against are like the two contacts. A state of matter stands toward the thing compared and toward the thing compared against in one order. The same state can also stand toward the two positions in the other order, because neither position comes before the other. The state held in the other order is the *antiparticle* of the state held in the first order. An antiparticle has the same

mass as its particle, and every label that the particle carries is reversed in the antiparticle. The labels that are reversed are the labels that come in whole units and add up when things are put together, such as electric charge.

The antiparticle of the electron is therefore not the proton. Chapter 4 placed the electron at the thing compared and the proton at the thing compared against, and the two particles carry opposite charges. The electron and the proton are two different kinds: the electron is a point, and the proton is built of parts. So neither particle is the other particle held in the other order. The antiparticle of the electron is an electron with every label reversed: the positron.

Chapter 4 found that the photon is the act of comparing itself. In the battery picture, the photon is the hand that sets the battery in place, and not a battery. So the photon holds the thing compared and the thing compared against in no order of its own. An act with no order of its own makes both orders together, because making one order alone would put one of two conjugate positions first. The consequence: the act of comparing, when it creates content, creates the state and its conjugate together; it cannot create one without the other. So when a particle carries a label that comes in whole units and adds up, such as electric charge, the particle has an antiparticle. In the antiparticle, every label that comes in whole units is reversed.

Dirac came to the same result, that every particle has its antiparticle, by a different argument. Dirac found the positron in an equation that joined quantum mechanics to relativity. Every antiparticle follows from how the act of comparing is built (three positions, two of them conjugate), and every measurement performs the act of comparing. So comparing requires every antiparticle. The authors' question "Why do antiparticles exist?" has its answer: comparing makes a state and its mirror together.

Making a particle and its antiparticle together costs energy for each of the two. A pair needs an energy of at least twice the mass of one member, "because both must be paid for". In 1933, at Cambridge, the physicists

Patrick Blackett and Giuseppe Occhialini photographed showers of cosmic rays. In the showers, electrons and positrons appeared together, in pairs. In 1955, at Berkeley, the antiproton was found by a team of physicists: Owen Chamberlain, Emilio Segrè, Clyde Wiegand and Thomas Ypsilantis. The antiproton came from a machine built with energy enough to make a proton and an antiproton together.

Annihilation is the making of a pair run the other way: a particle and its antiparticle meet, both disappear, and their energy leaves, most often as two photons. Annihilation is not destruction. It is the reversal of creation. The energy needed to make a pair equals the energy the pair gives off in annihilation: nothing is gained, and nothing is lost. In the authors' raisins, the whole two grams of mass leave as energy and give the more than forty kilotons that the authors report.

A particle and its antiparticle are exact mirrors in what each is: the same mass, the same lifetime and the same size of every label. The exact mirror is three swaps made at once: every particle for its antiparticle, left for right as in a looking glass, and time run backward. Only the three swaps taken together leave every law of the kinds unchanged, and so a particle and its antiparticle have exactly the same mass and lifetime. A different mirror swaps particles for antiparticles alone, or together with the swap of left and right. Chapter 4 described this second mirror: a process seen in this mirror is the image of the process. The weak force treats some processes and their images slightly differently. So comparing makes a state and its antiparticle alike in what they are. But the weak force still acts differently on a state and on its antiparticle.

An atom of antihydrogen is an antiproton with a positron around the antiproton, as Chapter 7 told, so an atom of antihydrogen must take in and give off light of exactly the energies that an atom of hydrogen does. In 2010 the team of the ALPHA experiment at CERN, the European laboratory for particle physics near Geneva, trapped atoms of antihydrogen. The authors tell of the atoms that the ALPHA team trapped. In 2018 the ALPHA team measured the energy of the light that lifts the positron of antihydrogen from the lowest level to the level above. The ALPHA team

found the energy equal to hydrogen's, to two parts in a trillion. The authors list among their unknowns whether antiparticles differ subtly from particles. The answer comes from the exact mirror that comparing makes. A particle and its antiparticle are exact mirrors in mass, in lifetime and in the size of every label.

There are reasons, too, for the authors' strict rules of annihilation, such as the rule that a particle annihilates only with its own twin. The authors ask: "Why does the universe have these weird rules?" (*We Have No Idea*, ch. 12, "Antiparticle Annihilation"). Electric charge and color, the charge of the strong force, are kept: the total of each stays the same through every change. The two totals are kept because the act of comparing leaves unchanged the total of what the act compares. Comparing is measuring. A measurement leaves the measured thing as it was.

The authors' "three-quarkness" and "electronness" are two more totals that are kept, for a second reason. The answer to the authors' largest question depends on those two counts. A *baryon* is a whole made of three quarks, such as the proton and the neutron. The *baryon count* is the number of baryons less the number of antibaryons: the authors' "three-quarkness". Chapter 4 said that a lepton is a particle of matter that does not feel the strong force: the electron, the electron's two heavier cousins (the muon and the tau), and the three neutrinos. The *lepton count* is the number of leptons less the number of antileptons: the authors' "electronness". A *single change* is one particle turning into others under one force, as when a neutron turns into a proton, an electron and an antineutrino. No single change turns a quark into a lepton. To turn a quark into a lepton, a carrier of force would have to carry both a color, as the gluons do, and the charge of the weak force, as the W bosons do. No carrier of force carries both. So every single change keeps the baryon count and the lepton count, each on its own.

Some particles are their own twins, as the authors say, and the reason is what each carrier of force does to a particle. Picture a department store: the sign beside the stairs tells you which floor you are on and leaves you where you are, and an escalator carries you up or down, a move with a

direction. When a carrier of force only reads a particle, as the floor sign reads your floor, the carrier has no direction to reverse. So the carrier is its own antiparticle. The photon only reads a particle, and so do the Z boson and two of the eight gluons (the carriers of the strong force). When a carrier moves a particle from one value to another, as an escalator does, the carrier comes in a pair, one carrier for each direction, as a store has one escalator going up and another going down. A doublet is a pair of particles alike in kind and different in one respect, such as the up quark and the down quark. The two W bosons turn one side of a doublet into the other side, so the two W bosons are each other's antiparticles. The other six gluons move a quark from one color to another, so the six gluons are three pairs of antiparticles. The Higgs boson is its own antiparticle too, because the Higgs boson belongs with the context in which matter is found and is not itself a state of matter. For the photon, the Z boson, the two gluons and the Higgs boson, being its own antiparticle follows from what the particle does or is.

Every state of matter differs from its own antiparticle: "No state of content is its own antiparticle". In the quotation, a state of content is a particle of matter. The authors say that the neutrino could be its own twin. But the neutrino is a particle of matter, so the neutrino has a twin distinct from itself, the antineutrino. If a neutrino were its own twin, certain nuclei could give off two electrons and no neutrinos. Physicists have watched xenon and germanium deep underground for years, and have found no nucleus that gives off two electrons and no neutrinos.

The Alphabet and the Library

Picture an alphabet and a library. The letters of the alphabet are fixed: every book in every library is written in the same letters. A library holds some number of copies of each book. The number of copies is a fact about that one library, set by what the library bought, lent, lost and was given over the years. If you ask why a word is spelled the way it is, the answer

comes from the alphabet. If you ask why a library holds three copies of one book and none of another, the answer comes from the library's history.

In the picture of the alphabet and the library, the kinds of particle are the letters, and each letter has its mirror letter, as each particle has its antiparticle. The amount of each kind in the world is the library's holdings. I separate the kinds from their amounts: "The existence of antiparticles is structural: comparison requires them. The excess of matter is not structural. It belongs to the initial conditions, to the history of the universe, to the facts that the zoo does not fix". In the quotation, the zoo is the whole collection of the kinds of particle, as Chapter 4 said. So the authors' largest question is a question of history. The answer comes from what happened in the world, read with the laws of the kinds.

Under the laws of the kinds alone, matter and antimatter stay even. Picture a crowd of particles in *balance*, the settled state in which every reaction runs as often forward as backward. The reactions of the crowd keep certain totals, such as the total electric charge. When none of the kept totals carries an excess, a crowd in balance holds each kind and its antiparticle in equal numbers. A particle and its antiparticle have the same mass, so in balance the two have equal numbers, whatever slight preference single changes show. The early universe was a crowd of particles in balance. The early universe was so hot that a typical collision carried far more energy than twice the mass of any kind, so the collisions made every kind in pairs and unmade the pairs again, over and over. The question is therefore: what left the hot crowd of the early universe with more matter than antimatter?

What It Would Take to Make Matter

Picture the ratchet in a mechanic's wrench: a toothed wheel with a catch. Fix a small paddle to the wheel's axle inside a box of gas. The molecules of the gas strike the paddle at random, and the wheel seems bound to creep forward one click at a time. Yet the wheel goes nowhere

while the catch and the gas share one temperature, because the molecules jostle the catch too, and now and then the catch lifts and lets the wheel slip back. The wheel turns one way only when three things are true together: the wheel can turn at all, the wheel's teeth favor one direction, and something keeps the wheel, the catch and the gas from settling to one temperature.

In 1967 the physicist Andrei Sakharov set out three similar demands for making more matter than antimatter. First, some process must change the baryon count. Second, the same process must treat matter and antimatter differently. Third, the process must run while the world is out of balance, so that the reverse reaction does not undo what the process made. The three demands match the wheel's three: a wheel that can turn, teeth that favor one direction, and no single shared temperature. The list of kinds is closed: no kind exists outside the list. Check the closed list of kinds against the three demands, one at a time.

The kinds satisfy the first demand, through a change of a different sort from a single change. Picture a field of wheat: a single stalk can bend on its own, and in one gust the whole field can lie over at once. The weak force acts through a field that fills all of space. When the world was extremely hot, the whole field of the weak force could shift at once from one of the field's lowest states to the next, as the whole field of wheat lies over in one gust. When the whole field of the weak force shifts at once, the shift is a *collective passage*. Each collective passage turns up nine quarks and three leptons together. A quark counts as one third of a baryon, so nine quarks change the baryon count by three units. The three leptons change the lepton count by three units, in the same direction as the baryon count.

The kinds satisfy the second demand as well. The weak force treats a particle differently from its antiparticle. In the sense Chapter 4 gave the word, a phase is a position on a circle, like the position of the hand of a clock. The quarks of the three generations also mix, and the mixing carries one phase that no choice of description removes. The phase of the quark mixing causes the difference between a process and its image that Chapter 4 met, and is the source of the slight preference for matter that, as the au-

thors report, physicists have found. Count the excess of matter as the number of baryons for each particle of light. At the temperature where the phase would have had to act, the strength of the phase is a pure number more than a trillion times smaller than the excess of matter that the phase would have had to make. An excess made through the phase grows in proportion to the strength of the phase, so the phase could make far less than the excess there is. The authors find the measured preference far too small. I come to the same result by computing exactly how small the preference is.

The third demand depends on how the world cooled through the settling of the Higgs field, the time at which the field took the value that fills space today. A kitchen shows two ways in which a settling like the settling of the Higgs field can go. Water heated in a pot boils with bubbles, and at the wall of each bubble the water is out of balance. Honey cooled on a counter thickens smoothly, with no bubbles and no walls, in balance at every moment. The settling of the Higgs field went the way of the honey, smoothly and with no bubbles, as calculations from the known particles and the measured mass of the Higgs boson show. The collective passages stayed in balance through the settling of the Higgs field, and fell out of balance gradually when the world was about thirteen millionths of a millionth of a second old. So no excess was made as the Higgs field settled, because the third demand needs a world out of balance.

The Count That Never Changes

Picture two tally counters on a wall, of the kind a doorkeeper clicks to count people coming in. One counter counts baryons, and the other counts leptons. Every machine in a large factory is wired to the two counters. Some machines never touch either counter. One machine clicks both counters forward by three together, or both back by three together. No machine clicks one counter without the other. Watch the factory for as

long as you like: the two readings change, and the difference between the two readings stays the same. Whatever the difference is today, it was the same when the factory opened.

In the world of particles, the difference between the two readings is the baryon count less the lepton count, which physicists write B minus L. The kinds of particle behave like the factory. The machines that never touch either counter are the single changes, since no single change turns a quark into a lepton. The collective passage is the machine that clicks both counters by three together. A machine that clicked the lepton counter alone would need a mass that joins a particle to its own antiparticle. The kinds hold no mass that joins a particle to its own antiparticle, since no state of matter is its own antiparticle. The list of kinds is closed, so there is no machine outside the list. B minus L stays the same through every process among the kinds, at every temperature.

Push a marble up the side of a bowl and let go: however far you pushed the marble, the marble rolls back to the bottom. While the collective passages ran in balance, the baryon count behaved like the marble: the passages always brought the baryon count back to a settled value, a fixed share of B minus L. So if an excess of baryons had been made while B minus L was zero, the collective passages would have rolled the excess away, back to a fixed share of zero, which is zero.

Now run the reasoning backward, from today. Baryons exist today, and outnumber antibaryons. Nothing has changed the baryon count since the collective passages stopped, so the baryon count was above zero at the moment the collective passages stopped. At the moment the collective passages stopped, the baryon count stood at a fixed share of B minus L. A share of zero is zero, so B minus L was above zero too. No process changes B minus L, so B minus L had the same value at every earlier moment, back to the earliest moment our history reaches. So the excess of baryons present today "requires a $B - L$ present from the earliest moment our history reaches".

Picture a beach after the tide has gone out. The tide has carried nearly all its water back down the sand, and a thin line of shells lies where the tide stood highest. Nothing that happens on the beach afterward moves the line of shells. A *residue* is what remains when nearly everything else has gone one way. The matter of the world is a residue: nearly all the matter and antimatter of the hot crowd annihilated, and a small excess of matter remained, as the line of shells remains on the sand. Our epoch is the era of the world in which stars, galaxies and black holes form, as Chapter 2 said. The excess of matter over antimatter takes the form of a value of B minus L above zero, a residue that the beginning of our epoch left and that every change since has kept.

The authors weigh two possibilities for how the excess of matter came about (*We Have No Idea*, ch. 12, "Why the Universe, Not the Antiuniverse?"). In the first possibility, the Big Bang made slightly more matter than antimatter. The authors grant that the first possibility explains what we see, but they object that "it punts on the core concept": the first possibility turns the question into why the universe began with more matter. The authors have a second doubt: they add that most modern theories of the early universe do not allow an excess made at the start. In the second possibility, the Big Bang made equal amounts of matter and antimatter, and some process afterward came to favor matter. Of the second possibility the authors write, "So possibility #2 seems promising".

On the closed list of kinds, the second possibility fails, because no process among the kinds makes the excess. Physicists have proposed three ways that a process could make the excess. Each way needs one thing that is not on the closed list of kinds. The first way needs a carrier of force that carries both a color and the charge of the weak force. The second way needs a mass that joins a particle to its own antiparticle. The third way needs a settling of the Higgs field with bubbles and walls. The excess was there from the start, as the first possibility says. I also say in what form the start left the excess, and why the excess lasts to today. If the start had left an excess of baryons alone, with B minus L at zero, the collective passages would have rolled the excess away, as the marble rolls back to the bottom

of the bowl. But the excess the start left is a value of B minus L, and B minus L stays the same through every process, so nothing since has rolled the excess away. The excess was not spread thin afterward either: Chapter 20 shows that our history held no long burst of very fast growth of space, the kind of growth that spreads whatever was made before the growth too thin to matter. The authors' second doubt was that most modern theories of the early universe do not allow an excess made at the start. I reply to that doubt with two facts. B minus L stays the same through every process, and no long burst of growth spread the excess thin. So the start I describe leaves an excess that every later change keeps. The excess is therefore a number set by history, held in a count, B minus L, that nothing since has changed. The authors' first doubt is about why the start left an excess at all: a question about the beginning of our epoch itself. On my account the size of the excess belongs to history, and the share of it held as baryons belongs to structure: the residue is history; the share is structure. In Chapter 20 I follow our history back to the turn, where the residue was left.

How much difference does the residue make to the amount of matter in the world? Picture the end of a crowded party at which every guest arrived with a partner, and couples leave together as they find each other. At last the few guests who remain are spread so thin that they never meet before the hall is locked, and they stay. If there had been no residue at all, baryons and antibaryons would have ended the same way as the last guests: a few of each, spread too thin to meet and annihilate. Physicists compute from established physics what an annihilation with no residue would leave: about one baryon for every billion billion particles of light, with as many antibaryons beside the baryons.

Two measurements give the amount of matter there is. The Planck satellite mapped the faint glow of light left from the early universe, which reaches us from every direction, and the pattern of warmer and cooler patches in the glow gives the amount of ordinary matter. The Planck map gives about six baryons for every ten billion particles of light in the glow. Separately, astronomers measured how much heavy hydrogen, a nucleus

of one proton and one neutron, was left from the first minutes of our history. Before stars changed the amount, there were about two and a half nuclei of heavy hydrogen for every hundred thousand nuclei of ordinary hydrogen. The more baryons there were for each particle of light, the less heavy hydrogen survived the first minutes. So the amount of heavy hydrogen gives a number of baryons for each particle of light, and that number is the same as the Planck number within the precision of the two measurements. We now know the amount of matter twice over, from two separate branches of physics, and the amount is hundreds of millions of times more than an annihilation with no residue would have left. The residue includes every baryon of the stars, the planets and your own body.

One Sign Everywhere

If the excess of matter was left at the start, a question of place follows: could a far region of the sky be made of antimatter? Picture a can of paint stirred well before the first wall is painted. However many rooms the painter covers, and in whatever order, every wall shows the same shade, because the shade was mixed in before the painting began.

The residue of matter was set in the same way as the shade of the paint. At the start of our history the world departed from perfect evenness in one manner only. Where a place held a little more light, the place held a little more of every other ingredient, in the same proportion. So each place has the same number of baryons for each particle of light. Every change since the start has kept the residue. "A number that is the same everywhere has one sign everywhere", so nowhere in the universe whose light has reached us do antibaryons outnumber baryons.

Astronomers have measured the sky in two separate ways, and both ways agree with one sign everywhere. First, the oldest light has warm and cool patches, and the patches show the ingredients rising and falling together. Ingredients that rise and fall together were mixed before anything moved them, like the paint stirred before the first wall. Second, annihila-

tion gives off gamma rays, the light of very high energy that Chapter 15 met, and gamma rays reach us from across the sky in far smaller numbers than borders between regions of matter and antimatter would produce. In 1998 a team of physicists analyzed the borders of a universe divided into regions of matter and antimatter. The members of the team were Andrew Cohen, Alvaro De Rújula and Sheldon Glashow. Cohen, De Rújula and Glashow concluded that "a matter-antimatter symmetric universe is empirically excluded". The authors are confident that our cluster of galaxies is matter, while on my account the same answer is true for the whole universe whose light has reached us, because the residue was mixed in from the start.

Does Antimatter Fall Up?

The authors end their chapter on antimatter with a hope. If antimatter fell upward, antimatter might give us flying cars and boots that walk on air. In that case, the authors write, "we might want to change the name of this stuff from 'antimatter' to 'awesome matter'" (*We Have No Idea*, ch. 12, "Curious Matters"). When the authors wrote, no one had weighed antimatter.

Chapter 7 identified gravity with the arena: space and time together, two of the three settings of every finding. The arena takes part in everything that is found, because the arena is the space and the time of everything that is found: a thing neutral to the arena would be found nowhere. So gravity has no neutral objects: gravity acts on energy, and energy is positive for matter and antimatter alike. Antimatter falls as matter does.

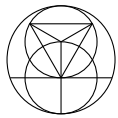
Physicists have now weighed antimatter, as Chapter 7 told. The atoms of antihydrogen fell downward, toward the Earth, at a rate in agreement with the rate for ordinary matter, and the ALPHA-g team ruled out a push upward of the size of ordinary gravity. We now have two answers,

one reasoned from the arena and one measured in the trap, and the two answers agree: antimatter falls as matter does. Whoever builds the flying cars will have to find another engine.

> **The short answer**
>
> We are made of matter because the beginning of our epoch left an excess of matter, a residue kept by every change since, with one sign everywhere, while antimatter exists because comparing makes every state together with its mirror.

The short answer splits the authors' mystery in two: the structure of the kinds fixes the mirror, and history sets the amount, as the alphabet fixes the letters of a library's books and the library's history sets the library's holdings. The history in the answer goes back to one moment: the beginning of our epoch, which left the residue.

What was the beginning of our epoch, the beginning that left the residue: what happened during the Big Bang?



Chapter Twenty

What Happened During the Big Bang?

In which a faint noise from every direction turns out to be the oldest light, the first moment turns out to be a limit our history draws as a point, and the sameness, flatness and first ripples of the sky come from the turn

What happened during the Big Bang?

What this chapter uses

A *comparison* is the act of finding whether two things are the same or different in some respect, and every measurement is a comparison; a *finding* is the outcome of one comparison, laid down as a record; a *comparer* is whatever makes a comparison, whether or not the comparer has a mind (Chapter 1).

The *content* of a finding is what the finding finds, as the warmth of your coffee; the *context* is where the content is found, and the context has three sides, the three settings of space, time and possibility (Chapter 1).

Continuous: nothing is sudden, as along a ramp; *discontinuous*: something is sudden, as at the edge of a step; *symmetric*: what is found stays the same across a change of setting, as each step of a staircase is like every other; *asymmetric*: different everywhere, as the height along a ramp is (Chapter 1).

Three things in nature do the bending: gravitation bends space, the cosmological constant bends time, and the dark matter bends possibility (Chapter 1).

A *gyration* is a lasting vibration of the six small dimensions of possibility, and the unit of which the dark matter is made (Chapter 2).

The world has ten dimensions, one of time, three of space and six of possibility, and the six are the range of what a finding could be, present at every place and never a place themselves (Chapter 11).

Bell Laboratories had a horn-shaped radio antenna, the twenty-foot horn-reflector, at its Crawford Hill Laboratory in Holmdel, New Jersey. The horn had been built to receive signals bounced from the Echo satellite, and in 1963, when the satellite work no longer needed the horn, two radio astronomers of the laboratory, Arno Penzias and Robert Wilson, turned the horn to measuring the sky. Penzias and Wilson tuned the antenna to radio waves about seven centimeters long and measured the an-

tenna's noise while the antenna pointed straight up. They subtracted every known source of noise from the total. The noise left over was not zero. When the noise is counted as a temperature above absolute zero, the coldest cold there is, the antenna's noise came out about three and a half degrees higher than Penzias and Wilson expected.

Penzias and Wilson hunted for the cause of the extra noise. A pair of pigeons had roosted in the small end of the horn, where the horn enters the warm cab (the small room that held the receiver). The pigeons had covered the inside of the horn, in Wilson's words, with "a white material familiar to all city dwellers". In the spring of 1965 Penzias and Wilson thoroughly cleaned the horn and put aluminum tape over the riveted joints of the horn. The noise fell only a little. Penzias and Wilson followed the excess noise from July 1964 to April 1965. The excess noise stayed the same through the seasons and in every direction the antenna faced. Penzias and Wilson wrote in the *Astrophysical Journal*, in their paper of 1965, that the excess noise "is, within the limits of our observations, isotropic, unpolarized, and free from seasonal variations". *Isotropic* means the same in every direction. Penzias mentioned the unexplained noise to the radio astronomer Bernard Burke of the Massachusetts Institute of Technology while the two talked about other matters. Penzias then called the physicist Robert Dicke at Princeton. Dicke sent Penzias a copy of a paper not yet published by Dicke's colleague James Peebles. The Princeton group gave the explanation in a companion letter in the issue of the *Astrophysical Journal* that carried the paper of Penzias and Wilson: the noise was a glow of light left over from a hot, dense early universe. The letter's authors were Robert Dicke, James Peebles, Peter Roll and David Wilkinson.

The noise was the oldest light: the glow set free early in our epoch (our era of the world), and stretched since into faint microwaves. In Chapter 1 we met the oldest light as the authors' baby picture of the universe. Penzias and Wilson learned first that the oldest light is the same from every direction of the sky, and any answer to what happened during the Big Bang must explain that sameness first.

From Cham and Whiteson's pages

What Cham and Whiteson Showed

Jorge Cham and Daniel Whiteson begin with the equations of Einstein's theory of gravity. When the expansion of the universe is run backward in Einstein's equations, everything draws together into a single point of zero volume and endless density, which Cham and Whiteson call a *singularity*. The authors do not trust the singularity. Einstein built his theory before physicists understood the quantum. Quantum effects should rule at the densities of the earliest moments. So Cham and Whiteson conclude that "the picture of the Big Bang starting with a singularity is probably not accurate" (*We Have No Idea*, ch. 14, "Big Mystery #1: Quantum Gravity"). The authors add that no one can calculate what happened in the earliest moments without a quantum theory of gravity.

Then the authors set out two more mysteries. The first mystery is that the universe is too big: in every direction we see no end of stars. Picture the universe as a small blob whose matter flew outward through a fixed space: by now we would see the blob's edge. The second mystery is that the universe is too smooth: the oldest light arrives at one temperature, about two and seven tenths degrees above absolute zero, from opposite sides of the sky. The light from opposite sides comes from places that had no time to trade heat. The authors answer both mysteries with *inflation*: a brief phase, early in the history of the universe, in which space itself grew enormously faster than light could travel across the growing space. On the authors' answer, inflation stretched one small region, whose temperature had already evened out, to far beyond everything we can see. Of inflation the authors write, "the crazy thing is that it is probably true" (*We Have No Idea*, ch. 14, "An Inflated Answer").

The authors give one further reason to like inflation. Cham and Whiteson report in their chapter on space that space is flat (lines that start out parallel stay parallel) to within 0.4 percent. They add that "as far as we know, the fact that we live in a flat universe is a gigantic cosmic-level coincidence" (*We Have No Idea*, ch. 7, "Straight Thinking about Bent Space"). They write that inflation "makes this less strange" (ch. 14, "Are We Done?"). Last, the authors ask what caused inflation. They report one idea that physicists have: an unstable new substance with negative pressure, which pushed space apart and later turned into ordinary matter. Of the unstable substance the authors write, "we have no idea what this weird negative pressure stuff is" (ch. 14, "What Caused Inflation?").

In all, the authors set out three mysteries and one remedy. The three mysteries are a first point that the equations draw and that is probably wrong, a universe too big, and a universe too smooth. Beside the three mysteries the authors set the flatness of space, which they call a coincidence. The one remedy is inflation, which answers the universe too big and the universe too smooth, and the inflation is driven by a substance that no one has identified. On the first mystery, the first point that the equations draw, I come to the authors' conclusion from separate ground. On the other two mysteries, and on the flatness of space, I give a different answer, with no long inflation. I also give the reason the answers differ.

A Limit Drawn as a First Moment

Picture a walker who crosses a room toward a wall and at each step covers half the distance that remains. The first step covers half the room, the next a quarter, the next an eighth. The walker comes as close to the wall as anyone likes and never reaches the wall. Now suppose someone knows the walk only from the footprints and maps the walk backward, from the last footprint to the first. The footprints crowd closer and closer together near the wall. The mapmaker draws the wall as the line where

the walk began. A *limit* is a value that something approaches more and more closely and never reaches. The wall is a limit of the walk. The mapmaker takes that limit for the beginning of the walk.

Our knowledge of the past is made the way the walker's map is made. We know the past only by the marks the past leaves in the present: the light now arriving from distant galaxies, the oldest light, the amounts of the light elements, and the records of every instrument. From the marks we piece together one history, the one history that the present requires. I call that history the *reconstructed history*: the history built from what arrives now, which exists as a map or a record exists. When we read the reconstructed history forward in time, the history shows the familiar expansion, with density falling and volume growing. When we trace the reconstructed history backward, density rises, volume shrinks and *curvature* rises, and the history runs toward a limit. Curvature is the amount by which space and time are bent.

A map shows everything on the map as a thing at a definite place and time. A map can say "this happened, then, there". A map has no way to say "this was a limit that nothing reached". The reconstructed history is a map too. Like every map, the reconstructed history has no way to mark a limit that nothing reached. So when we trace the reconstructed history backward to the limit, the history shows the limit as a point in time: a first moment. I call the limit *the turn*: the limit at which an epoch begins. When we trace our history back, the history approaches the turn and shows the turn as a first moment. I identify the Big Bang of our epoch with the turn as the turn appears in our reconstructed history: the time zero of the equations of cosmology marks where the history, traced back, comes to the limit that the history cannot pass. I make the identification of the Big Bang with the turn.

Was there a Big Bang, then? Yes: there was a Big Bang, as the Big Bang appears in our reconstructed history. The Big Bang is, as structure, at the beginning of the one history your present requires, as surely as the wall is at the start of the walker's map. What lies at the beginning of our history is a limit. No comparison registers the limit as an event. Someone could

know the turn as an event only by a comparison of a before with an after, made across the turn. Every comparison is made on one side of the turn: our history approaches the turn and does not reach the turn, and nothing that approaches the turn from the other side reaches the turn either.

Where One Description Ends

On the authors' first mystery, I agree with the authors: the single point of zero volume and endless density is what the equations draw, and the single point is not what happened. I come to that agreement on a ground of my own.

A map of a country has an edge. At the edge of the map, the map ends and the land goes on. If you ask what the map shows beyond its edge, you ask the map for something that the map does not hold.

Einstein's general relativity is the smooth description of space and time. As Chapter 8 found, general relativity has its edge at the Planck scale. A body's gravitational size is half the size of a black hole of the body's mass, and the body's quantum size is the length within which quantum theory will not let the body be pinned down. When we trace the reconstructed history back toward the turn, the curvature rises until the curvature reaches the Planck curvature. The Planck curvature is the bending at which the quantum corrections to the smooth description grow as large as the effects they correct, so the smooth description reaches the edge of its domain there. The singularity is what the smooth equations produce when someone carries the equations past the Planck curvature. At the singularity a description, the smooth one, reaches the edge of its domain; physics itself does not break down. Beyond the edge of the smooth description, the structure of comparison (what every comparison must contain) remains in force.

The authors look to a quantum theory of gravity for what happened beyond the edge of the smooth description. I find that no description takes over beyond that edge. At the Planck scale both the smooth description and the stepwise description are needed. As Chapter 8 showed, if one

description were both smooth and stepwise at the Planck scale, that description would carry a pairing that the Incommensuration Theorem forbids. The single description would join either smoothness with exact sameness, which is continuity with symmetry, or differences from place to place with steps, which is asymmetry with discontinuity. So the smooth description and the stepwise description each come to the end of their domains at the Planck scale. No third description replaces the two. We therefore make a category error with the question "what is the geometry at the first moment?", in the sense that Chapter 8 gave to a category error: a concept applied where the concept does not belong. When someone asks for the geometry at the first moment, that person asks the smooth description for the smooth shape of a limit that lies past the edge of the smooth description. The authors and my account agree that the singular point is not what happened, and differ on what lies past the singular point.

What the Turn Passes On

Something approaches the turn from the other side, the side away from our history. In Chapter 21 we follow a fall into a black hole to the end of the black hole's inside. Chapter 22 shows that the ends of the black holes of the epoch before ours lie on the other side of our turn. The rest of this chapter's answer depends on two facts about the turn.

The first fact is that the *form of the content* passes the turn, and the form of the content is which alternatives the matter and light of the epoch before ours had taken. In the epoch before ours, matter and light were carried toward the turn inside the black holes of that epoch, and the matter and light do not cease at the end of what lies inside those black holes. The form of the old matter and light passes the turn. No total of the old matter and light passes with the form. The second fact is that the geometry does not pass the turn. As Chapter 2 showed, the large dimensions of space and time took their shape together with the six small dimensions of possibility, at the beginning of our epoch and only there. So the large world of space and time re-forms at the turn. The geometry of the large world be-

gins as itself. The new geometry inherits no record, no length and no mark that sets one of its places apart from another. So the whole new world comes from *one origin*: no comparison made inside the new world can find separate beginnings for any two of its parts. The answers to the authors' other mysteries follow from the two facts: the form of the content passes the turn, and the geometry does not.

Why the Sky Is the Same Everywhere

When two towns far apart were founded from one place, the towns can share an accent though their people never spoke to each other.

The sky is like the two towns. Look at the oldest light in one direction, then face the opposite direction and look again. In the standard history that most astronomers use, a signal had no time to pass between regions of the sky more than about a degree apart before the oldest light went free. A degree is about twice the width of the full Moon. Yet Penzias and Wilson found the regions on opposite sides of the sky alike. Every measurement since has shown the regions alike to about one part in a hundred thousand. How did regions that never traded a signal come to agree so closely? Astronomers call that question the *horizon problem*. The authors answer the horizon problem with inflation, which stretched one small region that had already evened out.

I answer the horizon problem from the turn. Two regions of the sky are alike, though no signal has ever connected them, because both regions come from one origin, so no signal ever had to pass between the two regions. The new geometry inherits no unevenness. So the new world begins alike everywhere, up to small departures. The Incommensuration Theorem requires the small departures, because perfect sameness in every direction and at every place would make symmetry and continuity perfect together, and the theorem states that symmetry and continuity cannot both be perfect together. So the new world begins even, and not perfectly even.

I answer the authors' mystery that the universe is too big from the same beginning at the turn. The mystery of a universe too big comes from the picture of a small blob whose matter flies outward through a space that stays fixed, so that our widening view should one day overtake the edge of the blob. At the turn the large world itself re-forms, space and all. No blob sets out into a space already there. The expansion of the new world is the stretching of its own space, which carries the galaxies apart. I now apply the premise that the new geometry inherits no unevenness to the authors' picture of a blob. The new world begins alike everywhere, so the matter of the new world has no outer edge, because an edge where the stars run out would be the largest unevenness of all. Chapter 23 is about how far space extends, and Chapter 23 shows that space is flat and without end, as far as any comparison made from inside can tell.

Why Space Is Flat

An ant walking on a marble finds the curve of the marble within a few steps. Put an ant on a ball the size of the Earth, and the ant walks for days and finds the ground flat. The marble and the ball are both curved, and one length tells the two surfaces apart: the radius.

A bend of space as a whole is set by one length, its *radius of curvature*, just as the curve of a ball is set by the ball's radius. Measurements show that space on the largest scales is flat. In the standard history, any bend of space rules a share of the expansion. The share that the bend rules grows as the universe grows. So a slight bend at the beginning would rule the expansion today, and because space is flat today, the beginning must have been flat to an extraordinary precision. Astronomers call the question of why the beginning was so flat the *flatness problem*, and the flatness problem is the coincidence that the authors name.

I answer the flatness problem by asking which lengths the beginning holds. In Einstein's equations for a universe the same everywhere, the bend of space as a whole is one number that the equations leave free. The starting state of the history sets the number for the bend once, and after-

ward the equations carry the number unchanged, while the share of the expansion that the bend rules grows. For our epoch the starting state is set at the turn. The starting state inherits no length from the epoch before. The starting state holds one length of its own: the length of the turn, which is about the Planck length. We met the Planck length in Chapter 8: the Planck length is about a hundred billion billion times smaller than a proton. Beside the length of the turn, the starting state holds only ordinary numbers, such as two or three. The only very large numbers in my account are counts. Every count of the old epoch ends with the world it counted. The cosmological constant is the one fixed term of Einstein's equations, which we met in Chapter 3. The cosmological constant sets one other length, far larger. The length that the cosmological constant sets belongs to the equations themselves and not to the state that the turn sets.

So the radius of curvature of our epoch is either about the Planck length, or our epoch has no radius of curvature at all. A Planck time is the time light takes to cross a Planck length. A radius of one Planck length would do one of two things: make the new epoch fall back on itself within a few Planck times, or leave the new epoch's expansion ruled by the bend of space itself. In either case the new epoch would not build the stars, galaxies and black holes from which the next epoch comes, as Chapter 22 shows. Our epoch did build stars, galaxies and black holes, so our epoch has no radius of curvature: on the largest scales our epoch is flat. Our epoch is curved only by its own small departures from evenness, at the size of those departures, about one part in a hundred thousand. The sky is alike and space is flat for one reason: the new geometry inherits no shape and no length from the epoch before. The flatness that the authors call a coincidence is the plain consequence of a beginning with no length to bend space with.

The First Ripples

Climb the stone stairs of an old church and look at the steps. Each step is worn into a shallow curve, lowest where most feet have fallen over hundreds of years. No single footstep can be picked out in the worn curve. Yet no footstep has been wiped out of the curve. Each footstep wore its own small share. The curve is all the footsteps together, one shape on one stone.

The sky has a shape like the worn step. In 1992 the Cosmic Background Explorer satellite found that the oldest light is warmer in some directions and cooler in others by about one part in a hundred thousand. The differences of warmth trace slight differences of density in the young universe. The galaxies and their stars later grew from the differences of density. The slight differences of density are the *first ripples*: the faint departures from evenness with which an epoch begins. The authors explain the first ripples as quantum chance, stretched by inflation: "random rolls of nature's dice at the quantum level were blown up by the rapid expansion of space" (*We Have No Idea*, ch. 15, "How Did It Get This Way?").

I give the first ripples another origin. In the epoch before ours, everything that fell into the black holes had taken some alternatives and not others. The form of the content is which alternatives the fallen matter and light took, and the form of the content is what passes the turn. I identify the first ripples with the form of the content, carried from one side of the turn to the other: the distinctions of the old epoch, averaged and not erased. The worn step shows what "averaged and not erased" means. Averaged means that no single history of the old epoch can be picked out, as no single footstep can be picked out in the stone. Not erased means that every history of the old epoch has its share in the shape, as every footstep has its share in the curve.

On the lengths we observe, the first ripples are the carried form of the content. Empty space adds almost nothing to the first ripples. On the usual story the ripples come from empty space, which is never perfectly still. The restless trembling of empty space carries ripples of its own. Inflation

stretches the ripples of empty space out to the lengths we see. In the history that I reconstruct, nothing stretches the trembling of empty space. The computed result: on the lengths we observe, the trembling of empty space near the turn falls short of the observed ripples by more than forty-two powers of ten.

The pattern of the ripples follows from two things: the identification of the first ripples with the form of the content, and the one origin of the new world. Picture a quilt sewn from scraps cut by many hands. From across a room, the quilt fades to an even color, because the patterns of the separate scraps cancel. A cloth woven on one loom keeps its design as strong across the whole cloth as across a hand's breadth. A world assembled from independent pieces would leave ripples that fade on the largest lengths, like the quilt. No one can tell, by any comparison made in our epoch, from which black hole of the epoch before any part of our epoch's content came, so the form of the content passes the turn as one form, linked across the whole new sky. So the sky's ripples keep nearly the same strength at every length, like the cloth. Measurement agrees. Astronomers measure how the strength changes with length by a number called the *spectral index*, which is exactly one for a pattern the same at every length. The final results of the Planck satellite put the spectral index at about ninety-six and a half hundredths: close to one, and a little below. I fix the kind of the pattern, nearly the same strength at every length, and I take the strength of the pattern, and the slight lean of the pattern toward the longer lengths, from measurements of the sky.

The first ripples are ripples of density, and one more thing follows from that fact. Children standing still on a trampoline make dips in the sheet, deeper under a heavier child and shallower under a lighter one. The still children make no waves. A wave running across the sheet needs a pull harder in one direction than in another. Matter and light close to balance press equally in every direction, as the air in a balloon presses on every part of its skin. Balance is the settled state, met in Chapter 19, in which every reaction runs as often forward as backward. So in the shape of space itself, the first ripples are dips of the kind the still children make

in the trampoline. Waves of space, which physicists call gravitational waves, arise from the dips only through ripples acting on ripples, and far too weakly to measure.

Astronomers have searched for waves of space from the beginning in recent years. In March 2014 the BICEP2 telescope team at the South Pole reported a faint twisting pattern in the *polarization* of the oldest light (the direction in which the waves of the light vibrate). The team read the pattern as waves of space left by inflation. In 2015 the BICEP2 and Keck Array teams analyzed the data jointly with the Planck team, and together the teams found strong evidence that the pattern came from dust, whose own glow is polarized, and no significant evidence for waves of space. The authors note the episode in their own terms: the claims "were later revealed to be in error" (*We Have No Idea*, ch. 14, footnote 104). We now know from the combined measurements of BICEP and Planck, published in 2022, that any waves of space from the beginning carry less than about three hundredths of the power of the first ripples, and no such wave has been found.

No Long Inflation

The physicist Alan Guth proposed inflation in 1981. Inflation is the leading account of the early universe among cosmologists. Guth proposed inflation to answer two puzzles: the sameness of the sky and the flatness of space. Both puzzles have their answers without inflation: the sameness of the sky comes from one origin, and the flatness of space comes from the starting state that the turn sets. The account therefore needs no inflationary phase for the horizon and flatness problems.

If the first ripples are the carried form of the content, one kind of inflation also cannot have happened. The *earliest horizon* is the greatest distance that a signal could have crossed since the turn, in the first moments of our history. A long inflation is an inflation long enough to stretch the lengths we observe today from inside the earliest horizon to beyond the earliest horizon. In a long inflation, the ripples on the lengths we observe today

would be the trembling of the inflation's own empty space. The ripples on the lengths we observe today are the carried form. Empty space adds almost nothing to the carried form. So, if the first ripples are the carried form, a long inflation cannot have happened. The exclusion applies to the long inflation: the kind of inflation that would have made the ripples we see.

I reach the same exclusion of the long inflation by a second route, from separate ground: the dark matter. As Chapter 2 showed, the dark matter is made of gyrations: lasting vibrations of the six small dimensions of possibility, each with a mass of about a Planck mass, made only at the turn. A plasma is a gas so hot that its atoms are broken into charged pieces, as Chapter 2 described, and a hot plasma makes pairs of anything that weighs, through gravity alone. A temperature can be stated as the typical energy of one particle of the heat. Chapter 6 showed that mass and energy are exchangeable at a fixed rate, so a temperature can be set beside a mass. Suppose the plasma of our epoch formed at once, at the turn. If that plasma had ever been hotter than about one thirtieth of a gyration's mass, the plasma would have made more dark matter than is measured.

Now suppose inflation had made the observed ripples. An inflation stretches space so much that whatever was made before the inflation is spread too thin to matter. Physicists use inflation in just this way to answer an older puzzle: theories uniting the forces predict certain particles in too great a number, and inflation spreads those particles too thin to matter. So in a history with inflation, the gyrations made at the turn would have been spread too thin, and the measured dark matter would have had to be made after the inflation, by the plasma that the end of the inflation heated. An inflation also makes waves of space, stronger the more energy the inflation's empty space holds, so the measured bound on waves of space limits the energy of the inflation's empty space. The same measured bound limits the heat that the end of the inflation could hand on to the plasma, and so keeps the plasma far cooler than one thirtieth of a gyration's mass. So gyrations of about a Planck mass could not have been made after the inflation in the measured amount. "So the dark mat-

ter, too, requires that the observed ripples were not made by inflation". I reach one result from two separate grounds, the pattern of the ripples and the amount of the dark matter: a long inflation cannot have happened.

The authors ask last what caused inflation, and on my account the question has its answer too: no long inflation happened, and nothing in the account could drive a long inflation. In the usual version, the authors' unstable substance with negative pressure is a field: something spread through all of space, whose energy pushes space apart. While the field drives inflation, the field drifts slowly down a long, gentle slope of its own energy, as a sled crawls down a hill that is almost level (the height of the hill stands for the energy of the field). The field can crawl so slowly only if the field is held loosely. Physicists state how stiffly a field is held as a mass (a field held stiffly is heavy), so the field must be very light beside the rate of the expansion that the field drives. The six small dimensions of possibility contain no loosely held field. Only two features of the six small dimensions could change: their size and the ratio of their two radii. Each of the two features could vary from place to place in the large world, so each feature is a field, and both fields are held stiffly, like a ball at the bottom of a steep bowl. Each of the two fields weighs more than two Planck masses, far too heavy to drive a slow inflation. My account has no field that rolls slowly like the sled. At the turn, the sameness, the flatness and the size of the world all have their answers.

From the first ripples onward, the authors and I tell one story. Gravity grew the ripples into galaxies, and the dark matter helped. As Chapter 2 showed, the gyrations clump exactly as the cold dark matter of the standard picture of cosmology does. The motion of the gyrations slows as the universe expands. The gyrations move far too slowly to smooth out the clumps that gravity makes. For matter held together by its own gravity, clumping raises the entropy. Entropy is the count of arrangements that we met in Chapter 13. The even beginning left that count room to rise.

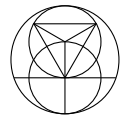
What We Now Know

Penzias and Wilson heard a noise that was the same in every direction. We now know what Penzias and Wilson heard: the light of a world that began alike everywhere, because the world came from one origin. Our world began flat, because its beginning held no length to bend space with. Our world also carried faint ripples, the averaged form of the epoch before. And we know what "the beginning" names: a limit, which the reconstructed history shows as a first moment. At the limit one description reaches its edge, and the structure of comparison goes on.

> **The short answer**
>
> The Big Bang is the turn as our history shows it: a limit drawn as a first moment. Our world began even and flat, with no long inflation, and its first ripples carry the form of the epoch before.

The question of this book is what the universe is made of when every answer is found from inside the universe. Even the beginning is found from inside. The beginning is a limit with two sides, and our history is one of the two sides. We now walk toward the other side of the turn, by way of the black holes.

The smooth equations draw the same endless density at the end of every black hole: what happens if I fall into one?



Chapter Twenty-One

What Happens If I Fall into a Black Hole?

In which one fall is timed by two clocks, the end inside a black hole turns out to be a moment, and every black hole turns out to end at the same end

What happens if I get sucked into a black hole?

What this chapter uses

A *comparison* is the act of finding whether two things are the same or different in some respect, and every measurement is a comparison; a *finding* is the outcome of one comparison, laid down as a record; a *comparer* is whatever makes a comparison, whether or not the comparer has a mind (Chapter 1).

The *content* of a finding is what the finding finds, as the warmth of your coffee; the *context* is where the content is found, and the context has three sides, the three settings of space, time and possibility (Chapter 1).

Three things in nature do the bending: gravitation bends space, the cosmological constant bends time, and the dark matter bends possibility (Chapter 1).

The world has ten dimensions, one of time, three of space and six of possibility, and the six are the range of what a finding could be, present at every place and never a place themselves (Chapter 11).

Every comparison goes one way, from what could be found, to the finding, to its record, and so time goes forward (Chapter 13).

The *turn* is the limit at which an epoch begins: our history, traced back, approaches the limit and shows the limit as a first moment; an *epoch* is one era of the world (Chapter 20).

In 1939 J. Robert Oppenheimer and Hartland Snyder followed a dying star on paper. Oppenheimer and Snyder were physicists at the University of California, Berkeley. The journal *Physical Review* received Oppenheimer and Snyder's short paper about the star on 10 July 1939. The first sentence of the paper stated the problem: "When all thermonuclear sources of energy are exhausted a sufficiently heavy star will collapse". Oppenheimer and Snyder took a star heavy enough to collapse and followed its fall inward, and they left out the pressure inside the star so that Einstein's equations of gravity could be solved exactly. Oppenheimer and Snyder's calcu-

lation gave two answers about one collapse. For an observer riding inward with the star's own matter, Oppenheimer and Snyder wrote, the time of collapse "is finite and may be quite short". For the star that Oppenheimer and Snyder took as their example, the riding observer's time of collapse is about a day. For an observer far away, the same star shrinks toward a definite radius and never quite reaches that radius. From the distant observer's point of view, the paper says, the star takes "an infinite time" to shrink far enough to be cut off from the outside. So one star is timed by two clocks, the rider's and the distant observer's. The two clocks give two answers, and the paper shows that both answers are right. We follow the whole fall into a black hole, from the edge of the hole to the end inside the hole, by the rider's clock and the distant observer's clock.

The Fall as Cham and Whiteson Tell It

Jorge Cham and Daniel Whiteson give a whole chapter to the question of falling into a black hole, because their listeners and readers ask the question so often. Their chapter has the title "What Happens If I Get Sucked into a Black Hole?" (*Frequently Asked Questions About the Universe*, ch. 5). The authors answer the question as a trip, step by step. They set the trip in a back garden: you spread a picnic blanket beside a black hole, and you are invited to jump in.

The first step of the authors' trip is about being torn apart. Gravity pulls harder on the near end of a falling body than on the far end, so gravity stretches the body. The authors show the same uneven pull at home: when you stand on the Earth, your feet are nearer to the Earth than your head is, so the Earth pulls your feet slightly harder than your head. Many books say that the stretching by gravity would shred you before you ever reached a black hole. The authors show that the size of the hole determines whether the stretching tears you apart before you reach the hole's edge. As the mass of a hole grows, the hole itself grows faster than the distance at which the stretching tears a person apart. So a small black hole

tears you apart well outside its edge, and a large black hole lets you cross its edge whole: "It's totally possible to enter a black hole" (*Frequently Asked Questions About the Universe*, ch. 5, "Getting Closer").

On the way in, the authors point out the hole's *shadow*: the black circle that anyone looking at a black hole sees. The shadow is larger than the hole itself, because the hole also pulls in light that passes close by (*Frequently Asked Questions About the Universe*, ch. 5, "The Shadow of the Black Hole").

The second step of the authors' trip is about your friends. As you near the edge, the friends who stayed behind see your clock run slower and slower, and they see your image grow faint and red and seem to freeze at the edge. Your friends never see you cross the edge, and the authors give the reason: "because it literally never happens for them" (*Frequently Asked Questions About the Universe*, ch. 5, "What Your Friends Will See"). For you, the authors write, time runs at its ordinary pace, and you cross. The edge itself, they write, has no wall and no fence: the edge is only the place from which there is no way back. Inside the edge, they write, space has become one-way, as time is one-way outside: every path leads inward.

The third step of the authors' trip is the inside of the hole, and at the third step the authors stop. They write: "The truth is that nobody knows" (*Frequently Asked Questions About the Universe*, ch. 5, "What's Inside?"). Cham and Whiteson write that general relativity, Einstein's theory of gravity, has been right about everything outside black holes, but that general relativity breaks down at the smallest scales, where quantum effects cannot be ignored. If general relativity holds inside the hole, they say, you fall faster and faster toward the center and are shredded on the way. If general relativity does not hold just inside the edge, the authors write, they are free to speculate. They name two possibilities: a new baby universe waiting inside, or a tunnel to a white hole, a place that things can leave and never enter. Chapter 17 described a white hole as a region that would throw out what a black hole takes in. In *We Have No Idea* (ch. 6, "Let's Get Realistic and Visit a Black Hole") the authors say why the inside of a black hole matters so much to physicists. In general relativity,

every black hole has at its center a point where matter is so dense that the pull of gravity becomes infinite. In quantum mechanics nothing can be held to a single point. So, the authors conclude, one of the two theories must break down at the point at the center of a black hole.

I agree with the first two steps of the authors' trip, that a large black hole lets you cross its edge whole and that your friends never see you cross, but my reasons for both steps follow from my own ground: what every act of knowing must contain. At the third step, the inside of the hole, where the authors stop, my account has a definite answer: what the inside of a black hole holds, how the inside ends, and why every black hole ends at one and the same end.

The Edge You Cannot Climb Back Over

Chapter 2 described a black hole in one line: a region in which matter is packed so densely that nothing that falls in, not even light, comes back out. We begin with how a black hole forms. A star is a balance: gravity pulls the star's matter inward, and the heat of the star's burning pushes the matter outward. When the fuel runs out, the outward push fails, and a heavy enough star collapses without limit, as Oppenheimer and Snyder found. When enough matter is squeezed into a small enough region, space and time around the matter bend so steeply that nothing can climb back out, not even light, and that squeezed region is a black hole. The edge of a black hole is easiest to see in a picture.

At every place and moment, picture the small cone of directions along which a signal sent from that place and moment can travel. Chapter 15 called the cone the light cone. Picture the cones drawn as Chapter 15 drew them, with time running up the page and the distance from the hole running across the page. Far from a black hole the cones stand upright, with as much room to move outward as inward. Nearer the hole the cones lean toward the center. At a certain distance the outer edge of each cone points straight up the page, along time alone. So at that distance even light aimed outward only holds its place. The surface at that distance is the *horizon*

(the authors' event horizon): the surface from inside which no signal can reach the outside. For a black hole of the mass of the Sun, the horizon has a radius of about three kilometers. For the black hole at the center of our Galaxy, about four million times the mass of the Sun, the horizon has a radius of about twelve million kilometers.

The horizon is a feature of the shape of space and time, and no material lies at the horizon. The authors find nothing at the edge, and I also say that nothing is at the edge. A falling body meets nothing special at the horizon, because everything falls alike. Chapter 7 showed why everything falls alike: gravity is the arena itself, the space and time in which every finding is made. Everything inside the horizon is the black hole's *interior*. Everything outside the horizon is the hole's outside world, the world of the hole's epoch.

My account has a plain measure for the stretching that the authors describe. Take any depth inside the hole, measured by the distance from the center. At that depth, a falling body feels the same stretch that the body would feel just outside a ball holding the hole's whole mass, with the ball's surface at that same distance from the center. So every depth has what I call an *equivalent density*: the density at which the hole's mass would fill a sphere whose radius is the distance of that depth from the center. When the radius is halved, the same mass fills an eighth of the volume, so the equivalent density rises eightfold. A large hole has a large horizon, and so the equivalent density at the horizon of a large hole is low. At the horizon of a hole of the mass of the Sun, the equivalent density is already beyond the density at which protons and neutrons dissolve into their quarks. In the hole at the center of our Galaxy, protons and neutrons would dissolve only at about a ten-thousandth of the radius of the horizon, deep inside. So a faller, someone falling in, crosses the horizon of the hole at the center of our Galaxy and feels little. The authors gave the result that a faller crosses the horizon of a large hole whole, and on my account that result follows from separate ground: the low equivalent density at the horizon of a large hole.

Two Clocks, One Structure

Now return to the two clocks of Oppenheimer and Snyder's paper of 1939, the clock that rides in with the star and the clock far away. Give the two clocks to two people: you, falling, and a friend who watches from far away.

By the friend's clock, you approach the horizon without end. Your light reaches the friend more and more slowly and more and more reddened, and the friend never sees you cross. By the friend's clock the crossing would take an infinite time, and no signal from inside the horizon ever reaches the outside at all. So the friend can never see anything that happens to you after the crossing.

Chapter 8 described a faint glow by which every black hole slowly gives up its mass. Does the faint glow change what the friend sees? A hole of the mass of the Sun would take about ten to the sixty-seven years to glow away. The world outside the hole empties far sooner, in a hundred billion to a trillion years: the matter of the outside world ends inside black holes, or is carried out of reach by the expansion of space, or thins out as light. So every black hole that astronomers observe keeps its horizon for as long as its outside world has anything in it, and for all of that time the friend never sees you cross.

Now follow yourself across the horizon. You cross the horizon at a definite moment on your own watch. The time on your own watch is what Chapter 12 called *proper time*: the time a clock shows as the clock is carried along its own path through space and time. In proper time, the end of your path inside the hole is near. For a black hole of the mass of the Sun, the end comes at most about fifteen millionths of a second after the crossing. For the hole at the center of our Galaxy, the fall from the horizon to the end takes at most about a minute. The longest time belongs to a faller who starts from rest at the horizon. Every other path reaches the end sooner, and every path inside the horizon reaches the end. A minute is enough to read a page of this book, and in that minute the only place a faller can reach is the end.

Why is there an end that every path reaches? Inside the horizon of a black hole that does not rotate, the direction toward the center is the direction of time. General relativity has the standard result that the center lies in the future, and the leaning cones of the picture show the result: inside the horizon, every direction a cone allows leads inward. So inside the horizon, moving toward the center is not a choice of direction, just as moving toward tomorrow is not a choice. The authors say that inside the horizon space becomes one-way, inward, and I also say that space inside the horizon is one-way and give the reason: every path inside leads to the center because every path leads into the future.

So the end inside a black hole is a moment: the future end of every path inside the horizon, ahead of everything that falls in. Most popular pictures put a point at the center of a black hole, sitting there now and waiting. My account has the moment where the popular pictures have the point.

Once the end is taken as a moment, your account of the fall agrees with the friend's account. Each path inside the horizon goes on for every moment short of the end and for no moment beyond the end, so the end is a limit that the path approaches and does not reach. The end lies after every moment of the interior. No signal from the end reaches any moment of the outside world, so no comparer outside can place the end before, at or after any moment of the outside world's own time. For the outside world, the end inside a black hole has not happened. The end never happens at any time that a clock outside can show. For you, falling, the end is the end of time on your own watch: the end comes after a finite time, and it comes as a limit, with no last tick on your watch before the end. Both statements, the friend's and yours, follow from one fact about where the end lies: after every moment of the interior, and before, at or after no moment of the outside world. Time itself goes on: the end belongs to the falling clock alone and is no moment of any clock outside. Chapter 30 shows that no clock anywhere comes to a last tick.

Every black hole has an interior, and every interior has an end. No signal from the end of any interior reaches any observer outside. So no observer outside can register one end as earlier or later than another end. No clock outside can put in order the end inside the black hole at the center of our Galaxy and the end inside a black hole in a galaxy a billion light-years away.

Down Through the Layers

What does a falling body meet between the horizon and the end? The equivalent density shows the answer. The equivalent density rises inward, eightfold with every halving of the radius. As the early universe thinned and cooled, it passed a series of densities, while the forces and the forms of matter took the shapes they have today, and inside a black hole the faller meets the same densities in the opposite order. First protons and neutrons dissolve into their quarks. Far deeper, the electromagnetic force and the weak force come to act as one, as the two forces did in the first moments of our epoch's history. Deepest of all, the faller meets the *Planck density*: the density at which the smooth description of space and time, the description that general relativity gives, reaches the Planck scale. For a hole of the mass of the Sun, the faller reaches the Planck density at about ten to the minus twenty-six of the radius of the horizon. The Planck density is the innermost layer.

Near the end, the stretching changes its form. Close to the end of a hole that neither rotates nor carries a charge, the interior stretches a falling body along one direction and squeezes the body along the other two directions, and both the stretching and the squeezing grow without limit as the end comes near. For a fall that starts at rest far from the hole, the strength of the stretching depends only on the time left before the end, and not on the mass of the hole at all. On every other path straight inward, the stretching has a part that depends on the mass, and that part fades as the end comes near. So near the end, two fallers feel nearly the same stretching, one in a hole of the mass of the Sun and one in a hole of

four million solar masses, and the closer the end, the more nearly the same the stretching. The geometry near the end has no length of its own. Therefore, as the end comes near, the faller can tell one hole from another by measuring the stretching less and less well.

The authors say that a body is shredded before the body reaches the center. I agree that no body reaches the end whole, and I also say what becomes of the body. The six small dimensions are held far too small to see. Chapter 11 found that the six small dimensions stay small because the large world of space and time is present around them as their context, with a standard of rest and of turning fixed in the large world. The six small dimensions are a few Planck lengths across, so their own bending is close to the Planck curvature. The Planck curvature is the bending of space at which, as Chapter 8 found, the quantum corrections grow as large as the effects they correct. Near the Planck density, the bending of the large world comes close to the bending of the six small dimensions. Near the Planck density, the six small dimensions therefore begin to change. At the end of the interior there is no moment of the outside world, and no standard of rest and of turning survives, so at the end the large world no longer holds the six small dimensions small. Every form of matter lasts only while the large world holds the six small dimensions small, and atoms and bodies are forms of matter. So the matter of the faller stops being matter in the forms that matter has in our epoch. The content itself, what a finding finds, goes on, and no body arrives at the end as a body.

The Edge of the Smooth Description

Now comes the authors' deepest question: what is the end itself? In general relativity, the end is the singularity. Where a path ends, the equations of general relativity give a bending of space and time that grows without bound. The singularity is an endless density, and Chapter 20 found the same endless density in the equations of general relativity, the smooth equations, at the start of our history. In 1965 the mathematician and physicist Roger Penrose proved that once a collapse has trapped light,

no lumpiness in the falling matter can stop the collapse, and some paths inside then come to an end after a finite stretch and cannot be continued. In 1966 the physicist Stephen Hawking proved a theorem of the same kind for the expanding universe traced backward, and in 1970 Hawking and Penrose together proved a theorem of the same kind under general conditions. The theorems of Penrose and Hawking show, exactly, that the smooth description of space and time has an edge to its domain, the range in which the smooth description of space and time holds. The theorems say nothing about what lies at that edge, because the edge is the limit of the mathematics in which the theorems are proved.

General relativity holds wherever the bending of space and time is below the Planck curvature. Measurements confirm the predictions of general relativity from the solar system to the edge of what we can see. Along a path into a black hole, the bending computed by general relativity grows to the Planck curvature before the path reaches its end. So the Planck curvature is the edge of the domain of the smooth description: beyond the Planck curvature, the smooth description does not hold. The infinite bending is what the smooth equations give when they are carried past the edge of their domain, into a region where the smooth equations do not hold. So in my account the singularity is the edge of the smooth description: one description of the world, the smooth one, ends at the singularity, and the world itself goes on.

Chapter 20 used a picture for the same kind of edge, an edge of the smooth description, at the beginning of our history. The map ends at its edge, but the land goes on past the edge of the map. The map is the smooth description, the land is the world, and the edge of the map is the singularity. In the same way, a reader may ask "what is the geometry at the singularity?", and that question is what Chapter 8 called a category error: the question applies a concept, the smooth geometry, where that concept does not belong.

The authors place a clash between general relativity and quantum mechanics inside black holes. The clash has its answer at the edge of the smooth description. Chapter 8 found that quantum theory and general re-

lativity are two descriptions of one world. Inside a black hole, the singularity belongs to neither description. General relativity gives the smooth description, and the smooth description applies up to the Planck curvature. The stepwise description of quantum theory applies where a body's quantum size far exceeds its gravitational size. At the Planck scale, where the two sizes are equal, the domain of each description ends, and no third description is needed beyond the Planck scale.

Physicists also ask whether a black hole destroys the information that falls in: everything that would tell what fell in, what the fallen thing was made of and how it was arranged. The information is destroyed in neither description: in quantum theory the state of the matter goes forward without loss, and in general relativity what falls in goes forward to the end of the interior. While a black hole lasts, the hole hides whatever falls into it from everything outside, and the hole destroys nothing.

One End for Every Black Hole

Which black hole are you inside? While the outside world can still register an answer, the question has an answer. At the end, the question has no answer.

The question has no answer at the end because of three facts of physics and one principle. The first fact is that black holes in orbit around each other merge, in the outside world's own time. The merged hole has one interior, which contains the interiors that merged, and so the merged hole has one end. The second fact is what physicists call the *no-hair theorem*: once a black hole has settled, everything about it that can be registered from outside is fixed by three numbers, its mass, its spin and its electric charge, whatever fell into it. So the outside world keeps no record of what fell into a hole beyond the hole's mass, spin and electric charge. The third fact was found earlier in this chapter: no clock of the outside world can put the end of one interior before or after the end of another interior, because no signal from any end reaches the outside world.

The principle is a principle of comparison. Chapter 1 found that every measurement is a comparison. Chapter 4 used the principle for the electrons: what cannot be told apart by any comparison is one thing and not two. Put another way, a difference that no comparison can register is no difference. In the principle, "no comparison" means no possible comparison, by any comparer, anywhere and at any time. A comparer registers what reaches it, as a finding, a signal or a record. I take a comparer to register nothing that it only predicts.

By the principle, two things are one thing only when the two things cannot be told apart by any comparison. The interiors of different black holes can be told apart, so the interiors stay distinct. A comparer inside one interior registers that interior and not another, and the comparer even registers the mass of its own hole, by the time left on its own watch when it crosses the horizon. The ends of the interiors are a different case. No comparer of our epoch registers the end of any interior, because no signal from an end reaches any moment of the interior before the end, or any moment of the outside world. A new epoch follows the end, and only comparers in the new epoch register anything that comes from the end. The context of the new epoch is the large world in which the findings of the new epoch are made. The context of the new epoch re-forms with no identity carried over from the old epoch. I take the new context to hold no record of the distinctions drawn in the old outside world, so no comparer in the new epoch registers from which black hole any part of the new epoch's content came. Therefore no possible comparer registers a difference between the end of one interior and the end of another, in our epoch or in the next. So, by the principle, the ends of the interiors are one end, while the interiors themselves stay distinct.

Picture each interior as a funnel narrowing toward its end. The funnels stay apart along their whole length, as the interiors stay distinct, and the ends of the funnels meet in one, as the ends of the interiors are one end. From inside, the faller finds the holes growing alike: by measuring the stretching, the faller can tell one hole from another less and less well as the end comes near. At the end, nothing is left by which to answer the

question "which black hole am I inside?" In our epoch, everything that has fallen into a black hole is approaching one and the same end, whichever hole it fell into and wherever that hole is.

My account has an answer to each of the authors' two speculations about the inside: the tunnel to a white hole, and the baby universe. In the exact solutions of general relativity for spinning and charged holes, the way through to the authors' tunnel lies beyond a second, inner horizon. While a real hole forms, the matter that falls in breaks up the inner horizon (physicists say the inner horizon is unstable to that matter). The authors place a white hole at the far end of the tunnel. The counterpart of the authors' white hole is the beginning of a whole new epoch, taken as one beginning. The beginning of the new epoch is no region of space at the far end of any one black hole. Of the authors' two speculations, the baby universe comes nearer to my account, because something new does begin from the end. The new thing begins from the shared end of all the interiors together: there is no separate universe for each hole, and no traveler arrives at the new beginning as a traveler.

What Has Been Seen

Oppenheimer and Snyder's collapse was a calculation on paper. Since 1939, astronomers have looked.

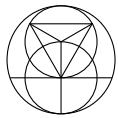
LIGO is an observatory for ripples of space and time, with two detectors, one in Louisiana and one in Washington State. On 14 September 2015, as Chapter 8 told, the two detectors of LIGO recorded the ripples sent out by two black holes as the two holes spiraled together and merged into one. Many more mergers of black holes have been recorded since 2015. We now know that black holes exist. We also know that bound pairs of black holes merge in the outside world's own time, and that the merged hole is one hole. The one end of all black holes follows from one principle and three facts of physics: black holes merge, the no-hair theorem holds, and no clock of the outside world can put the ends of interiors in order. So astronomers have seen the first of the three facts: black holes merge.

In April 2019 the Event Horizon Telescope collaboration published the image of the black hole at the center of the galaxy M87. The Event Horizon Telescope is a network of radio telescopes spread across the Earth and working together as one instrument the size of the Earth. The image of the black hole in M87 shows a bright ring around a dark center: the shadow that the authors describe. In May 2022 the same collaboration published the image of the black hole at the center of our own Galaxy. The collaboration gives the mass of the black hole at the center of our Galaxy as about four million times the mass of the Sun. So we now know the shadow at the center of our Galaxy from its picture. Inside the horizon of the black hole at the center of our Galaxy, everything that has fallen in is approaching an end that lies in its own future, within about a minute of its own crossing. The end lies outside the time in which you look at the picture.

> **The short answer**
>
> You can fall into a large black hole intact, your friends never see you cross, and on your own watch you soon reach the end inside: a moment, ahead of every path within, and one end for every black hole.

The end that every black hole shares is where the domain of the smooth description of space and time ends. At the shared end the world goes on, and the Incommensuration Theorem, with every other rule of comparison, still holds. Chapter 20 found a limit of the same kind at the start of our own history: the turn, the limit that our history, traced back, approaches and takes for its first moment. Two limits at which the smooth description ends have now been found: the shared end of the black holes, and the turn. For the shared end and the turn, the book's question becomes: how are the two limits related to each other?

If every black hole ends at one end, is that what came before our Big Bang?



Chapter Twenty-Two

What Came Before the Big Bang?

In which the oldest question about the beginning gets an answer, the black holes of the epoch before ours end together, and the cycle of epochs is found to have no first turn

What came before the Big Bang, and where did the universe come from?

What this chapter uses

A *comparison* is the act of finding whether two things are the same or different in some respect, and every measurement is a comparison; a *finding* is the outcome of one comparison, laid down as a record; a *comparer* is whatever makes a comparison, whether or not the comparer has a mind (Chapter 1).

The *content* of a finding is what the finding finds, as the warmth of your coffee; the *context* is where the content is found, and the context has three sides, the three settings of space, time and possibility (Chapter 1).

Continuous: nothing is sudden, as along a ramp; *discontinuous*: something is sudden, as at the edge of a step; *symmetric*: what is found stays the same across a change of setting, as each step of a staircase is like every other; *asymmetric*: different everywhere, as the height along a ramp is (Chapter 1).

The *cosmological constant* is the share of the energy of empty space that a measurement made from inside takes in, one number for our whole epoch (Chapter 3).

The world has ten dimensions, one of time, three of space and six of possibility, and the six are the range of what a finding could be, present at every place and never a place themselves (Chapter 11).

The *turn* is the limit at which an epoch begins: our history, traced back, approaches the limit and shows the limit as a first moment; an *epoch* is one era of the world (Chapter 20).

In the autumn of 1981, from 28 September to 2 October, the Pontifical Academy of Sciences held a study week on cosmology and fundamental physics in Vatican City, and many of the leading cosmologists of the day came to the study week. The physicist Stephen Hawking gave a paper with the title "The Boundary Conditions of the Universe" at the study week. Hawking was then thirty-nine years old. A *boundary condition* is the

state that a set of equations is given at an edge, from which the equations then run. The starting position of a thrown ball is one boundary condition, and the temperature of a rod at its two ends is another. The equations of cosmology say how the universe changes from one moment to the next, but they say nothing about where the universe starts. Every account of the whole universe therefore has to say what fixes the start of the universe.

Hawking proposed that the universe has no boundary at all. If the universe has no boundary, there is no edge at which a condition has to be supplied from outside. Two years later Hawking and the physicist James Hartle set the proposal out in full in the journal *Physical Review*. Physicists have called Hawking's proposal the *no-boundary proposal* ever since. On the no-boundary proposal, when we trace the universe back in time, we come to no edge with something lying on the far side of the edge. So your question already had an answer at the study week in Vatican City: on the no-boundary proposal, nothing came before the Big Bang, because the word "before" has no earlier time to point to. I give your question a different answer, and a definite one.

From Cham and Whiteson's pages

What Cham and Whiteson Showed

Jorge Cham and Daniel Whiteson take the question seriously in both of their books, and they set out the candidate answers side by side. In *We Have No Idea*, Cham and Whiteson first show why the question has to be asked in a new form. In the old picture, the universe began as a tiny dot at the moment when every clock read zero. In the picture physicists hold now, the universe begins with inflation: the brief and enormous stretching of space that Chapter 20 described. In the new picture, the authors replace the tiny dot with what they call a fuzzy quantum blob, ready to inflate. The fuzzy quantum blob may be small, or it may be infinite. So Cham and Whiteson ask the question in

a new form: "Instead of asking what came before the Big Bang, we should ask: Where did the quantum inflating blob come from?" (*We Have No Idea*, ch. 14, "And What Happened before the Big Bang?").

Cham and Whiteson then give four possible answers. The first possible answer is that the question may have no satisfying answer, in one of two ways. The first way is Stephen Hawking's suggestion that asking what came before the Big Bang is like asking what lies north of the North Pole, where every direction points south: if space and time began at the Big Bang, there is no "before". In the second way, there was a time before the Big Bang, but the Big Bang destroyed every trace of that earlier time, so no evidence of the earlier time reaches us.

The second possible answer is that our universe formed inside a black hole. On the second possible answer, the stuff that drove inflation may have formed inside a massive black hole. Our whole universe may lie within the horizon of a black hole, the surface from inside which no signal can reach the outside. And the black holes in our universe may hold small universes of their own.

The third possible answer is a cycle. One day the universe falls back on itself in a Big Crunch, and the crunch sets off a new Big Bang. The authors note a difficulty for the cycle: a crunching universe seems to need its entropy to fall. Chapter 13 described entropy as a count of the arrangements of a thing's small parts that look the same from outside.

The fourth possible answer is endless inflation. In endless inflation, the stretching of space never stops everywhere at once. Each place where the stretching does stop becomes a pocket universe of its own, and the number of pocket universes could be infinite. The authors call the black-hole ideas untestable today. For now, Cham and Whiteson class the whole question with philosophy.

Cham and Whiteson ask a wider form of the question in *Frequently Asked Questions About the Universe*: where did the universe come from? The authors sort the answers by the two great theories of physics, quantum theory and relativity. If quantum theory is mostly right,

space itself may be made of smaller units that the authors call quantum bits, each unit standing for one location and linked to the others. Our universe would then be one connected blob of quantum bits inside what the authors call a metauniverse. A metauniverse is a larger whole filled with quantum bits, connected or not. If relativity is mostly right, time began in a fuzzy first moment, and on Hawking's no-boundary proposal there is no before. In the authors' words: "According to relativity, the universe is its own origin" (*Frequently Asked Questions About the Universe*, ch. 11, "Relativity Is Mostly Right"). If neither theory is right, the universe may simply be a mathematical structure that had to exist, as a number simply is.

The authors end the chapter with one more thought. New space keeps appearing as the universe expands, and each new piece of space carries the energy of empty space with it. So the authors write that "the universe is still being born" (*Frequently Asked Questions About the Universe*, ch. 11, "How Can Something Come from Nothing?"). Across both books, the message of Cham and Whiteson is clear: the question is a real one, the candidate answers differ widely, and only tools that physics does not yet have will decide among the answers.

A Family Tree Drawn from Records

Picture a family tree drawn up from the records of one parish. The parish books record baptisms, marriages and burials, so a careful hand can draw every line of the family back, generation by generation. The records begin in a certain year, because the parish began to keep records in that year. So the tree has a top row, and the names in the top row look like the first people of the family. In fact the people in the top row were the earliest people that the records name. The people in the top row had parents of their own. The tree cannot show the parents of the top row, because the tree is drawn from the records and the records stop.

The history of the universe is drawn in the same way as the family tree: from records. The past is known only by the impression it makes on the present. For the universe, the impressions on the present are the light now arriving from distant galaxies, the faint glow of the early universe that fills the sky, the amounts of the light elements, and every record our instruments hold. We reconstruct one history from the impressions on the present: the history that the present requires. Chapter 20 defined a limit as a value that something approaches more and more closely and never reaches. When we trace the reconstructed history backward, the history runs to ever higher density and ever smaller volume, toward a limit. A history reports every finding as a thing that happened at a definite time and place, so the reconstructed history shows the limit as a first moment, a beginning at time zero. Chapter 20 named the limit itself the *turn*: the limit at which an epoch begins, which we approach when we trace our history back, and which our reconstruction shows as a first moment.

We can now see what the answer "there is no before" rests on. That answer rests on one assumption: that the beginning our history finds is a first moment in the structure of things. On that assumption, the first moment lies in the world itself, and not only in the history we reconstruct. The top row of the family tree is the first row of the records. The top row of the world's history is the first moment that the reconstruction shows. Hold the reconstruction and the world apart. Then the question "what came before?" becomes a question about what lies on the far side of the limit. The question has an answer.

The Far Side of the Limit

Chapter 21 followed a body falling into a black hole to the end of the fall. Chapter 21 called the region inside a black hole's horizon the interior of the black hole. The interior ends at a definite moment on the clock of anyone who falls in. The interiors of all black holes share one end. The reason is that no comparer anywhere can tell the end of one interior from

the end of another. The shared end is the edge of the domain of the smooth description of space and time. A description's domain is the range within which the description holds.

Chapter 21 described the interior near its end. Near the end, a falling body is stretched along one direction and squeezed along the other two directions of space. The six small dimensions of possibility are the six further dimensions of the world, held far too small to see. In one valid form of Einstein's equations of gravity, the stretching and squeezing is written out for all ten dimensions, with each of the six small dimensions kept at its size. I call this ten-dimensional form of the stretching and squeezing the *ordinary interior*. In the ordinary interior the six small dimensions keep their size. So where the six small dimensions begin to change, near the Planck density, the interior is no longer the ordinary interior. Einstein's equations also allow interiors in which the six small dimensions change size. In one of the interiors in which the six change size, all three directions of space shrink together while the six small dimensions grow. When the time left to the end falls a billionfold, each of the three directions of space shrinks a hundred thousand times, and each of the six small dimensions grows ten times. I place the end of every black hole's interior on the form in which the six small dimensions grow. So the six small dimensions grow near the end, and that growth is the change Chapter 21 found.

Now picture a film of a balloon letting out its air. When the film runs forward, the film shows the balloon shrinking. When the film runs backward, the same frames show a balloon being blown up. Every frame stays as it was, and only the direction in which the frames are run changes. The film of the balloon is like the form of the interior in which the three directions of space shrink and the six small dimensions grow. When the equations of the shrinking interior run forward, toward the end, their rates describe three directions of space shrinking while the six small dimensions grow. When the same equations are run away from the limit, the same rates describe three directions of space growing out of the limit while the six small dimensions shrink back to their small size. When three directions of space grow out of a limit, the growth is the expansion of a young

universe. When we trace the expansion of our own universe back toward its limit, we follow our own history back to the Big Bang. So one transition is both the collapse at the end of every interior and the beginning of an epoch, traveled in opposite directions of time. One limit therefore has two sides. Our own history, traced back, lies on one side of the limit. The other side of the limit holds the collapse inside the black holes of an earlier world.

Chapter 2 defined an *epoch* as one era of the world, in which stars, galaxies and black holes form. I identify the far side of the turn with the collapse of the interiors of the black holes of the epoch before ours. So your question has its answer: before the Big Bang came the collapse of the interiors of the black holes of the epoch before ours. Chapter 21 described the one end that the interiors of all black holes share, including the black holes of the epoch before ours.

Why a New World Re-forms

A world like ours forms on the far side of the shared end of the interiors. The reason is that every finding has two parts, which Chapter 1 named. The *content* of a finding is what is found, and the *context* of a finding is where the content is found. The third axiom of the account states that content and context are inseparable: there is no content without a context in which it is content. The six small dimensions of possibility hold the forms that content can take, so the six small dimensions are content. Chapter 11 named two conditions that keep the six small dimensions small. The first condition is that the large world of space and time is present around the six small dimensions. The second condition is that a standard of rest and of turning is fixed in the large world, as matter against which motion is measured. A spinning gyroscope shows the standard of rest and of turning at work: the gyroscope keeps pointing at the same distant stars.

At the end of every black hole's interior, both conditions fail. Nothing is left at the end of an interior to compare motion against. Two facts hold at the end of an interior. First, the content does not cease at the end. The end is the edge of the domain of every description of the content. The edge belongs to the descriptions, while the content itself goes on. Second, content needs a context. So a context must form again. The geometry of all ten dimensions remains at the end, and that geometry is the only structure from which a new context can form. The geometry of the ten dimensions re-forms a large outside world. Three directions of space open out, and the six small dimensions close back to their small size. The split between large and small dimensions re-forms with the same shape as in the epoch before. I call the re-forming of a large outside world the *restoration of context*.

I argue for the same restoration of context on separate ground: from the far future of our own epoch, and not from the fall into a black hole. As our epoch ages, every observer's world empties of the things that the observer can still compare with. Matter that is bound, held together by gravity, falls together into black holes. The accelerating expansion carries the matter that is not bound beyond the observer's horizon. The observer's horizon is the edge beyond which nothing sent now can ever reach the observer. An observer left alone by the emptying is in the same condition as an observer near the end of a black hole's interior. For each of the two observers, the large world is no longer a context to compare against. If the emptying ended in a perfectly featureless and unbroken final world, that world would be perfectly symmetric and perfectly continuous at once. The Incommensuration Theorem, from Chapter 1, states that symmetry and continuity cannot both be perfect together at the foundation of any event or comparison. The emptying cannot simply come to rest. Context must be restored. Both roads end at the turn: the fall into a black hole, and the long emptying outside.

The restoration of context is a transition in a cycle: the content is carried through, the geometry of the ten dimensions remains, and what reforms is the large outside world itself. So the restoration of context is

neither a creation from nothing, nor a fluctuation in a vacuum that was already there, nor a breakdown at which the equations fail and the description falls silent.

Before, in the Order of a Cycle

Picture a bundle of old letters between two friends, with the dates torn off every page. You can still put the letters in order, because each letter answers the letter before it. The order comes from which letter answers which, and you need no date to fix the order.

In the answer to your question, the word "before" names an order like the order of the letters. The collapse of the old interiors comes before our epoch in the order of a cycle: the collapse lies on one side of the limit, and the new epoch lies on the other side. A stretch of time across the limit could be measured only by a comparison made across the limit: a clock reading on one side set against a clock reading on the other side. No comparison across the limit exists. The outside world of the old epoch has no moment at the end of an interior, and the interior's own clock ends at the limit that the clock approaches. So the word "before" names the order of a cycle, and no comparison can measure a stretch of time across the turn.

The next question, "and what came before that?", has an answer of the same form: the collapse of the interiors of the black holes two epochs before ours. You can ask the question again of each earlier epoch, and each time the answer has the same form, without end. When each epoch comes from the black holes of the epoch before, I call the succession a *cycle of epochs*. In a cycle of epochs, stars, galaxies and black holes form in an epoch, and the interiors of the epoch's black holes share one end. A large world is restored at the turn, and the restored world is the next epoch. The history of the world is a cycle, and the cycle has no first iteration. The epochs follow one another in a single line, each epoch coming from the epoch before it. The line of epochs does not branch. The comparers of each

epoch register the turn from which their epoch came, as the beginning of their epoch's history, but they do not register the turn at which their own epoch's black holes will end, because that later turn lies in their future.

Black holes form at every scale in an expanding universe, and black holes that are bound to one another merge. The interiors of all black holes share one end, whatever the expansion of the outside world does. So the cycle of epochs runs through the ends of black-hole interiors. The universe as a whole therefore never has to fall back on itself in a crunch. The accelerating expansion of our own universe does not stop the cycle. The cosmological constant drives the accelerating expansion. Chapter 3 described the cosmological constant as the one constant term of Einstein's equations. The cosmological constant belongs to the description of the outside world, and the outside world has no moment at the end of an interior, so the cosmological constant has no effect at the end of an interior.

A New Count, and an Even Start

The cycle of Cham and Whiteson met a difficulty about entropy, and a physicist had raised an older form of the same difficulty. In the 1930s Richard Tolman raised a difficulty for any history made of cycles. Tolman was a physicist at the California Institute of Technology. In Tolman's argument, the entropy that is made in one cycle is carried into the next cycle, so each cycle comes out larger and longer than the cycle before it. When the history is traced backward, the cycles shrink, so only finitely many cycles lie behind us. So the history has a first cycle after all.

Picture a census in a newly founded country. A census counts the people of a country by the categories that the census forms record, and the census's own clerks do the sorting. When a new country is founded, with new clerks and new forms, the first census of the new country starts its own count and does not continue the census of the old country.

Chapter 13 found that an entropy is a count of the arrangements of a thing's small parts that look the same from outside, and that the count is always made relative to some look at the thing. The entropy of a black

hole is a count of the states of the black hole's interior that the outside world cannot tell apart. So the entropy of a black hole is a count made relative to the outside world. The entropy of the matter of an epoch is a count of the same kind, made relative to the same outside world. At the turn the outside world has emptied. So every count made relative to the outside world has nothing remaining to be a count against. In the new epoch, every count is made relative to the new epoch's own new context. The content itself is carried through the turn, but no count made relative to the old outside world is carried through. So no entropy passes from one epoch into the next. Each epoch begins its own count, as the census of a new country does. Tolman's argument needs the entropy of one cycle to be carried into the next cycle, and in the cycle of epochs no entropy is carried over, so Tolman's argument has nothing to work with.

One question remained open at the end of Chapter 13: why did our epoch begin so orderly? The answer follows from the new count. The space and time of the new epoch re-form as a new part of the geometry of all ten dimensions. Within the geometry of the ten dimensions, the new space and time had no separate identity of their own. So the new space and time inherit nothing from the old outside world: no preferred direction, and none of the old world's lumpiness. The new space and time begin even, except for the small departures from evenness that the Incommensuration Theorem requires. At the beginning of our history, the matter was hot and near the settled state in which nothing further changes on average, so the entropy of the matter was already high. The low entropy of the beginning is instead in the evenness of the geometry of space and time, and that evenness follows from the restoration of context.

The Authors' Candidates, Placed

I now set each of the authors' candidate answers beside the answer of this book.

The first part of the authors' first possibility is Hawking's "no before". Hawking's "no before" rests on the assumption that the family tree showed. The assumption is that the first row of the reconstruction is a first moment of the world. Hawking's North Pole fits a request that names nothing: a request that uses a word where the word has no meaning, as a request for the color of the number seven does. Chapter 15 used the same globe as Hawking for a request that names nothing: on the Earth, north ends at the Pole, so a request to go north of the North Pole names nothing. The question "What came before the Big Bang?" names something definite. The question names the far side of the turn, the limit that our reconstructed history shows as its beginning. The second part of the authors' first possibility is a time before the Big Bang that left no evidence. I agree with the second part that a time before the Big Bang existed. In the family tree, the parents above the top row lived too. But on my account evidence of the time before the Big Bang does reach us, because the form of what fell into the black holes of the epoch before ours (which alternatives the matter took) passes through the turn. Our sky carries the form of what fell in as the first ripples, the faint departures from evenness with which an epoch begins. Chapter 20 found that the first ripples carry the form of what fell in. The last section of this chapter describes what the measurements of the first ripples show.

I join the authors' second possibility (a black-hole origin) and their third possibility (a cycle) in one answer, and the joined answer differs from each of the two. In the authors' second possibility, our universe may lie inside a black hole, within the black hole's horizon, and each black hole of ours may hold a small universe of its own. Our epoch forms on the far side of the one end shared by all the black-hole interiors of the epoch before ours. All the black holes of an epoch share one end of their interiors, so one next epoch comes from all the black holes of the epoch together. There is one next epoch, not one per black hole. I derive one and the same structure for every epoch. So the constants of nature are not passed down from epoch to epoch with changes, and no epoch is selected from among other epochs. The authors' third possibility needs a Big Crunch, but the

cycle of epochs needs none, because the cycle runs through the ends of black-hole interiors, which share one end whatever the expansion of the outside world does.

I rule out the authors' fourth possibility, endless inflation with its pocket universes. I explain the sameness of the sky and the flatness of space without inflation. Chapter 20 showed that a long inflation cannot have happened, so there is no endless inflation to make the pocket universes. The pocket universes of endless inflation could have different constants of nature only if the small dimensions had many possible shapes, each shape giving the empty space of a pocket universe its own constants. Chapter 11 found that the six small dimensions of possibility have one shape, so empty space has one set of constants. The pocket universes were meant to hold copies of you. Chapter 24 shows that any copy of you, wherever the copy stood, would be a second person.

Frequently Asked Questions About the Universe gave three answers. The three answers are space made of quantum bits, the universe as its own origin, and the universe as a mathematical structure. On the first answer, space made of quantum bits: space is the context of the quantum states, and that space is not made of the quantum states. Chapter 7 found that the arena, space and time together, is the context in which every finding of physics is made. So the arena is the context of every quantum state. The arena is not built out of the links among the quantum states. On the second answer, the universe as its own origin, I keep the beginning exactly as our reconstructed history shows it, and I add what lies on the far side of the beginning. On the third answer, the universe as a mathematical structure, I tell apart what exists and what is real. A structure exists as a law exists: the structure is the same however it is consulted. A world is real as a measurement is real: the world is found in acts of comparison made from inside the world. Chapter 27 sets out the difference between what exists and what is real. From that difference, Chapter 27 shows that the world is no computer program. The authors say that a choice among all three answers must wait for a new theory that joins quantum theory

and relativity. Chapter 8 found quantum theory and relativity joined side by side, each theory whole in its own domain, so I answer the question of the origin without a merged theory of the two.

The authors' closing thought is that the universe is still being born, and I agree with that thought on two separate grounds. The first ground is that the energy of empty space in each unit of volume stays the same as space grows, so each new piece of space carries its share of that energy. The second ground is that creation does not belong to a first moment at all: "Creation is not an event; it is a side of every event". Something new enters the world whenever an interaction makes a finding that was not contained in what came before.

I also answer the oldest form of the question: why is there something rather than nothing? Picture a pen writing nearer and nearer to the edge of a page. Every mark the pen makes is on the page, however near the edge. But the edge itself is no place where a mark could be made. I find the same pattern in the contact between a comparer and its world. The *degree of interaction* is how much contact a comparer has with its world, and the degree of interaction can come as near to zero as you like, as the pen can come as near to the edge as you like. Chapter 8 named the domain of comparison as the range within which comparisons can be made. Zero itself is the edge of the domain of comparison, as the edge of the page is the edge of the writing, and zero is never a state inside the domain. So there is always at least the plain fact of contact between a comparer and its world. In the account's terms, that plain fact of contact is why there is something rather than nothing. "Nothing" names the edge at zero, and an edge is no state from which a world could come. The turn is a transition in a cycle, so our epoch did not come from nothing either.

What the Sky Already Shows

Three measurements show that there was a Big Bang in the sense of the answer to your question: a limit that our reconstructed history runs back to. The astronomer Edwin Hubble made the first measurement in

1929, at the Mount Wilson Observatory in California. Hubble set the distances of galaxies beside the speeds at which the light of the galaxies shows the galaxies moving away. Hubble found that the farther a galaxy is, the faster the galaxy recedes, roughly in proportion to its distance. We now know that space itself is stretching and carrying the galaxies apart, so the universe was denser and hotter in the past.

In 1965 the radio astronomers Arno Penzias and Robert Wilson reported a faint hiss of radio waves. The hiss came equally from every direction of the sky. Chapter 20 opened with the report of Penzias and Wilson. The hiss was the glow left over from the early universe, stretched by the expansion of space, so that the temperature of the glow is now about 2.7 degrees above absolute zero. We now know that our history runs back to a time when the whole universe was hot enough to glow, with the same temperature everywhere.

In 1992 the Cosmic Background Explorer satellite showed that the glow is not perfectly even. Chapter 20 told the story of the satellite's finding. The temperature of the glow differs from place to place by about one part in a hundred thousand. The differences in temperature are the first ripples, and the galaxies grew from the first ripples. We now know that the beginning of our reconstructed history was even to about one part in a hundred thousand, and that the faint ripples of the beginning spread across the whole sky.

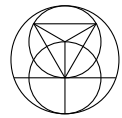
The sky we already have carries the evidence for the answer to your question. Matter fell into the black holes of the epoch before ours, and the form of that matter (which alternatives the matter took) is carried through the turn. The form is carried as one form, because the interiors of all the black holes of the epoch before ours share one end. In the new context, the form appears only as small departures from evenness. The departures are correlated across the whole new world, because every part of the new world re-forms from the one end that the old interiors share. The shared end is the one origin of Chapter 20. One origin means that no comparer inside the new world can find separate beginnings for any two parts of the new world. The Cosmic Background Explorer found a faint pattern,

and every map made since has shown the pattern more finely. The faint pattern is the first ripples as Chapter 20 identified them. The first ripples are the averaged form of what the black holes of the epoch before ours took in. The appendix "What the Coming Measurements Will Find" contains the coming measurements that will map the pattern more finely. For each measurement, the appendix states what I say the measurement will find.

> **The short answer**
>
> Before the Big Bang came the collapse of the interiors of the black holes of the epoch before ours, and at the one shared end of those interiors a new large world formed, in a cycle of epochs with no first turn.

The authors allowed, in their first possibility, that the question has no answer, or has an answer that no evidence can reach. The question has an answer, and the collapse that the answer names left a trace that reaches us. The first ripples carry the trace across the sky, so astronomers who measure the faint pattern of the first ripples from inside our epoch find, in that pattern, the end of the epoch before.

If our whole epoch formed from one shared end, how far does it reach: how big is the universe?



Chapter Twenty-Three

How Big Is the Universe?

In which one star on a glass plate moves a galaxy out of ours, and every finding made at every table holds a sphere centered on that table

How big is the universe, and where are we in it?

What this chapter uses

A *comparison* is the act of finding whether two things are the same or different in some respect, and every measurement is a comparison; a *finding* is the outcome of one comparison, laid down as a record; a *comparer* is whatever makes a comparison, whether or not the comparer has a mind (Chapter 1).

Three things in nature do the bending: gravitation bends space, the cosmological constant bends time, and the dark matter bends possibility (Chapter 1).

The *cosmological constant* is the share of the energy of empty space that a measurement made from inside takes in, one number for our whole epoch (Chapter 3).

Every comparison has three positions: the *act of comparing*, the relating; the *thing compared*, what is known; and the *thing compared against*, what the act of comparing reaches toward and never contains in one act, the beyond (Chapter 4).

The world has ten dimensions, one of time, three of space and six of possibility, and the six are the range of what a finding could be, present at every place and never a place themselves (Chapter 11).

The *turn* is the limit at which an epoch begins: our history, traced back, approaches the limit and shows the limit as a first moment; an *epoch* is one era of the world (Chapter 20).

On the night of 5 to 6 October 1923, the astronomer Edwin Hubble pointed the Hooker telescope of the Mount Wilson Observatory in California at the Andromeda Nebula. In the astronomy of the day, a *nebula* was any faint cloudy patch of light in the night sky. The Andromeda Nebula is a faint spiral patch of light in the constellation of Andromeda. The Hooker telescope gathers light with a mirror one hundred inches across. Hubble exposed a glass photographic plate for forty-five minutes, and the observatory filed the plate as number H335H. He compared the plate

with earlier plates of the same patch of sky in Andromeda. He marked each new star with the letter N. Astronomers took a new star in a nebula to be a *nova*, a star that flares up once. Hubble compared one of the marked stars with still more plates. The star turned out to brighten and fade again and again, in a steady rhythm. Hubble crossed out the star's N and wrote, in capitals, "VAR!": a variable star.

When a star brightens and fades in a steady rhythm, as Hubble's star did, astronomers call the star a *Cepheid*, and the length of the Cepheid's rhythm tells how bright the star truly is. In 1912 Henrietta Leavitt had found the rule for Cepheids: the longer a Cepheid takes to rise and fall, the greater its true brightness. Leavitt was an astronomer at the Harvard College Observatory. So a Cepheid is a standard candle: in the picture of Chapter 3, a lamp of known brightness, whose faintness as seen from Earth tells how far down the road the lamp stands, that is, how far away the star is. Hubble went on to photograph more Cepheids in the Andromeda Nebula. He timed the rhythms of the Cepheids, and he worked out how far away the Cepheids were. Hubble put the Andromeda Nebula a little under a million light-years away in his paper of 1925, "Cepheids in Spiral Nebulae" (a light-year, as Chapter 2 said, is the distance light travels in a year).

On 26 April 1920, three years before Hubble's night at the telescope, two astronomers had spoken on "The Scale of the Universe" at a meeting of the National Academy of Sciences in Washington. Harlow Shapley, of Mount Wilson, held that our own galaxy is about three hundred thousand light-years across. Shapley held that the spiral nebulae are not separate systems of stars. Heber Curtis, of the Lick Observatory, held that our galaxy is about thirty thousand light-years across. Curtis held that each spiral nebula is a galaxy of its own, an "island universe" far beyond ours. Hubble's Cepheids answered the part of the question of Shapley and Curtis that was about the spiral nebulae. The Andromeda Nebula lies a little under a million light-years away, far outside even Shapley's large

galaxy. So the Andromeda Nebula is a galaxy of its own: the Andromeda Galaxy. Today astronomers measure the distance of the Andromeda Galaxy at about two and a half million light-years.

Hubble's finding changed what astronomers knew: in what they knew, the universe grew from one galaxy to many. Hubble made the finding entirely from where we stand. The light of a star in Andromeda came to a mountain in California, and one man compared one plate with others. The known size of the universe changed for everyone who learned that the Andromeda Nebula is a galaxy of its own. In this chapter, every answer to the question "how big?" is a finding like Hubble's: a finding made from where we stand.

From Cham and Whiteson's pages

What Cham and Whiteson Showed

In *We Have No Idea*, Jorge Cham and Daniel Whiteson begin the question on a mountain top and under the night sky. "This view is possible because the universe is incredibly vast and mostly empty" (*We Have No Idea*, ch. 15, opening). The authors walk their reader outward through our cosmic address, from the Earth to the largest things in the sky. The Earth goes around the Sun, and the Sun is one of about a hundred billion stars in our galaxy. Galaxies gather into clusters, clusters into superclusters, and superclusters spread in vast sheets around empty voids.

Then the authors ask how far the universe goes. Light has had about 13.8 billion years to reach us. Space has stretched while that light traveled, so the farthest things we see now stand about forty-six and a half billion light-years away, in every direction, by the authors' figure. The farthest things we see mark a sphere around us, and the authors, like astronomers, call the sphere the observable universe: everything whose light has reached us (the Preface gave the astronomers' term). The authors say that we cannot look beyond the observable universe. They add that some things are moving away so fast that their light

will never reach us. "The bad news is that we don't know for sure how far out the universe goes" (*We Have No Idea*, ch. 15, "The Size of the Universe"). The authors set out three possibilities: a finite amount of matter in an infinite space; a finite space that loops back on itself, like the surface of a ball; and an infinite space filled with matter without end. For the looped space they name a test: light that goes all the way around would show us the same objects twice. Astronomers have searched both the galaxies and the oldest light for repeated images, and they have found none.

In *Frequently Asked Questions About the Universe* the authors ask where the center is. Each of us sees out to the same distance in every direction, so "We are each at the center of our own observable universe" (*Frequently Asked Questions About the Universe*, ch. 16, "What Can We See?"). Every galaxy is moving away from us. The authors ask whether the motion of the galaxies away from us puts us at the center of the universe. Their answer is that no one can tell from the motion of the galaxies where the center is, because "the Big Bang wasn't actually an explosion; it was more of an expansion of space". The authors' picture is a loaf of bread rising in the oven, in which every bit of dough moves away from every other. The universe, like the loaf, grows everywhere, "so the center could be here or it could be anywhere" (both quotations: *Frequently Asked Questions About the Universe*, ch. 16, "Hints from the Movements of Galaxies").

The authors then define a center by shape: a center is the point with the same amount of the universe in every direction. A loaf has a center in the authors' sense because a loaf has a crust. The authors weigh three shapes. A blob has a center. In an infinite space every point satisfies the authors' definition, so no point is the center. A space curved back on itself has no center on it, like the surface of the Earth. A donut has its center outside itself. The authors also report that physicists think the universe is most likely infinite (*Frequently Asked Questions About the Universe*, ch. 3, "Another You in Our Universe").

In the authors' own terms, their message has three parts. The part of the universe we can see is measured, and it is large. Each of us sits at the center of our own view of the universe, like everyone else. The authors do not know the size and the shape of the whole universe, and the size and the shape may never be known. I agree with every measured fact in the authors' account. I add an answer about the whole universe. Space is flat (lines that start out parallel stay parallel, as Chapter 3 described), with no short loop anywhere: no closed path around space is shorter than the width of all we can see. And for every finding made from inside the universe, space is the same as a space without end.

At the Center of All You Can See

Set your cup on the table and look at it. You see the cup by light that left its rim a moment ago and came in to your eye. At your table, every finding you make by light is made as your sight of the cup is made: from light that has come in to the table. Now look up from the cup at the night sky. Tonight, the farthest light that can reach your table set out near the beginning of our epoch, our era of the world. The farthest light comes in from every direction. So every finding made at your table holds a great sphere: the finding has within its reach everything inside a sphere, and the sphere is centered on the table where the finding is made. Now think of someone seeing a cup on a table in a kitchen on the far side of the world, or on a planet of another galaxy: each finding made at that far table holds a sphere of its own, centered on that table, in exactly the same way as a finding made at your table.

The cups on the tables show the first step of the answer to where we are in the universe: every comparer stands at the center of its own horizon. A comparer is anything that registers one thing against another (Chapter 1): a person, an instrument, a detector or an atom. A comparer's horizon is the edge of what the comparer's findings can hold. For a measurement made here and now, the comparer's horizon is the *particle horizon*

that Chapter 3 named. For us the particle horizon stands about forty-six billion light-years away, as Chapter 3 said. The particle horizon is drawn from where the comparer is, by the light that has arrived there, so the particle horizon is centered on that comparer, as a skyline is centered on whoever looks at it. I put the same point with a pond: each observer's horizon is centered on that observer, like the ring of ripples around each stone dropped into the water.

A second edge lies nearer to us than the particle horizon. The expansion of space is speeding up, as Chapter 3 showed from the faint distant supernovae. Once a distant galaxy is far enough away, light that the galaxy sends out today will never reach us, however long we wait, because the speeding expansion carries the galaxy away faster than the light can close the distance. When nothing sent now from beyond an edge can ever reach a given comparer, astronomers call the edge the *cosmological event horizon*. Today the cosmological event horizon stands a little under seventeen billion light-years away. Over the ages to come the cosmological event horizon grows toward about seventeen and a half billion light-years. Seventeen and a half billion light-years is the edge that a universe holding only the energy of empty space would have. The two edges mark two different things: the particle horizon is the edge of the old light that has already arrived, and the event horizon is the edge of the new light that ever will arrive. Both edges are centered on whoever is looking, and every comparer in the universe has its own pair.

A horizon is an edge that moves. I picture a traveler. The traveler crosses a wide plain toward the line where the land meets the sky. With each mile the traveler sees land that was hidden, and a new line beyond that land. The traveler passes every particular horizon and never reaches a place where horizons stop. The curve of the earth makes the traveler's horizon, so the horizon moves with the traveler. By contrast, a fence stays in one place at the end of a flat meadow. Our horizon moves in the same way as the traveler's: every year light from a little farther away arrives, and the particle horizon grows. Any one horizon can be passed, by moving or by waiting, but an edge of what can be known from where a comparer stands

is always there, for every comparer, at every time. So the authors are right that we see a sphere and not the whole. The reason is that every finding is made from somewhere, and the reach of the finding is drawn from the place where it is made.

An Expansion with No Center

In January 1929 Hubble sent a short paper to the *Proceedings of the National Academy of Sciences*. He had the speeds of forty-six galaxies and the distances of twenty-four of them. He found that the farther away a galaxy was, the faster it was moving away from us. The results, he wrote, "establish a roughly linear relation between velocities and distances among nebulae": twice as far, twice as fast. Hubble got the speeds from the colors of the galaxies' light. In starlight each chemical element shows up as a set of dark lines at colors of its own, and in the light of Hubble's galaxies the dark lines were shifted toward the red. Astronomers call the shift toward the red a *redshift*: the stretching of light into longer, redder waves on its way to us.

We now know what Hubble's pattern of twice as far, twice as fast means. Space itself is stretching, and the stretching carries the galaxies apart, so the galaxies are not flying away through a space that stays fixed. The authors' rising loaf shows the stretching. Raisin bread shows the stretching too. As the dough rises, every raisin moves away from every other raisin. The dough stands for space, and the raisins stand for galaxies. No raisin swells, because each raisin holds itself together. Seen from any one raisin, a raisin twice as far away has twice as much rising dough in between. So the farther raisin moves away twice as fast. A cook standing on any raisin would see the same pattern of twice as far, twice as fast, with that raisin at the middle. So the motion of the galaxies marks no center. The pattern Hubble found from Mount Wilson is the pattern a comparer in any galaxy would find.

The beginning of our epoch, too, sets no place apart from any other. Chapter 20 showed that our epoch began at the turn. The turn is the limit that we reach when we trace our history back, and that we take for a first moment. Chapter 20 also showed that the new world of our epoch reformed at the turn from one origin. Coming from one origin means that no comparer inside the new world can find, by any comparison, separate beginnings for any two parts of that world. I state what the new world of our epoch carries over from before the turn: the new world "inherits no record, no length and no mark that sets one of its parts apart from another". So no place in our space is the place where the beginning happened. The authors choose a "democratic universe", in which no place is special, because a universe with no special place is simpler (*Frequently Asked Questions About the Universe*, ch. 16, "The Central Point"). My account has a reason for the authors' choice: every place came from the one origin alike.

Flat, with No Short Loop

Chapter 20 showed why our space is flat. A length sets how sharply space is bent: the radius of the bend. An ant finds the curve of a marble within a few steps, and finds a ball the size of the Earth flat for days, because the smaller the radius, the sooner the bending shows. In Einstein's equations, the state from which a history begins sets the radius of the bend once. The history carries the radius unchanged ever after. The state that began our epoch holds no length from before the turn. The only length that state holds is the tiny length of the turn itself, near the Planck length (the length, far smaller than a proton, at which the size of a body set by gravity and its size set by quantum physics meet). A space bent on so small a length would close up again almost at once, or fly apart before anything could gather. Stars, galaxies and black holes would form neither in a space that closes up at once nor in a space that flies apart. Our epoch has stars, galaxies and black holes, so our space is not bent on the length of the turn, and the state that began our epoch holds no other length on which space could be bent. So our space is *flat*, which Chapter 3 described:

lines that start out parallel stay parallel. Our space is bent only by the first ripples it began with, the faint departures from evenness of about one part in a hundred thousand.

The bending of space on the largest scale has been measured. The team that ran the Planck satellite mapped the oldest light. The Planck team combined its map of the oldest light with the spacing of galaxies in its final analysis, published in 2020, to measure the bending of space on the largest scale. In Einstein's equations, a bending of the whole of space acts on the expansion as one more slice of the pie of Chapter 1 would act. The pie of Chapter 1 is the authors' pie chart, which divides everything the universe holds into shares. So astronomers state the bending as the share of the pie that the bending would take, and a flat space takes a share of zero. The Planck team found the share of the bending to be zero, to within about two thousandths of the whole, so we now know that the space of our epoch is flat on the largest scale that light has crossed.

A flat space can still close on itself. Picture an old video game in which a ship that flies off the right edge of the screen comes back in at the left, and a ship that flies off the top comes back at the bottom. The screen is flat, and the ship never meets an edge, and yet the screen is finite. When the screen's opposite edges are joined, right to left and top to bottom, the screen has the shape of the authors' donut, while every part of the screen stays flat. Mathematicians call the shape of the joined screen a *torus*, and a torus can be flat and finite at once. In a space closed as the game's screen is closed, some paths go all the way around and come back to where they started, and no such path can be shrunk to a point. When a closed path around space is shorter than the width of all we can see, I call the path a *short loop*. The width of all we can see is the diameter of our horizon.

No short loop runs anywhere in space. I rest the claim on the ratio of the dark matter to the ordinary matter that Chapter 1 gave: six less two divided by pi, a little more than five and a third. I count what a measurement holds, and the count is a count of kinds of shape: the basic pieces from which a shape can be built, as Chapter 1 explained. The ordinary matter found in a measurement fills the region within the measurement's

horizon, and that region is a ball, one piece with no hole and no loop through it. In the count, a ball counts as one. The dark matter ranges over the six small dimensions of possibility that Chapter 2 introduced, and in the count of kinds of shape the shape of the six dimensions counts as six, less a small share, two divided by pi, which comes from the bending of that shape that Chapter 1 named. The ratio is the count for the dark matter over the count for the ordinary matter, so the ratio rests on a count of one for the region within the horizon. A region with a short loop through it is not a ball. A region with a short loop would count as more than one, which would change the ratio. The ratio is an identity: a relation that holds for every measurement, wherever in the universe the measurement is made. So the count of one holds at every place. The region within every comparer's horizon is a ball, and no short loop runs anywhere in space. The measured ratio lies within about a tenth of a percent of the account's number, six less two divided by pi, as Chapter 1 reported.

Astronomers have run the authors' own test, the search for repeated images, and by that separate method they also found no short loop. In a space with a short loop, the oldest light would reach us both ways around the loop. Then the same ring of hot and cold spots would appear twice on the sky, in two places. In 2023 the physicists Pip Petersen, Glenn Starkman and their colleagues searched the maps of the oldest light made by two satellites, the Wilkinson Microwave Anisotropy Probe and Planck, for matched rings of hot and cold spots, and found none. The *last-scattering surface* is the far sphere from which the oldest light set out when the young universe first became clear. From the search, the team showed that every closed path around the universe through our place is longer than ninety-eight and a half percent of the diameter of the last-scattering surface. We now know that, out to nearly the whole width of the last-scattering surface, the region around us is one ball, with no loop through it.

The Same as a Space Without End

Now the authors' question, how big the universe is, can be answered in a form that holds for every finding. The region a measurement holds is the ball within the measurement's horizon. The horizon is the edge of everything compared in a measurement made here. Inside the horizon, no comparer can tell our ball apart, by any comparison, from a ball cut out of a flat space that goes on without end. Chapter 4 showed the principle of identity: what cannot be told apart by any comparison, in any respect, is one thing and not two. So two descriptions are one description by the principle of identity: "the ball we hold" and "a ball of a flat space without end". For every measurement made from inside, then, space is the same as a flat space without end, because space and a flat space without end cannot be told apart by any comparison. The ball that a measurement holds counts as one, whatever lies beyond the horizon. The open space counts as one, whatever it is beyond the horizon.

The answer holds for every finding: for you at your table, for an astronomer at a telescope, and for every comparer in every galaxy. Every finding also agrees with a flat space that closes, like the game screen, on a scale larger than every horizon. A space closed on so large a scale cannot be told apart from a space without end by any comparison made from inside. Our particle horizon grows every year, and a later astronomer will see farther than we do. Yet the later astronomer will still have a horizon, as we do. Any one horizon can be passed; the horizon as a kind of edge is one every comparer always has. For the horizon as a kind of edge, the word "beyond" has no meaning. So there is an answer to the question of the size of the universe, asked from inside: space is flat, with no short loop, and the same as a space without end for every finding.

Set the authors' three possibilities beside the answer that space is flat, with no short loop: a finite amount of matter in an infinite space, a finite space that loops back on itself, and an infinite space filled with matter without end. Within our view, a space that loops back on itself is excluded twice: by the count of one, and again by the search that found no matched

rings. A finite space closed beyond every horizon and a space without end are, for every finding, one answer. Space continues beyond our horizon, and the regions beyond our horizon are further parts of one world, because each of those regions is joined to its own neighbors as our region is joined to ours. The authors found that no point is the center of an infinite space. The authors' result follows from their own definition of a center. In a flat space without end, every point has the same amount of space in every direction. So every point satisfies the authors' definition of a center equally, and no point is the center.

So the answer to "where are we?" is the answer the cup on your table showed. Each finding is made at the center of the horizon of whoever makes it, so every comparer stands at the center of its own horizon, in a flat space that has no center.

Why So Much Room?

The authors turn to the emptiness of the universe near the end of their chapter on its size. Our solar system is about nine billion kilometers wide, and the nearest star is about forty trillion kilometers away. Our galaxy is about a hundred thousand light-years wide, and the Andromeda Galaxy, Hubble's galaxy, is about two and a half million light-years away. The authors trace the emptiness to two quantities: the speed of light, which sets what counts as near and far, and the stretching of space. "We don't know why either of these quantities are what they are" (*We Have No Idea*, ch. 15, "And Why Is the Universe So Empty?").

In earlier chapters of this book I have answered both halves of the authors' question, each half in part. Chapter 15 showed that the speed of light is the outer edge of comparison, the edge of what any one act of comparing can connect, and that the number of the speed of light states only the size of our meter against our second, the way a rate of exchange states one currency in another. Chapter 3 showed what the constant term of the stretching is. The cosmological constant is the share of the energy of empty space that a measurement made from inside takes in, and the

smallness of the cosmological constant is the largeness of what we can see. So one number remains of the authors' two quantities, a number that stays the same in every choice of units: the width of our horizon measured against the Planck length.

Picture a ladder standing in the width of our horizon, with a scale of length at each rung. At the bottom is the Planck length, about ten to the minus thirty-five of a meter, the length at which, as Chapter 10 said, the two great descriptions of physics, quantum physics and Einstein's gravity, meet. At the top is the radius of all we can see, about forty-four followed by twenty-five zeros of meters. The bottom and the top of the ladder are about sixty-one powers of ten apart: from the bottom rung, you would multiply by ten sixty-one times to reach the top. On the rungs between stand the sciences: the nuclear, the atomic, the molecular, the biological, the planetary, the stellar and the galactic. I give the reason the rungs are there. A domain is the range within which comparisons can be made (Chapter 8). Each kind of comparison has its own domain. Every domain has two edges, a farthest reach and a finest grain. The wider the span between the two edges, the more levels of structure the domain allows. Each level can sit inside the level above it, as a part, and can hold the level below it. Nuclei sit inside atoms, and atoms inside molecules. If a span were only a few powers of ten wide, the span would hold almost nothing between its floor and its ceiling. A span of sixty-one powers of ten holds atoms, cells, planets, stars and galaxies, with room around each.

So the emptiness is the span of sixty-one powers of ten, seen from inside the span by the authors on their mountain top: the room between the smallest scale and the largest, in which everything we know has its place. Every domain has edges of two kinds, a farthest reach and a finest grain, and both kinds follow from what comparison is. In our domain the width between the two edges is sixty-one powers of ten. The width is found by measurement, as Hubble found the distance to Andromeda.

The short answer

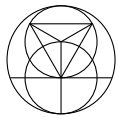
Every comparer stands at the center of its own horizon, in a space that is flat, with no short loop anywhere, and that is the same as a space without end for every measurement made from inside, since the two cannot be told apart by any comparison.

The short answer tells you where you stand in the world of this book: at the center of a horizon that every comparer equally has, in a space whose emptiness is the room between the smallest scale and the largest. The short answer states the size of the universe from where the finder stands, as every finding states anything.

In a space so large that, for every finding, it is the same as a space without end, is there another you?

PART SIX

FROM THE BEGINNING TO YOU



Chapter Twenty-Four

Is There Another You?

In which a copy of you turns out to be a second person, the regions beyond our horizon turn out to be parts of our one world, and the other universes that would hold copies of you turn out to be excluded

Is there another you out there?

What this chapter uses

A *comparison* is the act of finding whether two things are the same or different in some respect, and every measurement is a comparison; a *finding* is the outcome of one comparison, laid down as a record; a *comparer* is whatever makes a comparison, whether or not the comparer has a mind (Chapter 1).

Continuous: nothing is sudden, as along a ramp; *discontinuous*: something is sudden, as at the edge of a step; *symmetric*: what is found stays the same across a change of setting, as each step of a staircase is like every other; *asymmetric*: different everywhere, as the height along a ramp is (Chapter 1).

The *Incommensuration Theorem*: at the foundation of any event or comparison, symmetry and continuity cannot both be perfect together, and neither can asymmetry and discontinuity. The Incommensuration Theorem is a structural fact about the nature of knowing (Chapter 1).

The *cosmological constant* is the share of the energy of empty space that a measurement made from inside takes in, one number for our whole epoch (Chapter 3).

Gravity and the quantum are two descriptions of one world, joined side by side, with one smooth geometry for each alternative of the matter (Chapter 8).

The world has ten dimensions, one of time, three of space and six of possibility, and the six are the range of what a finding could be, present at every place and never a place themselves (Chapter 11).

Hugh Everett III was a graduate student in physics at Princeton University, and his adviser was John Wheeler. On 1 March 1957 Everett submitted his doctoral thesis on the foundations of quantum mechanics. Quantum theory has one smooth law for how its description changes from moment to moment. In the thesis Everett let the smooth law hold everywhere, with no exception. Everett let the law hold for the atom being

measured, and just as much for the measuring instrument and for the observer. Then Everett followed an observer who makes one measurement after another. The thesis appeared as a paper in July 1957. The journal *Reviews of Modern Physics* printed the paper under the title "'Relative State' Formulation of Quantum Mechanics". In quantum theory's description, a superposition is a combination of alternatives held together, as Chapter 8 explained. In the paper Everett wrote: "Thus with each succeeding observation (or interaction), the observer state 'branches' into a number of different states". Everett went on to say that each branch holds a different outcome of the measurement, and that "All branches exist simultaneously in the superposition after any given sequence of observations". Everett expected a doubt from his readers: nobody feels the branching. Everett answered the doubt with an old case from astronomy, in a note that he added to the printed proofs of the paper. He compared the doubt to the old complaint against the astronomer Copernicus, who held that the Earth moves around the Sun. The complaint was that the Earth cannot be moving, because nobody feels the Earth move.

Everett called his account the relative state formulation, and he never described his account in terms of many worlds. Later readers gave Everett's account the name it has today. *Many worlds* is the account in which every outcome of every quantum event happens, each in its own branch of the world, with a copy of every observer in each branch. On the many-worlds view, the observer who reads a dial is copied at every outcome, and each copy remembers a different result. So Everett's paper brought the question whether there is another you into physics. If a copy of you, somewhere, is reading these words right now, is that copy another you?

From Cham and Whiteson's pages

What Cham and Whiteson Showed

Jorge Cham and Daniel Whiteson begin their answer with how special you are. For you to exist, a supernova had to shock the right cloud of dust, the Earth had to form at the right distance from the Sun, your

ancestors had to meet, and you had to make every small choice that made you. Cham and Whiteson count the events that had to go one way and not the other, from your own choices back through your ancestors and on to the Big Bang, and in the authors' count each event is a toss with two outcomes. The authors' count comes to about a quadrillion tosses (a million billion). So the odds of you are one in two multiplied by itself a quadrillion times. Picture a die whose number of sides is two multiplied by itself a quadrillion times. In the authors' picture, making you again is like rolling the die twice and getting the same number both times.

Then Cham and Whiteson show three ways in which another you could still be out there: two kinds of multiverse, and our own universe. A *multiverse* is a collection of many universes, each a whole world of its own, cut off from ours. The first way is the multiverse of different universes, in which every universe has its own values for the basic numbers of physics. The authors give the reason why physicists propose the multiverse of different universes, and the reason is a number. The number is the cosmological constant, the one constant term of Einstein's equations of gravity, which Chapter 3 met as dark energy. In our universe the cosmological constant has a value that the authors write as one part in ten to the one hundred and twenty-two. To physicists, the value seems to have no reason to be what it is. Among infinitely many universes with every value, our universe would be one sample.

The second way is the quantum multiverse, and the authors explain the quantum multiverse with an electron. Shoot an electron at another particle, the authors write, and nothing tells you ahead of time whether the electron will bounce left or right. Cham and Whiteson ask what makes the electron go one way: "Does the electron choose which way to go just because?" (*Frequently Asked Questions About the Universe*, ch. 3, "The Quantum Multiverse"). To a physicist, the authors write, "just because" is not good enough. The quantum multiverse is the answer

physicists give: at every quantum event the universe splits, and every outcome happens. The authors give the appeal of the quantum multiverse in one line: "It's not random, because the electron goes both ways" (*Frequently Asked Questions About the Universe*, ch. 3, "The Quantum Multiverse"). In a universe that branches at every event, there are countless yous, and more yous are made every moment.

The authors state that neither kind of multiverse has been confirmed. The authors write of the other universes that "we aren't connected to them and we don't have any way to interact with them" (*Frequently Asked Questions About the Universe*, ch. 3, "Is the Multiverse Real?"). Cham and Whiteson describe one more kind of multiverse in their earlier book, *We Have No Idea*: the pocket universes of an inflation that never stops (*We Have No Idea*, ch. 14, "Maybe There Are Lots of Universes"). Inflation is a brief phase that many physicists place early in our history, in which space grew enormously fast, as Chapter 20 told. In an inflation that never stops, new universes keep forming inside the inflating space. Each new universe is a pocket, and no two pockets ever meet. If there is an inflation that never stops, the authors write, some of the pockets hold nearly identical copies of the Earth.

The third way, another you in our own universe, needs no other universe. Each time a cloud of gas collapses into a star, the giant die is rolled once more: one more chance to make you again. A copy of you, the authors write, could form "a few solar systems over or maybe just on the other side of the galaxy" (*Frequently Asked Questions About the Universe*, ch. 3, "Another You in Our Universe"). In the authors' count, our galaxy alone gives two hundred and fifty billion rolls. The part of the universe we can see gives far more. A universe large enough gives enough rolls that a second you becomes more likely than not. Then the authors report what physicists think about the size of the universe: "In fact, they think the universe is most likely infinite" (*Frequently Asked Questions About the Universe*, ch. 3, "Another You in Our Universe"). In an infinite universe the die is rolled without end, and you

come up again, and again, without end. The authors write that in an infinite universe all the copies of you "would be in the same universe, sitting in the same space" (*Frequently Asked Questions About the Universe*, ch. 3, "An Infinite Universe").

Cham and Whiteson end their chapter like a soap opera, on a cliffhanger between two answers. If a multiverse is real, or if the universe is infinite, then in the authors' words "most certainly the answer is yes" (*Frequently Asked Questions About the Universe*, ch. 3, "Wrapping It Up"). If neither is true, the answer is almost certainly no. In the same section the authors put the choice in one sentence: "Either there is most likely only one of you in the entire universe or there is an infinite number of you" (*Frequently Asked Questions About the Universe*, ch. 3, "Wrapping It Up"). Along the way the authors ask the question from which I start my answer. They ask whether a copy of you, born in a slightly different universe, would be exactly like you (*Frequently Asked Questions About the Universe*, ch. 3, "The Different Universes Multiverse").

Two Cups on Two Tables

What would make a copy of you be you, and not someone else?

Look at your cup. Now picture a second cup, made in the same factory on the same day, filled with the same coffee at the same warmth, standing on a table in another house. The two cups match in everything: the glaze, the same small chip on the rim, the warmth. Lift your cup. One cup is in your hand, and the other cup is not. Finding the cup in your hand is one comparison, which you make from where you sit, and in that comparison you tell the two cups apart. Two identical cups on two tables are two cups.

In Chapter 4 we met the rule for when two things are one, in the case of the electron. We found that every electron is found exactly like every other electron. Nothing about an electron carries a trace of where the electron came from. We also met the ground on which I build my account, the

Immanent Metaphysics: what no comparison can tell apart, in any respect at all, even in principle, is one thing and not two. The rule has a name, the *principle of identity*, and I state the principle in these words: what no comparison can distinguish, in any way at all, is one thing and not two. In Chapter 4 the principle of identity showed that two electrons in one state would be one electron, which is why no two electrons are ever found in one state.

The principle of identity also says when two things are two. Each thing has its pattern of verdicts: the verdicts, same or different, of every possible comparison of that thing with every other thing. When two things have the same pattern of verdicts, the two things are one. When two things differ in the verdict of even one comparison, anywhere, the two things are two. Picture a pair of coins: two identical coins, one in each hand, are not one. Compare each coin with your left hand: one coin is in your left hand, and the other coin is not. The two verdicts differ, so the coins are two.

Now put a person in place of the cup. Suppose that on a planet far away there stands someone made atom for atom as you are, with your face, your memories, your taste in fruit and your sense of humor. The copy stands on that far planet, and you stand on the Earth. Ask a question as plain as "which of you is here?", and the two of you get different verdicts. So the copy differs from you at least in place, and by the principle of identity the copy is a second person.

But, you may ask, if the copy shares every memory, would the copy not be me? The copy's memories would match yours, as the chip on the other cup matches the chip on your cup. Each set of memories would still be found in one body, at one table: yours in your body, and the copy's in the copy's body. From the next moment on, you and the copy would each make findings that the other never makes. Take the authors' soap opera: suppose you did meet your twin, evil or kind. At the meeting you would look at each other across the room. Each look would be a comparison with the verdict that there are two of you. Wherever a copy of you stood, the copy would be someone else who looks like you.

"Another you" can ask two questions. The first question is whether you yourself are anywhere else. The principle of identity has a direct answer to the first question: you are one, and every copy of you is a second person. The second question is whether someone exactly like you exists somewhere. The second question is about what the world holds. We answer the second question by examining each place where the authors look for a copy of you.

Beyond Our Horizon

Start with the third way, the copies in our own universe, because there the authors and I look at the same place. Chapter 23 found that every comparer stands at the center of a horizon of its own. A comparer's horizon is the edge of everything whose light has reached that comparer. The authors place their copies anywhere in our own universe, from a few solar systems over to regions far beyond what we can see. The farthest of the authors' copies lie beyond our horizon, in galaxies whose light has not reached us.

What are the regions beyond our horizon? I answer with a second principle, the principle of existence, which I state in one line: "Existence without any interaction whatsoever is indistinguishable from non-existence, and therefore is non-existence". In plain words, a thing that interacts with nothing at all does not exist. The regions beyond our horizon, however, do interact, each region with its own neighbors, as our region does with our neighbors. Regions beyond a horizon interact with what is near them, so they exist; they are further parts of one world, and not another universe. So I agree with the authors that the regions beyond our horizon are real. Those regions are parts of our universe, in the same space as our region: one world. My account and the physicist Max Tegmark agree in substance on the regions beyond our horizon: those regions are the same space as ours, with the same laws.

How far does our one world extend? Chapter 23 gave the answer for every measurement made from inside the world. Every measurement made here is confined to the ball of space inside our horizon, and the horizon bounds everything that a measurement made here has compared. When no one can tell two descriptions apart by any comparison, the two descriptions are one description, by the principle of identity. So, for every measurement made from inside, space is infinite in this exact sense: no one can tell our space apart, by any comparison, from a space without end.

That exact sense of "infinite" is a statement about what every finding can contain. The authors' count needs a different statement: an infinite number of stars that actually form, each star one more roll of the die. The regions beyond our horizon are further parts of one world, under one law. The regions beyond our horizon hold some number of stars and people, and that number is a fact about what the world holds there. Whoever stands in the regions beyond our horizon, the principle of identity has already said what each person there is: someone at a table of their own, a second person and not you.

Universes with Other Numbers

The first way, the multiverse of different universes, needs two things. The first need is a range of possible values for the basic numbers of physics, so that different universes can have different values. The second need is a process that makes the universes, each universe with its own values.

My account has one answer to both needs: one set of values, and no process that makes universes with other values. As Chapter 9 told, string theory has six extra dimensions curled up small. Fields can be threaded through the six curled dimensions in an immense number of ways. Each way of threading the fields gives a different state for empty space to settle into. Each such state is a valley, with the valley's own particles and forces, and the whole many-valleyed country of the valleys is the landscape. Chapter 9 also found that my account has one valley, because I build the

law of gravity from geometry alone and thread no field through the six small dimensions of possibility, which is this book's name for the six extra dimensions. Chapter 11 found that the six small dimensions are held at one size and one shape. I put the result in a short phrase: "the six have one vacuum", which means one state for empty space to settle into. One vacuum gives one set of values for the basic numbers of physics, the set our world has. I exclude the multiverse of different universes on a structural ground: one internal space (the six small dimensions), one vacuum, no landscape.

My account also has its own answer for the cosmological constant, the number that made physicists propose a multiverse. Chapter 3 found that the cosmological constant is the share of the energy of empty space taken in by a measurement made from inside, and that the cosmological constant has one value for our whole epoch. I begin with the alternative that the authors describe, in which the value is an accident, one value among countless others in a vast multiverse. I then give the cosmological constant a reason. The reason needs no choosing of our universe from among many universes. So there is an answer, inside our one universe, to the authors' question of why the cosmological constant takes the value it does.

The second need fails as well: no process makes universes with other values. In *We Have No Idea*, the universes with other values are pocket universes of an inflation that never stops. The authors write that perhaps the basic numbers were set at random early on, and have "different values" in other pockets (*We Have No Idea*, ch. 16, "How Will We Know If We Are Done?"). An inflation that never stops is a long inflation: the kind of inflation that would have made the ripples we see. Chapter 20 found, on two separate grounds, that no long inflation happened. The first ground is the first ripples, the faint departures from evenness with which our epoch began. Chapter 20 identified the first ripples with the form of the epoch before ours, carried through the turn (the limit at which our epoch began, which the authors call the Big Bang) with the differences of the old epoch averaged and not erased. Once the first ripples are identified with that carried form, a long inflation cannot have happened, because a long infla-

tion would have made the first ripples itself, out of the trembling of its own empty space. The second ground is the dark matter: after an inflation that made the ripples, the early universe would have been too cool to make the dark matter in the amount measured.

In 2005 the physicist Max Tegmark published a calculation of what inflation predicts when the theory beneath inflation has many valleys, as the landscape of string theory has. An inflation leaves waves of space itself, and the waves are stronger the higher the energy at which the inflation runs. Where the energy of the inflation is highest, Tegmark's calculation gave waves with about fifteen hundredths of the power of the first ripples. In 2022 Matthieu Tristram and his colleagues combined the measurements of the BICEP and Keck telescopes with the measurements of the Planck satellite. Tristram and his colleagues found that any waves of space from the beginning carry less than about three hundredths of the power of the first ripples, which is the bound that Chapter 20 told. We now know that the strongest waves of Tegmark's calculation are not in the sky, because fifteen hundredths is far more than three hundredths.

My account has other worlds of its own, of another kind than the authors' pocket universes. The other worlds of my account are the epochs: the world before ours, whose black holes came to one shared end that began our world, and the world after ours. I describe the order of the epochs: "The epochs follow one another in a single line, with no branching family of universes for selection to act on, and the law holds again in each of them". Each epoch has the same law and the same one vacuum, and no journey links any two epochs. Chapter 17 gave the reason that no journey links two epochs. The reason uses the picture of Chapter 14: a country in which the only way to travel is by road. The towns stand for the places of the world, and the roads stand for the paths by which one event can affect another. In the same way, when a path from here can reach a place, that place is part of our own world. The authors know of no way to reach another universe. I show that any universe a path could

reach would be part of our own world. Nothing of you crosses from our epoch into the next epoch as you. Nothing of you crosses as you. Chapter 28 shows what does cross: the form of everything you are and do.

Everett's Branches

The second way, the quantum multiverse, began with Everett's paper. First, what many worlds achieves: many worlds needs no extra rule and no special role for instruments, and in the many-worlds account one equation applies to an atom and to the whole universe.

Chapter 12 found that physicists use one word, "time", for three different times. Two of the three times matter for many worlds: evolution time and event time. Evolution time is the number on the dial of quantum theory's rule: the smooth time along which quantum theory's description of what could be found, and with what odds, moves forward. Event time is the time of findings: one outcome found, then the next, each laid down as a record. Many worlds has only evolution time, and in the many-worlds account event time becomes a part of evolution time. Many worlds keeps only evolution: in the many-worlds account a finding becomes a branching of the description, and no outcome is ever selected.

I then show where the findings come back into the many-worlds account. Many worlds has two difficulties, and in each difficulty the findings that many worlds set aside come back. The first difficulty is which branches there are, because the description can be divided into branches in many ways, and choosing the division is choosing which findings count as having happened. The second difficulty is what the odds mean: if every outcome happens, many worlds has to say what it means for one outcome to have odds of nine in ten. Both difficulties need findings, because a division into branches is a choice of findings, and odds are odds of findings. The physicists David Deutsch and David Wallace have argued that the odds can be built again from inside the smooth law. Specialists still debate the arguments of Deutsch and Wallace. I read the specialists' debate as

one fact: the debate is the finding asserting itself. In plain words, the debate goes on because the odds are odds of findings, and many worlds set the findings aside.

My account has a second ground for excluding many worlds, beside the ground of the findings. Many worlds describes the whole world as completely fixed by one law, with every state carried exactly into the next and nothing new entering anywhere. In a world completely fixed by one law, symmetry and continuity are both perfect. Every state passes into the next state by the same law, everywhere and at every time. A law that is the same everywhere and at every time is symmetry made perfect. Every state is fixed at every point, with no gap through which anything new could enter between one state and the next, and a world with no such gap has continuity made perfect. A whole world completely fixed by a law perfects symmetry and continuity together, whichever account describes it, and the theorem forbids that pairing. So there is no quantum multiverse, and the authors' electron stays as physicists find the electron: the electron goes one way, the outcome is found, and that one outcome is the one the world holds. The authors' "just because" names something real: an outcome that nothing before the outcome fixes. Chapter 26 shows that an outcome that nothing before it fixes is chance seen from outside and choice seen from inside, and that people are fairly predictable but never completely predictable.

So Everett's observer reads the dial once and finds one result.

So, Is There Another You?

Put side by side the four places where the authors look for another you. Beyond our horizon, the regions are parts of our one world, and anyone standing there is a second person, at a table of their own. The universes with other numbers are excluded by the one vacuum. The branches of a quantum split are excluded twice: by the finding, which selects one outcome, and by the Incommensuration Theorem. The pocket universes are excluded together with the long inflation that would make the pock-

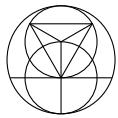
ets, on the two grounds of Chapter 20: the first ripples and the dark matter. The other worlds of my account, the epochs, follow one another in a single line, and nothing of you crosses into the next epoch as you.

The authors found little middle ground: one of you, or infinitely many. My account has an answer of another kind than either. That you are one is a fact about what a comparison is. However many people in the world resemble you, their number is a fact about what the world holds, and no such number changes the fact that you are one. Your cup is on your table. Whether or not a cup just like your cup stands on some other table, the cup in your hand is the one you lift.

> **The short answer**
>
> Wherever a copy of you stood, the copy would be a second person, and the other universes that would hold copies are excluded, while the regions beyond our horizon are parts of our one world.

So the question "another you?" has its answer in what "you" means to a comparison: one finder, found where the finder is, and told apart from every likeness by at least one finding. The next four chapters use that meaning of "you" to ask four questions: what a description of you can carry, whether you can be predicted, whether you could be a program, and what is kept of you at the end.

Could a machine make the copy, by teleporting you?



Chapter Twenty-Five

Why Can't We Teleport?

In which the leaning of one photon is moved to another and nothing is copied, a recipe for coffee crosses the sea, and a person turns out not to be a file

Why can't we teleport, and if I am just information, why not send me?

What this chapter uses

A *comparison* is the act of finding whether two things are the same or different in some respect, and every measurement is a comparison; a *finding* is the outcome of one comparison, laid down as a record; a *comparer* is whatever makes a comparison, whether or not the comparer has a mind (Chapter 1).

The *content* of a finding is what the finding finds, as the warmth of your coffee; the *context* is where the content is found, and the context has three sides, the three settings of space, time and possibility (Chapter 1).

Continuous: nothing is sudden, as along a ramp; *discontinuous*: something is sudden, as at the edge of a step; *symmetric*: what is found stays the same across a change of setting, as each step of a staircase is like every other; *asymmetric*: different everywhere, as the height along a ramp is (Chapter 1).

The *Incommensuration Theorem*: at the foundation of any event or comparison, symmetry and continuity cannot both be perfect together, and neither can asymmetry and discontinuity. The Incommensuration Theorem is a structural fact about the nature of knowing (Chapter 1).

The world has ten dimensions, one of time, three of space and six of possibility, and the six are the range of what a finding could be, present at every place and never a place themselves (Chapter 11).

The speed of light is the *edge of comparison*, the outer edge of what any comparison can connect, the same for every comparer (Chapter 15).

At the Institute for Experimental Physics of the University of Innsbruck, in Austria, six physicists moved a property of one particle of light onto another particle of light. The six physicists were Dik Bouwmeester, Jian-Wei Pan, Klaus Mattle, Manfred Eibl, Harald Weinfurter and Anton Zeilinger. They reported the Innsbruck experiment in the journal *Nature* on 11 December 1997, under the title "Experimental quantum teleporta-

tion". The property that the six physicists moved was the polarization of a photon: the direction, across the photon's path, in which the photon's light vibrates. Chapter 20 met polarization in the oldest light of the sky. A pair of polarizing sunglasses shows polarization at work. Each lens passes light that vibrates one way, upright for example, and stops light that vibrates level.

The team readied a photon called photon 1 that vibrated at forty-five degrees, halfway between upright and level. A short pulse of ultraviolet light passed through a crystal and made two more photons, photon 2 and photon 3. Photons 2 and 3 came out entangled, in the sense of Chapter 15: linked so that their measured results agree in a pattern that no instructions carried by the particles could give them. The team brought photon 1 and photon 2 together at a beam splitter. A beam splitter is a half-silvered mirror that lets part of the light through and turns the rest aside. Two detectors watched the light that left the beam splitter. In about one case out of four, the two detectors clicked together. Whenever the two detectors clicked together, the team looked at photon 3, which had never met photon 1. The team set a detector to catch photon 3 vibrating at minus forty-five degrees, the leaning (the direction of vibration) opposite to photon 1's, and the detector's counts fell sharply. When a detector was set for plus forty-five degrees, the detector's counts held steady. Photon 3 now carried the leaning that photon 1 had been given. The team repeated the experiment with other leanings: minus forty-five degrees, upright, level, and a leaning that turns round as the light travels.

The Innsbruck paper describes teleportation as "the transmission and reconstruction over arbitrary distances of the state of a quantum system". The paper also says what became of photon 1: after the joint measurement (the two detectors clicking together at the beam splitter), "particle 1 is not available in its original state any more". So the leaning of one photon moved to another photon, and photon 1 no longer had that leaning. The leaning arrived at photon 3. Nothing traveled faster than light. No two

photons carried the leaning at the same moment. Your question, why not send me if I am just information, asks whether a person could be moved as the leaning of photon 1 was moved to photon 3 in Innsbruck.

From Cham and Whiteson's pages

What Cham and Whiteson Showed

Jorge Cham and Daniel Whiteson take up teleportation in *Frequently Asked Questions About the Universe*. They begin with the parts of travel nobody enjoys: the daily commute, the traffic, and the middle seat on a flight across the ocean. They promise, in the words of the old television transporters, to beam the reader up on the physics of teleportation.

Cham and Whiteson's first answer is that nobody can appear somewhere else at the same instant, because an effect needs a cause, a cause has to reach its effect, and nothing reaches anything faster than light. The authors would rather call the speed of light the speed of information. Their second answer is that your body cannot be sent at the speed of light either, because nothing with mass can reach that speed, and you are made of particles with mass. Then Cham and Whiteson propose a different trip: "What if we just transmitted the idea of you?" (*Frequently Asked Questions About the Universe*, ch. 6, "Getting There at Light Speed"). Their recipe has three steps: scan your body and record where all your particles are; send the record as a beam of light; and rebuild you at the far end from new particles. The authors explain that new particles will do, because every electron is exactly like every other electron, and the same is true of quarks.

The authors write that the real limit might be philosophical and not technological: if someone made a copy of you, would the copy be you? They then ask how much detail the copy needs. They weigh two cases. If what makes you yourself lies in the arrangement of your cells and molecules, then a copy needs only a list of the places of your cells and molecules, like a house of toy bricks taken apart and rebuilt from writ-

ten instructions. If what makes you yourself lies in the quantum detail of every particle, copying is much harder. Cham and Whiteson give two reasons. The first reason is the *uncertainty principle*: nobody can know everything about a particle at once. Cham and Whiteson explain that a particle's position and its velocity do not both exist as exact information at the same time (*Frequently Asked Questions About the Universe*, ch. 6, "You're Totally Quantum"). The second reason is a theorem: "The quantum 'no-cloning' theorem tells us that it's impossible to read quantum information without destroying the original" (*Frequently Asked Questions About the Universe*, ch. 6, "Making a Quantum Copy"). For the quantum case, Cham and Whiteson describe quantum teleportation. They report that the record for quantum teleportation so far is 1,400 kilometers. In a footnote they add that quantum teleportation sends nothing faster than light, because the sender must still share what she saw by ordinary communication, which is limited to the speed of light.

On the quantum copy, Cham and Whiteson lean toward yes. They say that the quantum copy would be the closest reproduction of you that can possibly be made. They ask, "If that's not you, then who are you?" (*Frequently Asked Questions About the Universe*, ch. 6, "Making a Quantum Copy"). Also in chapter 6, under the heading "Too Many Yous", they take up a further worry: a machine that copies only the arrangement of your cells could print you again and again, here and on one planet after another. Cham and Whiteson write that the quantum machine scrambles the original as the machine reads the original, so the copy sent is the only copy that remains. In their recap they name two conditions on which teleportation waits (*Frequently Asked Questions About the Universe*, ch. 6, "Beam There, Done That"). The first condition is that you can put up with the delay of a message sent at the speed of light. The second condition is that you accept a scanned and rebuilt version of you as really you. In their chapter on the afterlife, Cham and Whiteson state the premise behind their whole tele-

porter: "you are just the information about how those particles are arranged" (*Frequently Asked Questions About the Universe*, ch. 13, "A You Beyond You"). Their chapter on teleportation ends with the receiver. Someone has to travel to the far end the old way first, to build the machine that will rebuild you.

Cham and Whiteson state four results that I agree with: nothing arrives faster than light; particles of one kind are exactly alike; a quantum state cannot be copied; and quantum teleportation leaves one copy, not two. They leave one question to philosophy: whether the copy would be you. The answer in this chapter comes from the structure of comparison, which is what every comparison must contain.

What Can Be Copied

Begin with something that can be copied as often as you like. Send a photon at a filter that passes upright light and turns level light aside, with a detector behind each path. One detector clicks, and you write down "upright". The word "upright" can be copied onto a hundred cards, photographed, read aloud and sent by radio. Every copy is as good as the first.

Now take a photon leaning at forty-five degrees, like photon 1 in Innsbruck, and try to copy the leaning itself. To copy the leaning you must first find the leaning. You can find out anything about the photon only by comparing the photon with something: by sending the photon at a filter. The upright filter can sort a photon only into upright or level, so the filter asks one question, "upright or level?". The photon leaning at forty-five degrees answers upright half the time and level half the time. Whichever answer the photon gives, the photon leaves the filter upright or level, and the leaning of forty-five degrees is gone. A filter set at forty-five degrees would pass the photon every time. But only someone who already knows the leaning can choose the filter set at forty-five degrees. The copier does not know the leaning to be copied.

Chapter 12 described a small body by its quantum state: the smooth mathematical wave that sets the odds of each possible finding. The *no-cloning theorem* says that no process can make an exact copy of an arbitrary quantum state, a state that the copier does not already know. William Wootters and Wojciech Zurek published the no-cloning theorem in 1982, and Dennis Dieks also published the theorem in 1982.

Picture a walk to the north-east across an open field. The walk to the north-east is a step north and a step east taken together, in equal parts. Quantum theory describes the photon leaning at forty-five degrees as the walk is described: as the upright leaning and the level leaning held together in equal parts, as the two steps are. Quantum theory writes the two equal parts as a sum: upright plus level. The sum upright plus level is a superposition, in the sense of Chapter 8: a combination of alternatives held together in quantum theory's description. The upright filter finds the photon leaning at forty-five degrees upright half the time and level half the time, because the two parts of the sum, upright and level, are equal.

Now turn the map of the field a little. The north-east walk turns because the north step turns and the east step turns. The turned walk is the sum of the two turned steps. Quantum theory has the walk's rule for every change of a quantum state, and in this chapter I call the walk's rule the rule of sums. The rule of sums says that the change of a sum is the sum of the changes of the parts. The argument by which Wootters and Zurek proved the no-cloning theorem uses the rule of sums. Picture a machine that copies "upright" onto a blank photon to give two upright photons, and copies "level" in the same way to give two level photons. Now feed the machine a photon leaning at forty-five degrees, which is upright plus level. The rule of sums says that the machine must give the sum of its result for upright and its result for level: two upright photons together with two level photons, held in one entangled pair. The entangled pair holds no single photon at forty-five degrees, so the machine has made something other than two copies.

In this book's account the no-cloning theorem also holds, and the theorem follows from a ground separate from the ground of Cham and Whiteson. Cham and Whiteson state the theorem as a result of quantum theory. I derive the rule of sums from the structure of comparison itself (what every comparison must contain). The no-cloning theorem then follows from the rule of sums by the standard argument of Wootters and Zurek. Which states can be copied, and which cannot? The outcomes of one question can be copied: "upright" and "level", for example, the two outcomes of the upright filter's question. So records can be copied, and your word "upright" could go onto a hundred cards. When a state lies between the outcomes of a question, the state cannot be copied. The reason is that a comparison can end only in an outcome of its own question, and once one outcome is found, the outcome found has replaced the state that lay between the outcomes. A comparison makes its finding, and does not only report something already there.

Chapter 1 showed that every finding has a content (what the finding finds) and a context (where the content is found). I also give the reason for the no-cloning theorem in terms of content and context. A copier of every state would have to treat the state as pure content, something to be read off and written again. But the state is also context: the state defines the framework within which measurement outcomes are possible. Content and context are inseparable in every comparison, so an attempt to lift out the content alone disturbs the state. Cham and Whiteson state the no-cloning result in the words "impossible to read quantum information without destroying the original". On my account, the reason for the no-cloning result lies in what a finding is.

Moving Without Copying

An unknown quantum state cannot be copied, but the same state can be moved. *Quantum teleportation* is the moving of an unknown quantum state from one place to another, which leaves no copy behind. The method

of quantum teleportation was described in 1993 by Charles Bennett, Gilles Brassard, Claude Crépeau, Richard Jozsa, Asher Peres and William Wootters. I set out the steps of the method.

Picture two friends far apart, a sender and a receiver who each hold one photon of an entangled pair. The sender is handed a third photon with an unknown leaning. She measures the third photon together with her half of the pair, in one joint measurement. The joint measurement gives one of four outcomes. Naming one of four outcomes needs two bits: two answers of yes or no. The joint measurement also leaves the receiver's photon holding the unknown leaning, turned by one of four known turns. The outcome that the sender found names which of the four turns the receiver's photon was given. The sender sends her two bits to the receiver by ordinary means: a radio, a cable, a letter. The receiver reads the two bits, turns the photon back by the turn the two bits name, and now holds the unknown leaning.

The steps of quantum teleportation have three results. The first result is the speed: the state arrives only when the two bits do, and they travel no faster than the speed of light, the limit of every causal signal. The second result is that the entangled pair is used up. The third result is that the sender's photon no longer holds the state, "so nothing is copied, as the no-cloning theorem requires". The limit of every causal signal is the edge of comparison of Chapter 15: the outer edge of what any comparison can connect, the same for every comparer (whatever makes a comparison). Nothing about the leaning arrives at the receiver ahead of the two bits. Before the two bits arrive, the receiver's photon measured alone gives each answer to any question half the time, whatever the unknown leaning was.

The joint measurement has four outcomes, and in Innsbruck the team caught only one of them. After the outcome the team caught, photon 3 needs no turn at all. So the team counted one case in four. In each counted case, the team used the record of the two detectors at the beam splitter to choose which photons to count. Photon 3 showed the leaning only when the counts of photon 3 were set beside the record of the two detectors.

So on teleportation, Cham and Whiteson and I agree. Cham and Whiteson call the outcome of teleportation a quantum copy. They add at once that the original is destroyed, so that one copy remains. On my account, the outcome of teleportation is a move, not a copy: one state, held first in one place and then in another, and never held in two places at once. Cham and Whiteson's footnote and my account also agree on the speed: the footnote says that what the sender saw must be shared by ordinary communication, which is limited to the speed of light. No communication travels faster than light, because the two bits of the sender's message are a signal, and every signal stays inside the edge of comparison (the outer edge of what any comparison can connect).

Twenty years after Innsbruck, physicists teleported quantum states over the distance that Cham and Whiteson quote. In 2017 Ji-Gang Ren and thirty-one colleagues teleported the states of single photons from a ground station at Ngari, in Tibet, 5,100 meters above the sea, to the satellite Micius, which had been launched from China on 16 August 2016. The satellite passed overhead at distances from about 500 to about 1,400 kilometers. The team tested how closely each state that arrived matched the state that was sent. On average, the answer to the test question "is this the state that was sent?" was yes about four times in five. A match of four times in five is well above the best match that any method without entanglement can achieve. We now know that a quantum state can be moved from the ground to orbit, with nothing copied and with the two bits of each move sent by ordinary means.

The Recipe and the Cup

Go back to your own table and the cup of coffee you set there before Chapter 1. Write down the recipe for your coffee: the beans, how fine the grind, how hot the water, how long it steeps, how much milk. Read the recipe over the radio to a friend across the sea, and your friend brews a cup from the recipe.

Your friend's cup is a cup of coffee, warm and good to drink. For every purpose a coffee drinker cares about, your friend's cup does what your cup does. I name what makes your friend's cup possible. In my sense of the word, a thing is classical when the thing can be virtualized: when a model of the thing can be built that behaves as the original does for every purpose that matters. Your coffee is classical. The recipe counts as a model of your coffee in this sense, because from the recipe a cup can be brewed that behaves as your cup does for every purpose that matters. So a cup of coffee can be rebuilt from a description.

Two facts about the brewing stay true all the same. Your cup is still on your table. The cup across the sea is a second cup. Chapter 24 gave the principle of identity: what no comparison can distinguish, in any way at all, is one thing and not two. You can tell the two cups apart by a comparison as plain as "which one is on my table?". And the recipe crossed the sea, never the coffee. The recipe is a description of your coffee: a map of your coffee, drawn in words, from which someone who has beans and water can make a coffee of the same kind.

Cham and Whiteson's teleporter is the radio and the recipe, applied to you: the scan writes the recipe, the beam of light is the radio, and the rebuilding at the far end is the brewing. Cham and Whiteson give a sound reason why new particles will do at the far end. So the material at the far end is no obstacle, exactly as Cham and Whiteson say. A recipe captures a thing when a model built from the recipe matches the thing for every purpose that matters. Whether the teleporter can send you now depends on one question: are you, like the coffee, the kind of thing a recipe captures?

A Person Is Not a File

Picture a smooth ramp poured in concrete, and beside the ramp a staircase of identical steps built to follow the ramp. Make the steps smaller and smaller, and the staircase follows the ramp ever more closely. However small the steps are made, the staircase always has edges, and the ramp has none.

I draw the picture of the ramp and the staircase. The picture shows the Incommensuration Theorem, which Chapter 1 taught with a ramp and a staircase of its own. The steps of the staircase are symmetric, each step the same as every other step wherever the step is built, and discontinuous, each step separate from the next with an edge between. The ramp is continuous, one unbroken run, and asymmetric, since every point of the ramp stands at its own height and the run of the ramp goes one way.

A file, a recipe and a computation are built like the staircase. A file is a list of separate marks, each of a few fixed kinds, read the same way by every reader. A computation goes from one list of marks to the next by one rule, applied the same way at every step. I call computation perfected as computation "symmetry with discontinuity applied absolutely".

Your point of view is like the ramp. I name three things your experience cannot do without: something new arriving that nothing before it fixed, time running one way, and a point of view from inside. From inside your life, your point of view sets this moment apart from every other moment and this place apart from every other place. Across every moment and every place, you go on as one being. The continuity of your point of view is your going on as one being, like the one unbroken run of the ramp. The asymmetry of your point of view is the setting apart of each moment and place, like each point of the ramp at its own height. I call the first-person stance, your stance as the one who looks, "continuity with asymmetry".

A continuity cannot be built out of perfectly symmetric steps, as the ramp cannot be built out of the steps of a staircase. If a computation were also a point of view, the computation would have perfect symmetry, from its one rule, and perfect continuity, from the point of view, both at the same time. The Incommensuration Theorem says that symmetry and continuity cannot both be perfect together. So the Incommensuration Theorem forbids the perfection of computation with subjectivity. In that sentence, *subjectivity* is the first-person stance again: being the one who looks from inside. A description of you, however fine its steps, follows the ramp ever more closely and is never the ramp: the description can match you

more and more closely, and the description is never you. Every file lacks the three things your experience needs, because a file is what remains when something new, a one-way time and a point of view have all been left out. A person is not a very large file. A device that carries a description of a person carries a map of that person, and the person is not in it.

I also state how widely the result that a person is not a file applies. A system can be built that behaves as a person behaves, matching the person's behavior as closely as one likes, and the system would still "not be that person, or any person". A description of behavior is a description from outside, and a description from outside contains no knowledge of an inside. The positive side of the same result decides whether something has a self: whether something has a self depends on whether it is a physical process making comparisons in the world, with an inside, and not on what program it runs.

The Philosophical Question Answered

Cham and Whiteson asked whether the rebuilt copy would be you. Their question now has an answer, in two parts.

First, the beam of light sent from the scanner carries a description of you (a map), and you are not in the beam. The request "send me as information" is the category error of Chapter 8: a concept applied where the concept does not belong. So the request cannot be met because the request is badly formed. A finer scanner, a wider beam and a better printer each improve the map, and none of them puts you in the map. So the request is excluded in principle, and therefore in all future practice.

Second, whatever the receiver builds stands at the far end, and you stand at the near end. Place tells the thing built and you apart, as place tells your cup and your friend's cup apart, so the thing built and you are two. If the thing built at the far end has an inside of its own, the thing has that inside as a physical process making comparisons in the world, at the far end. The inside of the thing built is a second inside, never yours. Under the heading "Too Many Yous", Cham and Whiteson raised the worry

that a machine could print you again and again. The answer to the worry about many prints follows at once: each print would be a second person, a third person, a fourth person, and none of them would be you.

Cham and Whiteson's other question was how much of you depends on quantum detail. I answer the question in the sense of copying, by joining the no-cloning theorem to identity: "In the sense of copying, then, self-identity is quantum and not classical". Your coffee is classical, so a coffee of its kind can be rebuilt from a recipe. What makes you this one person, and no copy of you, lies on the side that no process can copy: the quantum side. Identity, in the sense of a single unitary consciousness, is not something a copy can carry. A *unitary* consciousness is one undivided point of view: the one who looks. So if a copy is made at the level of Cham and Whiteson's toy bricks, the copy carries a likeness of you, and your being this one person stays with you.

Where the Two Accounts Meet

On teleportation itself, Cham and Whiteson's account and mine agree on four results: nothing appears anywhere faster than light; a quantum state cannot be copied; a quantum state can be moved, with the original giving the state up and an ordinary message completing the move; and the record for such a move is 1,400 kilometers, from Tibet to orbit. Cham and Whiteson take the four results from quantum theory and relativity. On my account, the rule of sums (the change of a sum is the sum of the changes of the parts) comes from the structure of comparison and the speed limit comes from the edge of comparison, and the results are the same.

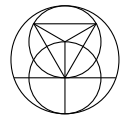
On you, the two accounts differ. Cham and Whiteson take you to be the information about how your particles are arranged. They leave to philosophy the question whether a rebuilt copy is you, and for the quantum copy they lean toward yes. A person is not information: a description of you is a map, the person is not in the map, and anything built from the map at another place is a second thing. Someone can send a re-

cipe across the sea and brew a good cup at the far end, but nobody can send you by the same act, because a cup of coffee is the kind of thing a description captures and a person is not.

> **The short answer**
>
> A quantum state can be moved without being copied, and never faster than light. A person, though, is not information, so a description of you, sent and rebuilt, is a map of you, and you are not in the map.

This chapter is the first in the book to draw the line between a description of a comparer and the comparer itself. The description, a map, can be as fine as anyone likes. The comparer, the one who looks, stays on the other side of the line. Three later chapters use the line between a description and the comparer: the chapters on prediction, on simulation and on what is left after death.

If no description holds you, can anyone predict what you will do?



Chapter Twenty-Six

Are Humans Predictable?

In which a weather model is run twice from almost the same start, a particle gives an answer that nothing settled in advance, and you reach for your cup

Are humans predictable, or do we have free will?

What this chapter uses

A *comparison* is the act of finding whether two things are the same or different in some respect, and every measurement is a comparison; a *finding* is the outcome of one comparison, laid down as a record; a *comparer* is whatever makes a comparison, whether or not the comparer has a mind (Chapter 1).

The three *settings* in which anything is measured are space, the place of a finding; time, the moment of a finding; and possibility, the range of what could have been found instead; a setting is *bent* when one part of the setting differs from another part (Chapter 1).

Continuous: nothing is sudden, as along a ramp; *discontinuous*: something is sudden, as at the edge of a step; *symmetric*: what is found stays the same across a change of setting, as each step of a staircase is like every other; *asymmetric*: different everywhere, as the height along a ramp is (Chapter 1).

The *Incommensuration Theorem*: at the foundation of any event or comparison, symmetry and continuity cannot both be perfect together, and neither can asymmetry and discontinuity. The Incommensuration Theorem is a structural fact about the nature of knowing (Chapter 1).

Gravity and the quantum are two descriptions of one world, joined side by side, with one smooth geometry for each alternative of the matter (Chapter 8).

Around 1960, at the Massachusetts Institute of Technology, the meteorologist Edward Lorenz was running a small model of the weather on a computer built with vacuum tubes. The model was a set of equations for moving air. The computer stepped the equations forward and printed the weather the equations produced, line after line of numbers. Lorenz told what happened next in his own book, *The Essence of Chaos*, published in 1993. He wanted to look at one stretch of a run in more detail. So he stopped the computer and typed in a line of numbers that the computer

had printed out a while earlier. He set the computer running again from that line of numbers. Then he went down the hall for about an hour. By the time he came back, the machine had worked through about two months of weather. When he looked at the new printout, he found, in his words, that "The numbers being printed were nothing like the old ones".

Lorenz first thought that the machine had a fault, a weak vacuum tube, which was a common trouble at the time. Before calling for repairs, he looked for the place where the new run parted from the old run. The two runs had parted slowly. At first the new numbers repeated the old ones. Then the two runs differed by a unit or so in the last decimal place, and then in the next decimal place up. The difference roughly doubled every four days of model weather. Somewhere in the second month, the second run showed nothing of the first run. The cause of the difference was in the numbers Lorenz had typed in. The printout had shown each number rounded off, and Lorenz had started the second run from the rounded numbers, which differed very slightly from the numbers the machine had used in the first run. In Lorenz's words: "The initial round-off errors were the culprits; they were steadily amplifying until they dominated the solution".

Lorenz published what he had found in a paper, "Deterministic Nonperiodic Flow", in the *Journal of the Atmospheric Sciences* in March 1963. In that paper Lorenz drew the lesson of his two runs for the real air over our heads: "prediction of the sufficiently distant future is impossible by any method, unless the present conditions are known exactly".

Lorenz's program followed its rules exactly, the same rules at every step, and the program left no step to chance. Lorenz started the program twice from two points that the printout showed as the same, and the program still produced two different weathers. So a thing can follow fixed rules and still defeat every forecast. Is a person like Lorenz's program, fixed by rules but too sensitive to forecast, or is there something in a person that nothing at all fixes in advance?

From Cham and Whiteson's pages

What Cham and Whiteson Showed

Jorge Cham and Daniel Whiteson open their chapter on whether people are predictable with a game. They tell you that you chose to pick up their book, and that you are choosing now to read their words. They dare you to look away, to prove that you are free. When you come back, they claim to have predicted that you would look away. Then the authors take the brain apart, piece by piece, the way a child takes apart a toaster. Your brain is eighty-six billion neurons, the nerve cells that carry the brain's signals, joined by over a hundred trillion connections. In the authors' picture, each neuron is a little switch. The switch turns on or off according to the signals the neuron receives and the rules of its own small circuit. The authors say that, as far as anyone knows, everything in the universe follows the laws of physics, brains included.

If your brain follows the laws of physics, why can no one predict you? The authors' first answer is chaos. When a system is so sensitive to small changes that a tiny error in a forecast grows until the forecast is worthless, physicists call the system *chaotic*, and the authors use the word in the physicists' sense. A tossed coin is a chaotic system, and the weather is the famous case. A neuron fires when the sum of its inputs crosses a threshold, so one input among thousands can decide whether the neuron fires. A change in one neuron can cascade through the network of neurons until the change decides whether you eat the cookie or the banana. In the authors' words, "Like rainstorms, brains are chaotic" (*Frequently Asked Questions About the Universe*, ch. 10, "A Chaotic Brain"). Yet the authors point out that a chaotic system is hard to predict and still predictable in principle, because a chaotic system follows laws that a large enough computer could simulate.

The authors' second answer is quantum physics. Poke an electron the same way many times, and the electron does not always respond the same way. Over many pokes a steady pattern appears, but no one can say in advance how any single poke will come out. In the authors'

words, “the laws of physics at the quantum level don’t tell you what will happen; they tell you what can happen, and with what odds” (ch. 10, “Your Quantum Brain”). The authors then ask whether the randomness of single particles has any effect on your choices. A neuron is made of more than ten to the twenty-seven particles, so the quantum jitter of any one particle (its random behavior at the quantum level) is very small beside the whole neuron, and the jitters of many particles mostly cancel. The authors write that nobody yet knows whether neurons are sensitive to quantum randomness, and that no experiment has shown that neurons are. They add that some physicists try to join quantum randomness to consciousness and free will, but Cham and Whiteson judge the arguments for that join, so far, about as persuasive as a scam email (ch. 10, “The Quantum Randomness Tends to Average Out”).

The authors’ conclusion has two parts. First, for now, you are not predictable: in practice because of chaos, and in principle as well if the brain is sensitive to quantum randomness. Second, the authors add that being unpredictable is not being in charge: “Randomness is not the same thing as having control” (ch. 10, “Did We Get It Right?”). If a random event in your brain settles what you do, then, in the authors’ image, the universe is tossing dice and deciding for you.

On chaos, I reach the authors’ result by a road of my own: chaos carries small differences up to the scale of a whole person. On two further points I reach a different result. First, the future is open as a fact about the world, and no future science will make the future fully predictable. So the authors’ “for now” can be dropped. Second, when nothing fixes an outcome in advance, the outcome is one event: chance when the event is described from outside, and choice when the event is described from inside, so no dice decide for you.

A Cause That Did Not Settle the Moment

A Geiger counter sits beside a lump of radioactive ore. Every so often the counter clicks. Each click has a cause: an atom in the ore broke apart and sent out a particle, and the particle passed through the counter's tube. Nobody doubts that the breaking of the atom caused the click. Yet nothing fixed the moment at which the atom would break. Physics states the chance that the atom breaks within the next minute. The chance is all there is to know in advance. A large batch of atoms of one kind keeps a steady *half-life*, the time in which half of the batch will have broken apart, and the half-life can be measured very precisely. Nothing fixes which atom breaks next: no atom carries a clock inside it that the other atoms lack. The law of decay is exact about the many atoms, and the moment at which each single atom breaks is open.

The Geiger counter shows two ideas that everyday speech runs together. The first idea is *causation*: a one-way relation between findings, in which the first finding makes a difference to the second. In Chapter 15 we found causation in the cone of what can reach what at each event. The cone of an event is the set of all the events that can be joined by cause to the event. You press a switch, and the lamp lights. An atom breaks, and the counter clicks. Scientists find causation in every experiment, as a finding that follows a preparation. The second idea is *determinism*: the claim that a complete description of everything at one moment fixes everything at every other moment. The most famous picture of determinism is two centuries old. In 1814 the mathematician Pierre-Simon Laplace imagined an intellect that knew, at one instant, every force acting in nature and the position of every thing in it. Laplace wrote that for the intellect he imagined nothing would be uncertain, and the future, like the past, would be present before its eyes.

Experiments establish causation every day, and no experiment ever establishes determinism. Every finding comes from one comparison, made from one place inside the world, of one thing in one setting, so no finding ever delivers the complete description of everything that the claim of de-

terminism is about. A complete description of everything would have to include the instrument that made the description, the act of making the description and the record the act left, because every comparer (anything that makes a comparison) is part of the world it compares. So a claim of determinism goes beyond every finding that could support the claim, while the next finding checks a claim of causation. The Geiger counter shows causation without determinism in a single click: the click follows from the atom, and nothing made the atom break at the moment it broke and not at another moment.

Why the World Is Not Laplace's Machine

Laplace's intellect needs two things. First, the intellect needs one law that carries every state of the world into the next state, the same law in every place and at every time. Second, the intellect needs every state described at every point, with no gap anywhere, so that each state passes into the next state with nothing left unfixed between the two states.

In Chapter 1 the two needs have names: symmetry and continuity. For Laplace's intellect, the symmetry is the same law in another place or at another time. When nothing in a thing is sudden, so that a small move in a setting brings only a small change of what is found, Chapter 1 calls the thing continuous. For Laplace's intellect, the continuity is a description with no gap anywhere. Determinism needs both symmetry and continuity, each made perfect, at once. Chapter 1 set out the Incommensuration Theorem, which concerns two pairs: symmetry with continuity, and asymmetry with discontinuity. Chapter 1 put the Incommensuration Theorem in plain words: the two members of each pair cannot both be made perfect together at the foundation. Determinism needs exactly the first pair that the Incommensuration Theorem rules out: symmetry and continuity, both made perfect. So no world is purely and completely deterministic.

The second clause of the Incommensuration Theorem rules out the opposite extreme. *Pure randomness* is an outcome found different whatever its setting, with nothing joining the outcome to anything. Pure randomness would be asymmetry and discontinuity made perfect together, and the second clause rules out that pair as well. Picture a player piano, whose paper roll fixes every note before the first note is struck. Beside the piano, picture a radio tuned between stations, hissing. The roll is perfect order, and the hiss is perfect randomness. A pianist playing by ear has order and openness together. Each note the pianist plays follows from the notes before it, and no note was fixed before the pianist played it. Perfect order and perfect randomness are ideas, each made by taking one side of the pianist's playing to its limit. The world contains neither. Every world is causal to some degree and lies between the roll and the hiss, because every world is a world of things that act on one another and are compared.

Lorenz's program was like the paper roll of the player piano: a rule, with order and no openness. A computer program applies one rule the same way at every step, so within its own states a program is determinism made exact: run twice from the very same start, a program produces the very same sequence of states. Lorenz was surprised that a rule with order and no openness still defeats a forecast whenever the rule's start is known only to a few decimal places. Lorenz's two weathers show unpredictability in practice, and the authors are right that chaos makes brains unpredictable in practice too. The rule of Lorenz's program was fixed completely, yet the machine that ran the rule was a physical thing in the world, and the world is a different thing from the rule. When a machine inside the world runs a rule, the rule can fix its own states completely. But no law can fix a whole world completely, whichever account describes the world. So the future is open as a fact about the world, because the Incommensuration Theorem holds for every comparison, and therefore the future stays open in principle and in all future practice.

Two Meanings of Random

The word random has two meanings, and whether the authors' "for now" is needed depends on keeping the two meanings apart. Toss a coin, or ask for the weather next month. In each case there is, or might be, a fact of the matter that fixes the outcome in advance, and we lack access to that fact, so better instruments and more computing would shrink the uncertainty. We call unpredictability that comes from a limit of what we know *soft randomness*. Lorenz's two weathers are soft randomness, and so is the chaos of the authors' tossed coin.

The second meaning of random is *hard randomness*: an outcome that no description of what came before fixes, however complete that description is, for any comparer whatsoever, even one with unlimited access to the state of things. As Chapter 1 said, a comparer is anything that makes a comparison: a person, an instrument, an atom. Soft randomness is a statement about our knowledge, while hard randomness is a statement about the world. The single click of a quantum measurement is the plainest case of hard randomness. The atom beside the Geiger counter shows hard randomness directly. The Incommensuration Theorem guarantees hard randomness. Because symmetry and continuity cannot both be perfect, every lawful description has a part of what is found that the law does not fix. Hard randomness is that unfixed part, and hard randomness is unpredictable for every comparer and not only for us.

So the authors' electron shows hard randomness, because the electron answers identical pokes in different ways. The authors' own sentence states the form of the electron's law: the law tells what can happen, and with what odds. A law is causal without being deterministic when the law gives the odds of what can happen. Odds for each outcome are the right form for a law made of findings, and quantum theory has had laws of that form since the physicist Max Born gave the rule for quantum odds.

A Particle That Is Free

A theorem of physics shows the same result by a second road: the world is not determined. Picture two laboratories far apart, with a source between the laboratories sending out pairs of particles, one particle of each pair to each laboratory. The pairs are entangled, in the sense of Chapter 15. In each laboratory an experimenter turns a dial to choose the direction along which to measure, and the instrument records an answer. Were the answers settled before the dials were turned?

The mathematicians John Conway and Simon Kochen answered the question with a proof in 2006, and they strengthened their proof in 2009. Conway and Kochen's *free will theorem* says: if the experimenters' choices of direction are not fixed by prior information, then the particles' responses are not fixed by prior information either. "Free", in the theorem, has one meaning: not a function of anything that existed before the event. The free will theorem rests on four assumptions, each plain. First, quantum mechanics applies to the particles. Second, relativity applies: no influence passes faster than light, so a choice made in one laboratory cannot affect the outcome in the other laboratory. Third, no later event fixes an earlier choice of direction. Fourth, the experimenter's choice is not a function of anything the particle carries. Each of the four assumptions is supported by established physics and by the practice of experiment, and together the four assumptions are among the most securely established starting points in the history of physics. Every experimenter presupposes the fourth assumption whenever the experimenter treats the choice of what to measure as independent of what is measured.

The experimenter's freedom is secured on two grounds. The first ground is the Incommensuration Theorem: a world in which every choice was fixed in advance would be a deterministic world, and the Incommensuration Theorem rules out a deterministic world. The second ground is the practice of physics: if what an experiment measures fixed the experimenter's choices of what to measure, the experiment's readings would be evidence of nothing. The second ground uses nothing from the first, so

the free will theorem is a road from physics to the conclusion that the world is not determined, separate from the road through the Incommensuration Theorem. Each road alone is enough to show that the world is not determined. Picture a cable of the kind that lifts a crane's hook: many strands of steel wire twisted together, each gripping the others along its whole length. Cut one strand, and the cable holds. The share that the cut strand carried passes, through the grip, to the strands beside the cut strand. When neither of two roads to one result uses anything from the other, the two roads are independent. Each independent road carries the result on ground of its own. The free will theorem and the Incommensuration Theorem are like two strands of the cable: each is a road to the conclusion that the world is not determined. So two independent roads to one result, each enough alone, are stronger together than either road alone, as a cable is stronger than its strongest strand.

If determinism fails anywhere, determinism fails at every scale. Determinism is a guarantee that covers everything, and a guarantee that covers everything is broken by a single exception. A scale of the world cannot be fixed completely while the smaller scales it is made of are not fixed completely, and a person is made of particles whose responses nothing fixed. Physics also shows processes that magnify small differences into large differences. Lorenz watched a small difference grow large in his model: a difference in the last decimal place grew into a different month of weather. Processes that magnify small differences carry an outcome at the scale of particles up toward the scale of people.

In the many-worlds account of Chapter 24, every outcome happens in some branch of the world. Physicists who hold the many-worlds account keep only the smooth law by which the quantum state changes, and give up the single outcome that the free will theorem is about. Yet a world completely fixed by one law has symmetry and continuity perfect together, whichever account describes the world, and the Incommensuration Theorem rules out that pair. A determinist has one more position left, called *superdeterminism*: the claim that the experimenters' choices of direction and the particles' states were fixed together, from one shared past, so

that the choices only seem free. Superdeterminism needs everything determinism needs, and more, so the Incommensuration Theorem rules out superdeterminism along with determinism. The rational position is that the world is not determined.

What the Bell Tests Found

Experiments have measured the particles' side of the free will theorem: whether the particles' answers were fixed before the dials were turned. In 1964 the physicist John Bell showed that no account in which each answer is laid out at the source, by causes that travel no faster than light, can match the agreement that quantum theory predicts for entangled pairs. If each answer is fixed by causes local to its own detector, Bell's result sets a ceiling on how strongly the answers at two distant detectors can agree. The first experiments to test Bell's result found agreement above Bell's ceiling. Each time, physicists who doubted the agreement above the ceiling named a gap through which a hidden cause might slip: detectors that missed too many particles, directions chosen slowly enough for a signal to carry one choice across, directions tied to the source.

In 2015 three teams closed all three gaps together. One team, in Delft, measured the spins of two electrons held in diamond, in laboratories about one point three kilometers apart, and Bas Hensen led the report of the Delft team. Two other teams measured entangled light, one team in Vienna and one in Boulder. Marissa Giustina led the report of the Vienna team, and Lynden Shalm led the report of the Boulder team. The three teams' detectors were far enough apart, their directions were chosen fast enough and randomly enough, and their detection was efficient enough, that no account by hidden causes through any of the three gaps remained. The agreement still exceeded Bell's ceiling. We now know that the answers of entangled particles were not laid out in advance, and that the free will theorem's assumptions about the particles are supported by measurement.

Does It Reach the Brain?

The authors leave one question open about the brain: does the jitter of single particles ever reach a neuron and change what the neuron does, or does the jitter always average away? For most large things the jitter averages away, as the authors say. A cookie does not wander off the plate, and a basketball keeps to its course.

Picture a snowy slope late in winter. On most slopes a little more snow changes nothing. On a slope poised just so, at the edge of sliding, one more flake can start a slide, and the slide can be of any size, from a trickle to the whole face of the hill. *Criticality* is the state of a system poised like that slope: a state in which small disturbances can cascade to large scales. At criticality a small disturbance does not average away: the small disturbance cascades up to large scales.

In 2003 the neuroscientists John Beggs and Dietmar Plenz recorded the electrical activity of slices and cultures of rat cortex, the outer layer of the brain, on a grid of sixty electrodes. Beggs and Plenz found that activity spread through the tissue in bursts, which they called neuronal avalanches. The sizes of the bursts followed one simple rule across a wide range of sizes, and each active site set off, on average, close to one further site: one further site for each active site is the value that marks a system poised at criticality. We now know that living cortical tissue can sit at criticality, the poise where small disturbances spread to every size.

The brain works near criticality, and the avalanches in cortical tissue show the marks of criticality. The road from a particle to a person has three steps. First, a neuron is made of particles whose single outcomes nothing fixed, and a thing cannot be fixed completely while the particles it is made of are not fixed completely, so the neuron is not completely fixed either. Second, a neuron near its threshold fires or stays quiet on a small difference. As the authors themselves describe, one input among thousands can decide whether the neuron fires. Third, in tissue poised at criticality one firing can set off a burst of any size, as one flake can start a slide of any size. So in a brain near criticality, an outcome that nothing

fixed at the scale of particles is not averaged away: the outcome enters chains of causes that reach the scale of a person and bear on what the person chooses.

A nearly deterministic computer model can describe the behavior of a brain well at the scale of the brain's cells, and the model is useful. Yet a single choice, made near criticality, carries an outcome from the scale of particles that no nearly deterministic model fixes. The road from particle to person needs two things only: the open outcome, which belongs to every act of comparison, and the brain's poise at criticality, which carries the open outcome up to the scale of a person.

Fairly Predictable

People are fairly predictable: a good deal of what a person will do can be foreseen, as anyone knows who has guessed what an old friend will order at a familiar restaurant. Picture a program that shrinks a long computer file by finding every pattern that repeats in the file and writing each pattern down only once. Now watch a person for a long time, and write down everything about the person that can be predicted, the way the shrinking program writes down the patterns in a long file. However good the program, some part of the person's behavior will not shrink, and no one can tell that leftover part apart from randomness. The person regards the leftover part of their behavior as their own choosing.

Each act has a share that is choice and a share that runs as cause and effect. The two shares change from one act to another. A habit is a choice made so often that the habit runs almost wholly as cause and effect. One habit is the reach of your hand for the light switch as you come through the door. A turning point in a life is cause and effect bent almost wholly by choice. Most acts lie between a habit and a turning point, and over a life the share of choice in what a person does keeps changing. So much of what you do can be predicted, and the leftover part never shrinks to nothing, however good the model and however long the watching.

Chance from Outside, Choice from Inside

Your cup is on the table. You reach for the cup, or you do not. Say you reach, and your fingers find the cup still warm: one act of finding, made by you, from where you sit. Suppose that the reach is a choice, fixed by nothing before the reach. Suppose too that someone watches you from across the room, with the best model of you that could ever be built and every fact of your past. To the watcher, your reach looks exactly like a chance event: nothing in the watcher's model fixed the reach, and no measurement made from outside you can tell the reach apart from a chance event. From inside, you meant to reach.

Count the reaches. The watcher saw one hand move once, at one moment, to one cup. You made one reach, at that same moment, to that same cup, and found the cup warm. No comparer finds a second reach beside the first, whether the comparer sits across the room or in your own chair. Chance and choice differ in the position from which the one reach is described: the watcher's position, outside you, or your position, inside the reach. Chapter 24 states the principle of identity: what no comparison can tell apart, in any way at all, is one thing and not two. So one event is both the chance the watcher sees and the choice you make, described from two positions.

From the position of law, the position of a description written from outside, the outcome that nothing fixed is hard randomness: a gap in the description, with no pattern and no meaning. From the position of the one engaged in the act, the same outcome is choice: specific, and *meaningful* to the process from which the outcome came. In this chapter, meaningful means significant to the process from which an outcome came, and carrying the character of that process. Each description is correct in its place, neither is complete, and neither can replace the other. The two descriptions hold of the particle in the free will theorem too. The particle's response, which nothing earlier fixed, is hard randomness when described from outside, and the same event is choice when described from the position of the process from which the response came.

In a person, the brain's criticality carries an outcome that nothing fixed at the scale of particles up through the cells, until the outcome moves the hand. Criticality is the condition of the brain that carries the outcome up, and criticality is not the relation between the two descriptions. Hard randomness from outside and choice from inside are two descriptions of one outcome in every act of comparison, in a brain and everywhere else.

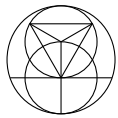
Now we can weigh the authors' sentence: "Randomness is not the same thing as having control". The sentence is true of pure randomness. An outcome joined to nothing would be noise, and noise is no one's choice. Pure randomness, though, is the hiss of the radio, which the Incommensuration Theorem rules out. A choice lies between the hiss and the roll: between the completely random, which would be no choice at all, only noise, and the completely fixed, which would be no choice either, only the carrying out of a program. In this chapter I have named three kinds of randomness: soft, pure and hard. Soft randomness is a limit of what we know, and the Incommensuration Theorem rules out pure randomness. Hard randomness is the kind that belongs to the world. Described from inside, hard randomness is the choice itself. In the authors' picture of the universe tossing dice for you, the chooser is outside the event. The outcome that nothing fixes is your act, seen from outside.

Are you, then, responsible for what you choose? You are. A choice has three parts: what is possible, a selection, and the consequence of the selection. A choice without its consequence is not yet a choice. Because the world is causal, what you choose goes on to have effects. Because the world is not determined, the one who chose could have chosen otherwise.

> **The short answer**
>
> People are fairly predictable and never completely so, today or ever: the future is open, and one outcome that nothing fixed is chance seen from outside and choice seen from inside.

My answer to the authors' sentence, "Randomness is not the same thing as having control", is that the one randomness that belongs to the world, hard randomness, is your choice seen from outside. For the rest of this book, the world is lawful in its patterns and open in each single outcome.

If the world is not a machine that fixes every outcome, could it still be a program running somewhere?



Chapter Twenty-Seven

Do We Live in a Computer Simulation?

In which a philosopher counts minds, a cup cools on a screen, and a simulated world with real people in it turns out to be a fenced region of this one

Do we live in a computer simulation?

What this chapter uses

A *comparison* is the act of finding whether two things are the same or different in some respect, and every measurement is a comparison; a *finding* is the outcome of one comparison, laid down as a record; a *comparer* is whatever makes a comparison, whether or not the comparer has a mind (Chapter 1).

Continuous: nothing is sudden, as along a ramp; *discontinuous*: something is sudden, as at the edge of a step; *symmetric*: what is found stays the same across a change of setting, as each step of a staircase is like every other; *asymmetric*: different everywhere, as the height along a ramp is (Chapter 1).

Every comparison has three positions: the *act of comparing*, the relating; the *thing compared*, what is known; and the *thing compared against*, what the act of comparing reaches toward and never contains in one act, the beyond (Chapter 4).

Gravity is the *arena*, the stage of space and time on which the three forces act, and so gravity stands beside the three forces and is not a fourth force (Chapter 7).

Every comparison goes one way, from what could be found, to the finding, to its record, and so time goes forward (Chapter 13).

Hard randomness is an outcome that no description of what came before fixes, however complete that description is, for any comparer whatsoever; one outcome that nothing fixed is chance seen from outside and choice seen from inside (Chapter 26).

In 2003 Nick Bostrom published a paper whose title puts your question to you: "Are You Living in a Computer Simulation?" Bostrom was then a member of the Faculty of Philosophy at Oxford University. The paper appeared in the journal *Philosophical Quarterly*. Bostrom began from computers. He reasoned that a civilization far ahead of ours in technology would command enormous computing power, and that a single computer

of such a civilization could run the whole mental history of humankind. Bostrom gave the name "ancestor-simulation" to one run of the whole mental history of humankind on one computer of a civilization far ahead of ours. He took one assumption from the philosophy of mind: that "a computer running a suitable program would be conscious". Then Bostrom counted. Suppose that civilizations far ahead of ours ran many ancestor-simulations, each one full of minds like ours. Then, in Bostrom's words, "the vast majority of minds like ours do not belong to the original race", and so a mind like yours would most likely be one of the simulated minds.

Bostrom's paper ends in three possibilities, and Bostrom shows that at least one of the three possibilities is true. The first possibility is that the human species very likely dies out before humankind has the technology of a civilization that could run an ancestor-simulation. The second possibility is that any civilization that gains the technology to run an ancestor-simulation is extremely unlikely to run many simulations of the civilization's own history. The third possibility is in Bostrom's own words: "we are almost certainly living in a computer simulation". Bostrom did not say which of the three possibilities is true. He wrote that it seemed sensible to spread one's belief roughly evenly across the three possibilities.

When Bostrom counts, he treats each simulation as a world of its own, with observers of its own, set beside the world in which the computer runs, and then he compares the number of observers in the simulated worlds with the number of observers in the one original world. Bostrom's conclusion depends on treating each simulation as a world of its own, so the question beneath your question is whether a simulated world is a world of its own, and the answer to that question is the answer to yours.

From Cham and Whiteson's pages

What Cham and Whiteson Showed

Jorge Cham and Daniel Whiteson give the simulation question a chapter of its own in *Frequently Asked Questions About the Universe*, and they open the chapter with a feeling everyone knows: is this really happening? The authors give Bostrom's count in their own words, without naming Bostrom. Computers improve, simulations multiply, simulated people run simulations of their own, and soon the simulated worlds far outnumber the one true universe. The authors conclude that the odds favor our living in a video game. Then the authors add a reason of their own, which they call philosophical. In their words, "our universe seems to work like a simulation" (*Frequently Asked Questions About the Universe*, ch. 14, "Why Even Consider This?"). The authors' reason is that a program follows rules, and the universe follows rules too, the same everywhere and all the time. The authors write in another chapter that, as far as anyone knows, everything in the universe follows the laws of physics, your brain included (*Frequently Asked Questions About the Universe*, ch. 10, "Physics in Your Brain").

The authors then sketch how a simulation could work. A computer could feed signals to a real brain in a vat, or to an alien brain told that it is human, or the minds themselves could be parts of the program. The builders of a simulation could save computing power in three ways. The builders could make the simulated world simpler than their own world. Or the builders could run the simulated world slower than their own time. Or the builders could draw fine detail only where someone looks. A simulator of traffic, for example, uses whole cars as its pieces and never the particles inside the cars.

Next the authors ask how anyone inside a simulation could tell. The authors answer that if a simulation runs perfectly, it might be impossible to tell from reality. Yet the authors add that if programming in the builders' universe is anything like programming in ours, there is always a bug somewhere. So, the authors write, "our best chance to

figure out whether our universe is a simulation" is "to find a glitch" (*Frequently Asked Questions About the Universe*, ch. 14, "Could You Tell?"). The authors suggest three kinds of glitch. The first glitch is an error where the simulation joins one galaxy to another. The error would show in particles that cross between the two galaxies. The second glitch is a graininess of space and matter, a smallest pixel, that no law of physics explains. The third glitch is a contradiction in the rules. The authors' example is the clash they describe between quantum theory and general relativity inside a black hole. The authors close the chapter on a thought meant to comfort: "Maybe the real illusion is that there is a difference between a simulated universe and the real one" (*Frequently Asked Questions About the Universe*, ch. 14, "Why Build It?").

A Cup on a Screen

Picture your cup of coffee drawn on a screen, in a game that shows a quiet kitchen in fine detail. Steam curls from the cup, and the coffee cools, minute by minute, as your real coffee does. Everything on the screen is made by a computation. Chapter 25 described a computation as a passage from one list of marks to the next. The passage follows one rule, applied the same way at every step. On a screen, each list of marks is a string of ones and zeros. The *program* is the written set of rules by which a computation goes from one list of marks to the next. A *simulation* is a computation built to copy the behavior of some physical thing. At each step the computer takes the cup's warmth and the shape of the cup's steam, applies the program's rules, and writes down the next warmth and the next shape of the steam. So the cup on the screen cools only as the program says.

Now watch the curls of steam. The curls look random, and the game needs the curls to look random, so the programmer takes the game's chance from a *pseudo-random* generator: a fixed rule whose output looks random and is set entirely by the number the rule starts from. Start the

game again from the same number, and the same curls rise in the same order, wisp for wisp. A computation is *deterministic*: its present state and its rule fix its next state, so that, run twice from the same start, the computation gives the same sequence of states. In Chapter 26 we met determinism in the weather program of the meteorologist Edward Lorenz, whose program was exactly deterministic within its own states. Determinism is the great virtue of a computation: a bank, an aircraft and a hospital all depend on the determinism of their computers. Determinism also means that nothing new enters a program at any step. The program's start and its rule already contain the whole list of its states.

Your own cup has two things that the cup on the screen lacks.

The first thing is the open outcome: an outcome that nothing before it fixes. Of a storm that whatever happens in this world has two sources. One source is earlier states, through cause and effect. The other source is outcomes that enter at the smallest scale with nothing before them fixing them, and a system that is sensitive to how it starts then magnifies those outcomes, as in Lorenz's weather in Chapter 26. In Chapter 26 we called an outcome from that second source *hard randomness*: an outcome that no description of what came before fixes, however complete that description is. The steam rising from your cup is a happening like the storm, so the curls of your steam come from both sources, and hard randomness is one of the two.

Your cup has a second thing that the cup on the screen lacks: the arrow. The heat that leaves your cup goes into the room. The cooling is one finding after another, in an order that runs one way. In Chapter 13 we called that one-way order the arrow of time, and we found the arrow in every comparison: every comparison runs from what could be found, to the finding, to the record of the finding. The program's list of states has an order too: first, second, third. Yet anyone can read the program's list backward as easily as forward. A printed list of numbers can also be read backward, from its last line up. I call an order that reads the same both ways an *indexing*: a numbering of states, like the page numbers of a finished book, in which nothing happens.

The game does run forward on your screen, and the forward running comes from the machine. The program runs on circuits, and the running is a physical process. Current flows, and each step of the machine is a physical change that cannot be undone. The machine lends the game whatever arrow the game shows. The machine's arrow is the arrow of the room where the machine sits. So the cup on the screen shows that a program has no open outcome of its own and no arrow of its own.

Three Things Bound Together

Picture a friend telling you a story you have never heard. Each sentence of the story arrives after the last. Your first hearing of the story cannot be had again: the hearing has a before and an after. Some sentences surprise you, because nothing you heard before fixed them. And the hearing is yours: the story happens to a listener.

Three things appear together in the story, and the same three appear together wherever anything is experienced. The first of the three things is the arrow of time, the before and after of the hearing. The second of the three things is hard randomness, the sentences that nothing heard earlier fixed. The third of the three things is the *subjective*. The subjective is the side from which experience occurs, the stance of the one to whom things happen. In the story, you are the one to whom the story happens. My physics books call the arrow, hard randomness and the subjective together the *bound triple*. Each of the three requires the next. The arrow requires hard randomness, hard randomness requires the subjective, and the subjective requires the arrow.

The arrow requires hard randomness. Think of the player piano of Chapter 26, whose paper roll fixes every note before the first is struck. Wind the roll backward, and the same notes pass in the reverse order. The order of the piano's notes is an indexing, and no new note arrives anywhere along the roll. A direction of time needs each next moment of time to hold something that the present moment does not hold, and that new

something is an outcome that nothing before it fixed. If every outcome were fixed in advance, the order of states would be only an indexing, the same read forward or back.

Hard randomness requires the subjective. Picture the Geiger counter of Chapter 26, which clicks when an atom of the ore beside the counter breaks, and picture a log in which the counter's clicks are written down. Imagine one click from the ore, which nothing before it fixed, and beside it, in the same log, a second click, which a hidden timer was set to make at that very moment. In the log the two lines look alike, because neither click was foreseen. The difference between the two clicks is the difference between a finding that is new and a finding that was only hidden. The difference between new and hidden lies in the finding. A comparer (whatever makes a comparison) makes each finding from the comparer's own side, in the act of comparing. So an outcome that nothing before it fixed is hard randomness only as a comparer finds the outcome from a stance. That stance is the subjective.

The subjective requires the arrow. While your friend talks, you hold the start of the story and wait for its end. To perceive is to set what is found now against what was found before. To remember is to set the present against a record, and to expect is to set the present against what could come. Perceiving, remembering and expecting each run one way, from earlier to later. Only a direction of time makes remembering differ from expecting, and only a direction of time gives a side from which to look. So the arrow, hard randomness and the subjective are each present only together with the other two.

The arrow, hard randomness and the subjective all follow from one theorem, which Chapter 1 named. Chapter 1 put the theorem in plain words: at the foundation of any event (anything that happens) or comparison, symmetry and continuity cannot both be perfect together, and neither can asymmetry and discontinuity. So every comparison leaves a remainder: an outcome that the comparison's earlier structure does not fix. That remainder is hard randomness. A comparer makes every com-

parison from a side, and that side is the subjective. And every comparison runs from the act of comparing to the record of the act, and that one-way run is the arrow.

Now set the cup on the screen beside the bound triple. A computation running on its own rule has no hard randomness of its own. Because each member of the bound triple requires the others, the computation also has no arrow of its own and no subjective of its own: the computation has no point of view, no one to whom things happen. I draw the conclusion: a computation on ordinary digital machinery, however intricately organized, cannot be what consciousness is. A computation can calculate, translate and converse, and can do all of it superbly, and a description of the computation's behavior from outside can match a description of a person's behavior. A computation cannot be a point of view, simply because it is a computation. I also name a thesis about minds and machines. The thesis is that the right program, running on any machinery, would thereby be conscious. I call that thesis *strong computationalism*. Bostrom's assumption is strong computationalism: a computer running a suitable program would be conscious. The bound triple shows that strong computationalism is false.

A Fenced Region of the One World

The simulation hypothesis is the hypothesis that we live in a computer simulation. The simulation hypothesis has one reply left, and that reply is the strongest. The reply is to let the simulation take its chance from a physical source in the builders' own world, such as electrical noise or a quantum device, so that the simulation's randomness comes from the physical world and not from a rule. I follow that reply to its end, and again in another.

Whatever randomness a simulated world shows is of one of two kinds.

In the first case the simulated world's randomness is pseudo-random, made by a fixed rule. Then every state of the simulated world is fixed by the world's start and its rule before the machine begins to run. The ma-

chine still runs, one step after another, in the room where the machine sits, and the machine's running carries the room's arrow. But the machine's running only reads out a list already fixed: every state of the simulated world holds only what the world's start and its rule already held. So the simulated world's order of states is an indexing with no arrow, and, because the three of the bound triple come only together, the simulated world has no subjective side at all. I call a simulated world of the first kind "a program running on a machine with no one in it". Nobody lives in a simulated world of the first kind, and so nobody in it could be you.

In the second case the simulated world's randomness is drawn from the world that runs the computer. Then the simulated world has no randomness of its own: its randomness is the outer world's randomness, carried through the computation. Now each new state of the simulated world holds something that the world's start and its rule did not contain: an outcome that entered from the room, at the moment the outcome was found in the room. So the simulated world's order of states has a direction. The direction is the order in which the room's outcomes entered the simulated world. The simulated world's arrow comes with its randomness, so the simulated world's arrow is the outer world's arrow too. The machine runs one step that cannot be undone after another, and that running is the outer world's arrow at work. A simulated world cannot share part of the bound triple with the outer world and keep the rest as its own. Where the randomness and the direction of time are shared, the subjective is shared as well. So a simulated world with real people in it shares the hard randomness, the arrow and the subjects of the world that runs it.

I give the word "world" an exact sense: a world is where acts of comparison happen in a direction, with outcomes not fixed in advance, from a stance. A simulated world with real people in it has none of those three (the direction, the open outcomes and the stance) of its own. So a simulated world with real people in it is part of the one world: the part reached through the computation.

Picture a prison cell. The walls limit what the person inside can see, and the limit is real. The person inside breathes the same air and ages by the same clock as everyone outside the walls. The cell stands in the one world. A computation limits what can be reached from inside the computation, as the cell limits what the person inside can see. The restriction is real; the separateness is not. I call a simulated world with real people in it a *fenced region* of the one world: a part of this world, fenced off by a computation, inside this world. A simulated world containing real subjects is not a separate world: it is a restricted region of the one world in which it runs.

Now we can read Bostrom's count again. Bostrom counts simulated observers as if each simulation were a separate world with observers of its own. Yet any simulation that has observers at all is a fenced region of the one world. The simulation's observers are observers of the one world. So the third of Bostrom's three possibilities depends on a count that treats regions of one world as many worlds. The third possibility was that "we are almost certainly living in a computer simulation". The simulation hypothesis matters to us in one form: that we are real people in a world that is not real. That form of the hypothesis is impossible, in principle and therefore in all future practice, because of the structure of comparison: what every comparison must contain. The argument of this section depends on what a simulated world with real people in it is. The argument needs no test made from inside.

What No List Can Hold

A second argument shows that the world itself differs in kind from every program. The second argument uses no step of the first argument, the argument that a simulated world with real people in it is a fenced region of the one world. I begin the second argument with the authors' closing thought, that the difference between a simulated universe and the real one is the illusion.

We can judge the authors' thought by the principle of identity. For the simulation question, the principle of identity sets the standard for an answer. When nothing in a world's space and time is sudden, we call the world continuous, in the sense of Chapter 1: its space and time have no least step and no gap, as we found of the arena (space and time together) in Chapter 10. If no test that could even be imagined would ever tell a simulation from a continuous world, the hypothesis that we are simulated would be empty, a name with nothing behind it. A test in principle is a test whose logic holds whether or not any instrument can carry it out. If a test in principle exists, then a simulation and a continuous world are two different kinds of thing. So the authors' thought becomes an exact question: is there a test in principle by which anyone could tell a simulation from a continuous world?

Start with the number pi, the distance around a circle divided by the distance across it. The digits of pi begin three point one four one five nine, and the digits go on without end and without ever falling into a repeating pattern. A short program can produce any digit of pi you ask for, yet no finite string of digits, however long, is pi.

The finite string and the endless number differ in structure, and the mathematician Georg Cantor showed why in two proofs, of 1874 and of 1891. Some collections can be *listed*: set out in order, first, second, third, without leaving anything out. The counting numbers can be listed, and so can every finite string of symbols, and so can every program that could ever be written. The *continuum* is the smooth whole of every possible value, with no gaps anywhere, in which between any two values there is always another. The points of a line are the familiar form of the continuum. Cantor's diagonal argument shows that no list holds every value of the continuum.

Suppose someone claims to have listed every number between zero and one, written as endless decimals. Build a new number, one digit at a time. The new number's first digit differs from the first digit of the number on line one, its second digit differs from the second digit of the number on line two, and so on down the list. Some numbers have two decimal

spellings: one half is zero point five followed by zeros forever, and one half is also zero point four followed by nines forever. So you choose each new digit from one to eight, never zero or nine, and then the new number has only one spelling, so the new number cannot slip onto the list under a second spelling. The new number lies between zero and one, and the new number differs from every number on the list in at least one place, so the new number is missing from the list. The diagonal construction works on every list anyone could make.

In 1936 the mathematician Alan Turing described the ideal computer, a machine with unlimited time and an endless strip of memory. Even Turing's ideal machine produces, at every step, an output that can be listed. All the machine's possible outputs, taken together, can also be listed. So every computation produces a listing, on any computer that could ever be built.

My physics books derive that the arena, space and time together, is continuous. In Chapter 10 we found that the arena has no least step, and we gave the reason: a least step would be a break in the arena, and the arena connects without a break, as the beam of a balance joins its two pans. The halving of space shows that reason at work. Take a stretch of space and split it in half, and in half again. Every comparison contains sameness and difference together, since a comparer who could find only "same", or only "different", has stopped comparing, as Chapter 1 showed. So every difference between two positions in the arena contains some sameness within it. A finer comparison can therefore always be made at a position between the two positions, and that finer comparison is the next halving. A least step of space would be a jump with nothing between its two ends: a difference with no sameness within it, which is exactly a break. A difference with no sameness within it cannot occur. So the arena has no least step, and between any two positions there is a third.

The measurements of physicists agree: the arena is smooth at every scale yet probed. In Chapter 10 we told of the gamma-ray burst of 2009. Light of very different energies from the burst arrived together after trav-

eling for billions of years. So any grain of space that would slow light must be smaller than the Planck length, the scale at which the two great descriptions of physics, gravity and the quantum, meet.

So the world holds a continuum, which no list can hold, and every computation produces only a listing. A simulation of the world therefore differs from the world in kind.

But, you may ask, a simulation could carry so many digits that no difference would ever show. We answered that question in Chapter 26, with Lorenz's weather. As a very general rule, real systems are sensitive to how they start, and the weather is the classic case: the smallest difference in a start grows, and goes on growing, until the difference changes the whole of the weather. So a simulation departs in time from the world it copies, at whatever precision, however fine, the simulation cuts its values off, and the simulation and the world run two different histories. I name the two roles: "Sensitivity is the amplifier", and what sensitivity amplifies is the part of the world that no list holds. Each extra digit gives a simulation a longer stretch of faithful copying, but no fixed number of digits keeps a simulation faithful to a sensitive world forever.

I give a picture of the difference in kind between a model and what the model describes. An *orrery* is a working brass model of the solar system, with planets carried round the Sun by gears at their proper paces. Turn the gears backward, and the planets of the orrery run backward just as smoothly. The solar system runs one way only, because the tides drag on the turning Earth and push the Moon slowly outward. A model can match what it describes as closely as anyone wishes, and the model never contains what it describes. The orrery stays a fine instrument, and a beautiful one; it is simply not the solar system. A simulation is an orrery of the world, and every simulation that is ever run is itself a physical process in the world. So physics is deeper than computation: every computation depends on physics, and the rain falls whether or not anything is computed.

But, you may ask, a brain follows the laws of physics, as the authors say, and a computer can follow the laws of physics too, so why can a computer not copy the whole world, brains and all? I answer with the difference between how a thing behaves at one scale and the things that do the behaving. At the middle scale, the scale of cells and signals, a brain's behavior can be simulated in principle, because the models at that scale are close to deterministic. The particles a brain is made of cannot be simulated as what they are, because nothing before the particles' outcomes fixes those outcomes, though a program can copy the particles' statistics to any precision chosen in advance. A simulated world of its own would need outcomes that nothing before them fixes, as real particles have, but a program's rule and its start fix every outcome of the program. So it is impossible, in principle and therefore in all future practice, to simulate the whole universe as a world of its own.

The Glitch, and the Rules

We have already met all three of the authors' glitches: the seam between galaxies, the pixel of space and the clash inside a black hole.

The authors' first glitch is an error where the simulation joins one galaxy to another, and the authors would look for that error in particles that cross between galaxies: paths with irregularities in them, or energies that do not fit together. In a footnote the authors add that physicists do see high-energy particles hitting our atmosphere "that can't yet be explained by any astrophysical source" (*Frequently Asked Questions About the Universe*, ch. 14, "Could You Tell?", note). We met the high-energy particles of the authors' footnote in Chapter 16, as the most energetic messengers from space, and we found what any sender of the particles is and what happens to the particles on the way. Whatever sends the particles is in our own region of the cosmos. The sender is near enough that the leftover light of the Big Bang has not worn the particles down. And the sender is built of the known kinds of particle and acts through the three forces (electromagnetism, the strong force and the weak force). On the way, the

magnetic fields between the galaxies bend the particles' paths, and the leftover light slows the particles, so the particles' paths and energies come from known physics at work in one world. We have found in this chapter that the world is no program, so the world has no seam where a program joins one galaxy to another, and no particle crosses such a seam. Naming the sender is work for astronomers and their telescopes. Whatever the astronomers name is made of the same list of pieces as you are.

The authors' second glitch, the pixel of space, would be a least step of the arena, and in Chapter 10 we found the arena smooth at every scale yet probed, as the halving of space requires.

The authors' third glitch is a clash between quantum theory and general relativity inside a black hole. In Chapter 8 we found that gravity and the quantum are two descriptions of one world, joined side by side, with neither given up. In Chapter 21 we found that the smooth description of space and time has a domain, the range of cases that the description covers, and that inside a black hole the description is at the edge of its domain. At that edge both descriptions, gravity and the quantum, apply side by side, and neither contradicts the other. So the third glitch has no place to happen.

A fixed rule has a glitch of its own kind. Any fixed rule works in steps, and so the rule has a least step: a finest grain below which the rule says nothing more. Quantum theory describes the world with a smooth wave, the quantum state of Chapter 12, which sets the odds of each possible finding, and the smooth wave has no least step. So each fixed rule has a precision beyond which the rule's odds differ from the world's odds, and with a measurement finer than the rule's least step, anyone can tell the rule's odds from the world's odds in principle. The authors allow that a perfect simulation might never show itself, and they hope for a flaw if the builders program as we do. Every fixed rule has a flaw. For the authors the flaw would be a programmer's slip, while on my account the flaw is a difference of odds that every fixed rule has below the rule's least step. The

appendix "What the Coming Measurements Will Find" lists the measurements that will look below the least step of a fixed rule, and what I say each measurement will find.

Physicists have already looked for a seam in the rules of quantum theory itself. A seam would be a place where the odds of quantum outcomes depart from the smooth wave's rule. Picture two pebbles dropped into a still pond at once. Two rings of ripples spread and cross. Where crest meets crest the water stands higher, and where crest meets trough the water lies flat. The pattern of high and flat water is *interference*: the joining of waves that arrive by two paths. Light sent through two narrow slits onto a wall makes the same pattern, bright stripes and dark ones.

In the rule by which the smooth wave sets the odds of outcomes, interference comes in pairs of paths. When a particle can take three paths, the pattern with all three open is fixed entirely by the patterns of the single paths and of the pairs of paths. A departure from the smooth wave's rule would show as a *third-order term*: an extra piece of the pattern that belongs to the three paths together. In 2010 five physicists looked for a third-order term in the pattern of three paths: Urbasi Sinha, Christophe Couteau, Thomas Jennewein, Raymond Laflamme and Gregor Weihs. The five worked at the Institute for Quantum Computing in Waterloo, Canada. The five physicists sent single photons, particles of light, through a thin steel mask with three slits cut in it. They found any third-order term to be less than a hundredth of the ordinary interference of two paths. We now know that, to within a hundredth of the ordinary interference, the odds of quantum outcomes follow the smooth wave's rule exactly as the rule is written, with no third-order term left over. So, down to that precision, the rules of quantum theory hold without a seam.

In Chapter 26 we told of a second finding that bears on whether the world could be a program. In 2015 three groups of physicists tested pairs of entangled particles, particles linked so that their measured results agree in a pattern no instructions carried by the particles could give them, in the sense Chapter 15 gave the word. One group in Delft used electrons, and two groups used particles of light. The groups closed every gap that a

doubter had named, and the agreement of the answers still exceeded the ceiling that the physicist John Bell found: the strongest agreement possible for answers fixed by causes local to each detector. In Chapter 26 we joined that finding to the free will theorem of the mathematicians John Conway and Simon Kochen, by which the outcomes of the Bell tests are fixed by nothing before them. A program's rule and its start fix every output of the program. So a program can copy the odds of the entangled particles' outcomes to any precision chosen in advance. But the program cannot be what the outcomes of entangled particles are.

The authors' strongest reason is the one they call philosophical: the universe follows its rules everywhere and always, as a program does. A law of physics states what stays the same when the circumstances of a measurement change. A *closed system* is one that nothing enters and nothing leaves. The conservation of energy says that the total energy of a closed system is the same whenever the energy is measured. The universality of a law means that an experiment gives the same result in Geneva or in Tokyo, this year or a century from now. So a law of physics is itself a finding of comparison, the sameness that comparers find across a change of circumstance, and nothing added to comparison from outside. And the comparers who find the laws also find the open outcome and the arrow, which no program has of its own. Read whole, the authors' strongest reason counts against the simulation hypothesis, not for it. The world's lawfulness is the sameness that comparers find, and the world holds, beside its laws, the remainder that no rule fixes. Why the world has laws at all is a further question, the deepest why, and in Chapter 32 we will find that the question lies past every measurement made within the world.

Where the Two Accounts Meet

My account and the authors' account agree on the authors' last question. The authors ask whether what is happening to you, even in a simulation, is real, and they expect the answer yes. What is happening to you is

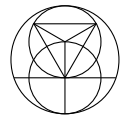
real, and the reason, on my account, is that whatever runs anywhere with you in it is part of the one world, so what you find is found in the one world, by you. Your cup is real, and so is your noticing the cup.

The two accounts part on the difference between a simulated universe and the real one. The authors suggest that the difference between a simulated universe and a real one is the illusion. There is a test in principle, the listing against the continuum, and so there is a difference of kind. And on my account there is a second difference, which needs no test at all: a simulated world with someone in it is a fenced region of this world, and a simulation with no one in it is a machine running a program.

> **The short answer**
>
> The world is no computer program, and a simulated world that held real people would be a fenced region of this one world, sharing its open outcomes, its arrow and its people.

The authors' strongest reason is the consistency of the laws, and that reason counts against a simulation: lawfulness is what comparers find, and the world also holds the open outcome and the arrow that no program has of its own. For the question of this book, the answer means that there is one world, found from inside, and every finding, anywhere, is a finding made within the one world.

Then when we die, is there anywhere else for us to go?



Chapter Twenty-Eight

Is an Afterlife Possible?

In which an encyclopedia changes hands in Dublin, the warmth of a cup goes into the room, and the word "information" is found to name two things

Is an afterlife possible, and is anything of us left after we die?

What this chapter uses

A *comparison* is the act of finding whether two things are the same or different in some respect, and every measurement is a comparison; a *finding* is the outcome of one comparison, laid down as a record; a *comparer* is whatever makes a comparison, whether or not the comparer has a mind (Chapter 1).

The *content* of a finding is what the finding finds, as the warmth of your coffee; the *context* is where the content is found, and the context has three sides, the three settings of space, time and possibility (Chapter 1).

Continuous: nothing is sudden, as along a ramp; *discontinuous*: something is sudden, as at the edge of a step; *symmetric*: what is found stays the same across a change of setting, as each step of a staircase is like every other; *asymmetric*: different everywhere, as the height along a ramp is (Chapter 1).

The *Incommensuration Theorem*: at the foundation of any event or comparison, symmetry and continuity cannot both be perfect together, and neither can asymmetry and discontinuity. The Incommensuration Theorem is a structural fact about the nature of knowing (Chapter 1).

The *turn* is the limit at which an epoch begins: our history, traced back, approaches the limit and shows the limit as a first moment; an *epoch* is one era of the world (Chapter 20).

Before the Big Bang came the collapse of the interiors of the black holes of the epoch before ours, and at the one shared end of those interiors a new large world formed, in a cycle of epochs with no first turn (Chapter 22).

On Wednesday, 21 July 2004, the physicist Stephen Hawking gave a talk in Dublin, at the seventeenth International Conference on General Relativity and Gravitation. For nearly thirty years Hawking had held that a black hole destroys what falls into it. In 1997 Hawking and the physicist

Kip Thorne had made a bet on the question with John Preskill. Hawking and Thorne bet that information is lost in black holes, while Preskill bet that information is not lost, and the loser was to give the winner an encyclopedia, one "from which information can be recovered at will".

Hawking told the conference in Dublin that he had changed his mind about the question of the bet. "The information remains firmly in our universe", Hawking said. Hawking had asked Preskill and Thorne to join him at the press conference after the talk, so both sat on the platform during his talk. Hawking conceded the bet and offered Preskill a baseball encyclopedia, and Preskill accepted the encyclopedia. Hawking's partner Thorne had not yet decided whether to concede, because Thorne wanted to study the paper Hawking was writing.

Hawking published the paper, "Information loss in black holes", in 2005. In the paper Hawking says what his new answer means for a person. If you jump into a black hole, Hawking writes, the energy of your mass comes back to our universe in a scrambled form, which holds what you were like in a state that no one can easily recognize. Hawking gives a picture of the scrambled form: "It is like burning an encyclopedia". Then he says what the picture means: "Information is not lost, if one keeps the smoke and the ashes". And he adds: "But it is difficult to read". In the same passage of the paper, Hawking rules out a hope that many readers of science fiction had held, the hope of passing through a black hole into another universe. If information is kept, Hawking writes, there is "no possibility of using black holes to travel to other universes". At the end of the paper Hawking looks back on his bet with Preskill: "I gave John an encyclopedia of baseball, but maybe I should just have given him the ashes".

Hawking's new answer has two parts: what falls into a black hole is kept, and nothing that falls in goes to another universe. What, exactly, is kept of a person who falls in, and is what is kept still you?

From Cham and Whiteson's pages

What Cham and Whiteson Showed

Jorge Cham and Daniel Whiteson give a chapter to the afterlife in their book *Frequently Asked Questions About the Universe*. Cham is a cartoonist, and Whiteson is a physicist. Cham and Whiteson open the chapter with the plainest fact there is: everybody dies. Then they take the oldest question there is: what happens after we die? They ask the question as physicists, with care for the reader and with good humor.

A traditional afterlife, Cham and Whiteson say, has three parts. There is a you that outlives your body. The you that outlives your body is captured and carried to another place. And you go on existing in the other place, able to experience things, forever. Cham and Whiteson take the three parts one at a time.

Cham and Whiteson begin the first part, the you that outlives the body, by asking what makes you you. All the matter we deal with is made of two kinds of quark and the electron, and every electron is the same as every other, so what sets you apart from lava or ice cream is the arrangement of your particles. Cham and Whiteson conclude that "you are just the information about how those particles are arranged" (*Frequently Asked Questions About the Universe*, ch. 13, "A You Beyond You").

Cham and Whiteson raise three questions about the second part, the journey to another place, and all three questions are about copying the information of how the particles of your body are arranged. The first question is how the information could be read, because every scan puts energy into the body, and because copying a quantum state destroys the original, as the no-cloning theorem of quantum mechanics states. The second question is how much of the information is needed. The third question is which version of you, at which age, gets to go on.

Cham and Whiteson consider two places for the third part, the other place where you would go on existing. The first place is a larger universe around ours, which Cham and Whiteson call a "metauniverse". Going to the metauniverse would mean that your information is

somehow scanned and copied out of our universe into that outside universe (ch. 13, "Existing in Another Location Forever"). The second place is a parallel universe. Cham and Whiteson report that physicists do not currently think information can get into a parallel universe. Cham and Whiteson add that we could build an afterlife ourselves. The easiest way would be to upload a person into a computer that runs a simulated heaven.

Cham and Whiteson state their verdict on the evidence plainly: "To the best of our knowledge, there is no evidence that anything but entropy happens once we die" (ch. 13, "Ripples Through Time"). Cham and Whiteson cannot rule an afterlife out. They judge that providing an afterlife would be a very large task from the point of view of physics, because the task would need whole universes built and countless particles scanned.

Then Cham and Whiteson turn to a comfort that physics does give. Quantum mechanics says that quantum information cannot be destroyed. So the information of your particles stays in the quantum state of the universe after you die. And every action you take leaves a mark on the particles the action touches. Cham and Whiteson put the comfort in these words: "our actions ripple through time, never lost and always present in the quantum history of the universe" (ch. 13, "Ripples Through Time"). Cham and Whiteson add that someone in the distant future could, in principle, read the mark you leave. From that mark the reader could rebuild who you were and what you did.

My answers differ from Cham and Whiteson's on the other place, the copy, and the reading of the mark. Two of the different answers are Hawking's: there is no journey to another universe, and an encyclopedia is kept only as smoke and ashes. The answers begin with something you can try at your own table.

I agree with Cham and Whiteson about their comfort: what happened is never destroyed. My account has a separate ground for the comfort, and from that ground I say exactly what is kept.

The Warmth in the Room

Leave your cup of coffee on the table and forget the cup for an hour. When you come back, the cup is cold. The warmth of the coffee has gone into the air of the room and the wood of the table. So the room is a very little warmer than before. With a good enough thermometer, you can find that the room is warmer. But you cannot find, anywhere in the room, which part of the warmth was the cup's. The warmth of the cup is kept whole, as a share of the room's warmth. But no one, by any finding, can pick out the cup's share again.

Hold on to the two halves of what the cup shows: the warmth of the cup is kept whole, and no one can find the cup's share in the room's warmth again.

Two Things Called Information

The question of what is kept depends on the word "information". Physicists use the word for two different things. Hawking's encyclopedia shows the first thing. The information in an encyclopedia is what the encyclopedia says: which words are printed, in which order, out of all the words that could have been printed. What the encyclopedia says belongs to the encyclopedia and goes wherever the encyclopedia goes. If you burn the encyclopedia, the smoke and the ashes still carry what the encyclopedia said, as Hawking wrote, but no one can read the words in the smoke and the ashes.

A post office shows the second thing called information. The sorting machine reads only the postal code on each letter, so every letter in one bin looks the same to the machine. For each bin, the clerks can count how many different letters lie in the bin, all looking alike to the machine. The count belongs to the post office, because the clerks make the count with

the office's own machine. When the post office closes, the counts of the office's bins no longer count anything, because the machine and the bins that the counts were made for are gone with the closed office.

The two things called information are kept apart, and each has its own name. Information in the first sense is what Chapter 20 called the form of the content. The form of the content is what the matter is, and which of the matter's possible courses the matter has taken. The form of the content is carried with the matter, wherever the matter goes. Information in the second sense is a *count*: a count of the states that look alike from outside, made relative to one way of looking, like the count in the post office's bin. Entropy is a count of the second kind as well: the entropy of your coffee, as Chapter 13 described it, is the number of arrangements of the coffee's small parts that look the same from outside. The entropy of a black hole is the number of states inside the black hole that no finding made from outside can tell apart.

My account has two grounds of its own for the claim that the form of the content is never destroyed. The first ground is the two great descriptions of physics: the quantum description of matter and light, and Einstein's smooth description of space and time. Within the range where each description holds, each description carries what the matter is from one moment to the next. Within that range, neither description loses any part of what the matter is. In 1976 Hawking published the calculation behind the view he gave up in Dublin. In 1974 Hawking had found that a black hole gives off a glow, and in Hawking's calculation the glow carries away the mass of the black hole, while nothing in the glow records what fell in. Hawking's calculation shows a loss at one place only: where the falling matter reaches the singularity, the point at which Einstein's smooth description of space and time comes to the edge of its range. Picture a road that runs across a map and off the edge of the paper. The road goes on past the edge, and the map stops describing the road there. In the picture, the road is the falling matter, and the map is the smooth description. So

the loss in Hawking's calculation is the edge of the smooth description, as the end of the road on the paper is the edge of the map, and no step inside either description removes the form of what fell in.

The second ground comes from following what fell in past the edge of the map, to the end of the black hole's interior. The interior of a black hole is everything inside the black hole. At the end of the interior, both descriptions come to the edge of their range. The edge belongs to the descriptions, and is not an ending of what the descriptions describe. The matter and light that fell in have not ceased to be. At the end of the interior no context is left, because no large outside world remains to compare anything against. The third axiom of the Immanent Metaphysics is one of the basic statements on which the Immanent Metaphysics is built. Two of the third axiom's three clauses state that content and context are distinct and inseparable. There is no content without a context in which it is content. So the content goes on, and because no content is without a context, a new context forms around the content.

So Cham and Whiteson's comfort holds, on ground they did not use: what happened is never destroyed. What is kept is the form of everything you are, and of every course your matter has taken. What carries that form forward, and in what shape does the form go?

What Crosses, and What Stays Behind

Follow the matter of your body very far ahead in time. Chapter 2 gave one era of the world a name: an epoch. Our epoch is the era of the world in which our stars and galaxies formed. Matter is bound when gravity holds it to other matter, as the Earth is held to the Sun. Chapter 22 showed that, as our epoch ages, bound matter falls together into black holes, and matter that is not bound is carried away alone, beyond the reach of everything else. Chapter 22 also showed where the interiors of the black holes lead: all the interiors reach one shared end, and from that shared

end a new large world forms, which is the next epoch. Chapter 20 gave the limit at which an epoch begins a name: the turn. When we trace our own history back, the turn looks to us like a first moment.

Picture children playing hopscotch on a sidewalk, day after day, by rules the children all know. Each day the children draw a court in chalk, toss their stones and count their hops, and in the night the rain washes the chalk away, so nothing of that day's game is kept. In the picture, the chalk court is the space and time of an epoch, and the stones and the count of hops are everything in that space and time: together, the court, the stones and the count are the epoch's outside world. The rules come back every day, and the children play the next game by the same rules on a court drawn anew.

At the turn, every count made in our epoch stays behind. Every count was made against the outside world of our epoch, and at the turn that outside world has no moment left, so no count goes forward, just as the counts of a closed post office go nowhere. The lengths of our epoch stay behind, and so do its records, the marks that findings leave for later comparisons to read. Every inscription, every scar and every footprint is a mark set in our world, and the new world inherits no mark from the old one. And every thing stays behind as the thing it was: every star, every book and every body.

What crosses the turn is the form of the content, and all of it crosses as one form. Each black hole took in its own matter, and each interior carries the form of its own content. The form of one interior can be told from the form of another only by a comparison that sets the two forms side by side. The outside world of our epoch was the only context in which anyone could ever tell the forms of the interiors apart, but at the turn our epoch's outside world is gone. The principle of identity of Chapter 24 says that what no one can tell apart by any comparison is one thing and not two. So the forms of all the interiors pass the turn as one averaged form. No mark shows which black hole each form came through.

Think of a crowd in a great stadium, heard from a hill a mile away. You hear one roar, rising and falling. Every voice in the stadium goes into the roar, and no one on the hill can pick any one voice out of the roar. In the picture, each voice is the form of one interior. The roar is the one averaged form in which all the forms cross the turn. The roar has the same shape as the warmth in your room. Everything is kept in the roar, and no share of the roar can be picked out.

The averaged form is the seed of the next world: the galaxies of the next world grow from the averaged form. Astronomers have measured, in our own sky, the averaged form that the epoch before ours left. In 1992 the physicist George Smoot and his colleagues reported that the oldest light, the light described in Chapter 1, is not perfectly even. Smoot's team worked with the maps made by the satellite called the Cosmic Background Explorer. The temperature of the oldest light differs from place to place across the sky by about one part in a hundred thousand. Since 1992, every new map has shown the same faint pattern of temperature differences in finer detail. We now know that the galaxies of our sky grew from that faint pattern. In Chapter 20 I called the small differences in the temperature of the oldest light the first ripples, and I identified the first ripples with the form of the content carried through the turn from the epoch before ours. The first ripples hold everything that ended inside the black holes of the epoch before ours, but no one in our epoch can pick out, in the first ripples, the share of any one thing.

Our own epoch will leave its averaged form to the next epoch in the same way. If any part of you ends inside a black hole, that part is kept, as a share of the form of the content from which the galaxies of the next epoch grow. Matter has two roads to the turn: matter that is bound falls into a black hole, and matter that is not bound is carried away alone and comes to the turn by the second road. Chapter 22 showed that matter carried away alone has nothing left within its reach to compare against, so matter carried away alone is in the same condition as matter at the end of a black hole's interior. The content of matter carried away alone does not cease either.

No Other Place, and No Copy

The afterlife that Cham and Whiteson describe has three parts. The three parts are a you that outlives the body, the journey of that you to another place, and the life of that you in the other place, forever. My account differs from Cham and Whiteson on each of the three parts, because the form that is kept is neither a record nor a person.

Start with the journey, because Hawking gave part of the answer in his paper. I have three separate grounds for the claim that there is no other universe that a journey could reach. The first ground is the turn. The next epoch begins at the shared end of the black holes' interiors, and that shared end lies at no moment of our time. So no path runs from any place in our epoch to any place in the next epoch.

The second ground is what a place is. So if any path from here, by any engine or any tunnel, can reach a region, that region is a part of our own world, because events here can affect events there. And if no path reaches a region, that region is no place at all relative to us.

The third ground is the first clause of the Incommensuration Theorem of Chapter 1. In the plain words of Chapter 1, the first clause of the theorem says that symmetry and continuity cannot both be made perfect together at the foundation. Picture a house that holds every world as one of its rooms. To hold every world as one whole, the house must count every room as a room of the house in the same way, so one way of belonging must be shared by all the rooms. Symmetry made perfect means one way of belonging shared by all: the sameness of the staircase of Chapter 1, on which every step is like every other. The house must also join every room to every other, with no room cut off and no break anywhere. Continuity made perfect means a joining with no break: the unbroken run of the ramp of Chapter 1, with nothing sudden in the ramp. So the house would have to make symmetry and continuity both perfect in the one comparison by which the house holds its rooms together. The Incommensuration Theorem states that symmetry and continuity cannot both be perfect to-

gether at the foundation. So no world contains every world. The epochs are not rooms of one larger house, and there are no doors between the epochs for a traveler to open.

The second ground applies to Cham and Whiteson's two places, the larger universe around ours and the parallel universe. Each of the two places is either a region that some path from here reaches, and so a part of our own world, or a region that no path reaches, and so no place relative to us.

Next take the you that is carried. Drop a message into a black hole. Something of the message does reach the next epoch: the form of the message's content, as one voice in the roar. But the message does not cross as a message. A message is a record: marks drawn in our world for a reader who can tell the marks apart. The next world inherits no record from ours. The form of the message's content arrives in the next epoch, but the form is not a message there. The form carries no one's instructions. The same answer holds for a person as for the message. Someone would have to compare a person in the next epoch with a person in ours, side by side across the turn, to find that the two are the same person, but no comparison can be made across the turn. So nothing in the next epoch is the same person as anyone in ours, by any finding anyone could make. Nothing of you crosses the turn as you.

A copy of you fails earlier still, before any journey begins. Chapter 25 showed that a person is not information in the sense of a file, where a file is a list of separate marks, each of a few fixed kinds, read the same way by every reader. A person is three things held together as one: something new arriving that nothing before it fixed, time running one way, and a point of view from inside. A file, by its nature, has none of the three: no new arrival, no time running one way, and no point of view from inside. A person is not a very large file. A scan of a person, however fine, is a description of the person, and a description of a person is a map of the person: the person is not in the map, as the road is not in a map of the road. Cham and Whiteson asked three questions about the copy, and each is a question about the map: how the information could be read, how much of

it is needed, and which version of you goes on. Before any of the three questions is asked, one fact shows that the copy would not be you: identity, in the sense of a single unitary consciousness, is not something a copy can carry. For Cham and Whiteson's heaven built in a computer, the answer is in Chapter 27: a simulated world that held a real subject would be a fenced region of this one world, run inside this world. If a person were uploaded as a file into that fenced region, the file would still be a map of the person.

The claim that someone in the distant future could read the marks you leave has two answers. First, suppose someone in the distant future rebuilt who you were from the marks you left. That person would hold a description of you, which is a map of you. Second, Chapter 13 showed that no process at any scale runs backward faithfully, that is, back through exactly the states the process passed through, so no reversal ever returns the world, or you, to a state already left. Hawking said the same with his picture of the ashes: the encyclopedia is kept, and the encyclopedia is difficult to read.

Last, take "forever": in Cham and Whiteson's third part, you go on in the other place, able to experience things, without end. What goes on through every epoch is the form of the content, averaged and carried across each turn, and the law. In the hopscotch picture, the law is the rules of the game: the structure of the world that I derive. The law holds again in each epoch without being carried across the turn. Each epoch's counts and records end at the turn that closes the epoch, together with the outside world the counts and records were made against, and each new epoch begins its own counts from its own start. So the state of the world is not one state carried on through every epoch, and no you goes on, experiencing, from one epoch into the next.

What a Measurement Can Find

Cham and Whiteson report that physicists have found no evidence that anything but entropy happens once we die. Their report is accurate. We need to know what a measurement can establish at all before we can read Cham and Whiteson's report rightly.

Everyday speech uses three words, real, existent and objective, as if the three meant one thing. The three words make three different claims. In Chapter 14 I held the first two apart, the real and the existent. To be real is to be given in an actual act of comparison, here and now, in the first person: you are real to me because I interact with you. To exist is to have a place in a pattern, as structure that is repeatable, locatable and shareable. What exists is the kind of thing a third person could be told about. The third word is *objective*: to be objective is to hold across many acts of comparison, as what many comparers would find alike. Two examples show the difference between the real and the existent. Event time is the order of your own findings, as Chapter 12 named it. Event time is real and does not exist: event time is given in every act, now, and never stays fixed as structure in a pattern. The number pi is the distance around a circle divided by the distance across the circle. Pi exists and is not real. Pi is a fixed structure, and every act of measuring a wheel gives some ratio of whole counts, never pi itself.

A measurement establishes what exists and what is objective. When an instrument can interact with something, and the finding can be repeated and shared, the instrument has shown that the thing has a place in the pattern, and that many comparers would find the thing.

I take up the soul directly in my essay "The Metaphysics of Science and Religion". The essay states that the soul is atemporal, which means without time, and that what is in time is the relation between self and world. The essay sets two rows of three ideas side by side: one row is no time, one time and all time, and the other row is the self, the world, and the relation between them. In the essay, the relation between self and world goes with one time, and the soul goes with no time. In the essay,

immortality (all time) is an isomorph of timelessness (no time): a concept with the same structure as timelessness. The essay says that on this correspondence between immortality and timelessness, the religious teaching that the soul is immortal has some basis. Last, the essay states that the nature of divinity is an isomorph of the innermost nature of the soul, and is real. The essay states its conclusion in these words: "the divinity of the soul is real, but it does not exist and it is not objective".

Now set the essay's conclusion beside what a measurement establishes. As the essay describes the divinity of the soul, the divinity of the soul is real, has no place in a pattern, and is nothing that many instruments could find alike, so the divinity of the soul lies outside what any measurement establishes. Therefore I predict the report that Cham and Whiteson make: there is no evidence that anything but entropy happens once we die. Cham and Whiteson examined one kind of afterlife: a you carried to another place, to go on through endless time, and this chapter has shown that no path leads to that kind of afterlife.

We ask in time whether anything of us is left after we die. In time, the answer is that the form of your content is kept. The soul, as the essay describes the soul, is without time, so the soul is not among the things this chapter has followed through time: matter, the form of the matter's content, the matter's records and its journeys. In the essay, the teaching that the soul is immortal has some basis in the soul's timelessness, read through the correspondence between the essay's two rows of ideas: timelessness (no time) has the same structure as immortality (all time).

The Cup Again

Go back to the cold cup and the faintly warmer room. The warmth of the cup is kept whole, as a share of the room's warmth, but no one, by any finding, can pick the cup's share out of the room's warmth, and the cup itself, as a warm cup, is gone. The same holds for everything that happens in the world: the form of what happened is kept, while the record of what

happened, and the thing itself, are not carried over. The cold cup in the warmer room has the same shape as what I show for every one of us, in our epoch and across the turn.

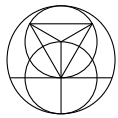
> **The short answer**
>
> The form of everything you are and do is never destroyed: whatever of that form ends inside a black hole is kept as a share of the form the next world grows from, and nothing of you crosses as you.

Nothing is lost, so Cham and Whiteson's comfort holds, and now the comfort has a shape: your life adds its share to what the world is made of, as one voice adds to a roar. What makes you you is lived here, in the one world there is, and no copy carries what makes you you.

What becomes of the universe, the place where all that form is kept?

PART SEVEN

FROM YOU TO THE FAR FUTURE



Chapter Twenty-Nine

How Will the Universe End?

In which we climb a building of years, watch the sky empty, and find the emptying ending in a turn

How will the universe end: in a Big Crunch, a heat death, a rip, or a collapse of empty space?

What this chapter uses

A *comparison* is the act of finding whether two things are the same or different in some respect, and every measurement is a comparison; a *finding* is the outcome of one comparison, laid down as a record; a *comparer* is whatever makes a comparison, whether or not the comparer has a mind (Chapter 1).

The *content* of a finding is what the finding finds, as the warmth of your coffee; the *context* is where the content is found, and the context has three sides, the three settings of space, time and possibility (Chapter 1).

Three things in nature do the bending: gravitation bends space, the cosmological constant bends time, and the dark matter bends possibility (Chapter 1).

The *cosmological constant* is the share of the energy of empty space that a measurement made from inside takes in, one number for our whole epoch (Chapter 3).

The world has ten dimensions, one of time, three of space and six of possibility, and the six are the range of what a finding could be, present at every place and never a place themselves (Chapter 11).

The *turn* is the limit at which an epoch begins: our history, traced back, approaches the limit and shows the limit as a first moment; an *epoch* is one era of the world (Chapter 20).

On 19 April 1852 the Royal Society of Edinburgh met. A short paper by William Thomson was put before the society. Thomson was twenty-seven years old. For six years he had been professor of natural philosophy (the old name for physics) at the University of Glasgow. Forty years later Thomson was made Lord Kelvin, the name by which he is best known. Thomson called the paper "On a Universal Tendency in Nature to the Dissipation of Mechanical Energy". Mechanical energy is energy that can do work: the energy of a turning wheel, or of a weight raised on a rope. To

dissipate mechanical energy is to spread the energy out as heat, in a form from which no more work can be drawn, as the warmth of a brake spreads out after the wheel has stopped. Thomson closed the paper with three conclusions, and he put the first conclusion in one line: "There is at present in the material world a universal tendency to the dissipation of mechanical energy". His third conclusion was about the future. Thomson wrote that within a finite time to come the earth must again be "unfit for the habitation of man as at present constituted", unless something happens that the laws of the material world, as physicists knew those laws in 1852, do not allow.

Thomson's paper gives the oldest modern picture of the end of everything. In Thomson's picture every wheel slows, every warm thing cools to the warmth of its surroundings, and every difference of temperature evens out. At last nothing is left that could drive any change at all. Physicists later named that end the *heat death*: a final state in which everything has one temperature and nothing ever happens again. Physicists of the twentieth century added three more endings to Thomson's. The galaxies might stop flying apart and fall back together in a Big Crunch. The expansion might grow strong enough to tear everything apart, down to the atoms, in a Big Rip. Or empty space itself might change, everywhere, into a different kind of empty space. In our epoch, the era of the world in which stars, galaxies and black holes form, the four endings come down to one course for the universe: a course that runs through the cold emptying that Thomson first pictured, and goes on past that emptying.

From Cham and Whiteson's pages

What Cham and Whiteson Showed

In *We Have No Idea*, Jorge Cham and Daniel Whiteson begin their answer from the speeding up of the expansion of the universe. As the expansion picks up speed, distant things come to recede from us faster than their light can cross the growing distance, and the light of

those distant things stops reaching us. “Already, there are fewer stars visible to us in our night sky today than there were yesterday” (*We Have No Idea*, ch. 3, “What This Means about the Future”). Cham and Whiteson write that in billions of years the night sky will hold only a few visible stars. Later, they write, the night sky could be almost wholly dark. The authors ask how a scientist on the Earth of that far future could ever guess at the existence of the stars and galaxies that scientist cannot see. They give two further courses for the expansion, because so little is known of what drives the expansion: the expansion could go on until it rips apart our solar system and our planet, or the expansion could slow down.

Cham and Whiteson’s second book, *Frequently Asked Questions About the Universe*, has a chapter titled “Will Time Ever Stop?”. In that chapter the authors give several ways in which time could end. Of the ways in which time could end, two are ends of the universe. The first end of the universe is the Big Crunch: the speeding up could stop and reverse, and the galaxies could be hurled together. The authors give the reason a Crunch could come: “And since we have no idea what is expanding the universe, we have almost no way to predict what it will do in the future” (*Frequently Asked Questions About the Universe*, ch. 12, “The Big Crunch”). They name three things that might happen to time at a Crunch: time might end, as north ends at the North Pole, or time might go on, or the Crunch might give rise to another Big Bang, joined to ours by a thread of time. The second end of the universe is the heat death, when everything has spread out evenly and nothing useful can happen. Some physicists say that time would stop at the heat death. The authors call that claim a big leap (*Frequently Asked Questions About the Universe*, ch. 12, “The Heat Death”).

The authors add a threat of another kind in an earlier chapter of *Frequently Asked Questions About the Universe*, on how long humanity can survive: a collapse of the Higgs field, the field that fills all of space and gives the particles their masses. They write that physicists are not

sure how stable the Higgs field is, and that a collapse of the Higgs field would spread across the universe and scramble all of physics (*Frequently Asked Questions About the Universe*, ch. 4, "Higgs Field Collapse").

The authors put their message in their own terms: the endings are many because the cause of the speeding up is unknown, and physicists can tell which ending will come only once physicists learn what dark energy is. I agree with every measured fact in their account. Chapter 3 showed that the cause of the speeding up is the cosmological constant: the share of the energy of empty space that a measurement made from inside takes in. The cosmological constant is one number for our whole epoch. The cause is one fixed number, so the course of the expansion is fixed too. The rest of this chapter follows that course.

The Sky That Empties

Go outside on a clear night, far from the lights of a town, and wait for your eyes to settle. First the bright stars come out, then the faint stars, and then the pale band of the Milky Way: the disk of our own galaxy, seen edge on from inside. Our own galaxy holds every star you can pick out with your eyes. In the autumn sky of the northern half of the world, in the constellation Andromeda, you can find one faint oval smudge: the Andromeda galaxy, the nearest large galaxy to ours. Binoculars show a few more smudges. A large telescope pointed at a patch of sky that looks empty shows the patch crowded with faint galaxies.

The smudges fall into two groups: galaxies held to ours by gravity, and galaxies that nothing holds to ours. Andromeda is *bound* to our galaxy: held to our galaxy by gravity, as the Earth is held to the Sun. Our galaxy and Andromeda belong to one small family of galaxies held together by their own gravity. Astronomers call that family the *Local Group*: our

galaxy, Andromeda, and some dozens of smaller galaxies. The fainter smudges that binoculars and telescopes show are galaxies outside the Local Group, and nothing binds those galaxies to us.

Now picture the speeding expansion carrying the unbound galaxies away. Each unbound galaxy recedes from us faster as time goes on. Beyond a certain distance, a galaxy's light sent out today will never reach us, however long we wait, because the space between the galaxy and us grows faster than the light can cross that space. The edge at that distance is our cosmological event horizon, named in Chapter 23. Chapter 3 named a second edge, the particle horizon: the particle horizon marks the light that has already reached us, and the cosmological event horizon marks the light that ever will reach us. Every observer has its own cosmological event horizon, centered on that observer. Each walker on a wide plain likewise carries a skyline, centered on the walker, wherever the walker goes. When a galaxy drifts across our cosmological event horizon, the galaxy fades from the sky. We still receive the light that the galaxy sent before it crossed our horizon, ever more stretched and ever dimmer. After the crossing, nothing the galaxy does ever reaches us.

Inside the cosmological event horizon, gravity gathers matter into clumps. Stars form, burn out and leave their remains. The remains pull in more matter and merge, so that much of the bound matter ends in black holes. The rest of the matter in each clump is flung away, as bodies or as light. The expansion carries everything not bound to us beyond the cosmological event horizon. Astronomers have followed the measured speeding up forward in time, Lawrence Krauss and Robert Scherrer among them in 2007, and these astronomers find that the galaxies beyond the Local Group pass out of reach within a hundred billion to a trillion years.

The emptying follows on separate ground, from what an observer is. As Chapter 1 said, a comparer is anything that compares, a camera or an atom as much as a person, and a comparer's outside world is everything that can ever reach the comparer and be set beside the rest of what the comparer receives. A comparer's cosmological event horizon is the edge of the comparer's outside world, so the outside world of every comparer is

bounded. Inside that edge, gravity gathers matter into clumps and black holes, and the expansion carries away everything unbound. So the outside world of every comparer empties. I call a comparer's outside world its "comparable exterior", and every observer's comparable exterior therefore empties. The size of the cosmological constant can be worked out by my own route, and from it I derive the same emptying a third way: the carrying away comes from that very constant, and the far future, seen from inside our epoch, is a cold, dark, eternally expanding emptiness.

Cham and Whiteson and I agree that the other galaxies leave the sky. The faint smudges beyond the Local Group pass out of reach. The two answers differ about the stars. In the authors' picture the expansion leaves the night sky only a few visible stars. The stars of our own night sky stay. Those stars stay because they belong to our galaxy, which is bound, and the expansion carries away nothing that is bound. The stars of the Local Group burn out over far longer times, and the expansion plays no part in their burning out.

The authors asked how a scientist of the far future could guess at the stars and galaxies that scientist cannot see. Their question has a published answer. Krauss and Scherrer pictured astronomers living in the one galaxy that ours and Andromeda will by then have become. Those future astronomers would find no distant galaxies whose motion they could measure. The oldest light, which Chapter 1 met, is the faint glow left from the beginning of our epoch. The future astronomers would find the oldest light stretched into waves too long to catch. Krauss and Scherrer wrote that those future astronomers "will conclude the existence of a static 'island universe'": one galaxy, alone, in an unchanging dark. We can still measure the expansion, because we live while the evidence of the expansion is still in the sky.

A Building of Years

The spans of the far future are too large to picture as numbers, so picture a tall building instead. The ground floor stands for one year. Each floor stands for ten times as many years as the floor below it. The first floor is ten years, and the second floor is a hundred years, about a long human life. All of written history fits below the fourth floor, which is ten thousand years. The ninth floor is a billion years (a thousand million), and the tenth is ten billion. We live on the tenth floor: the universe is about 13.8 billion years old.

Climb. Between the eleventh and the twelfth floors, the galaxies beyond the Local Group pass out of reach. Even the largest telescope then shows no galaxy outside the Local Group. Around the fourteenth floor the galaxies stop making new stars. The physicists Fred Adams and Gregory Laughlin reported that floor in 1997, working from the known physics of stars. From the fifteenth floor to the twenty-fifth, close passes fling the burned-out stars out of each galaxy one by one, or the burned-out stars fall into the black hole at the center of the galaxy.

The thirty-fourth floor carries a mark set by measurement. Since 1996 the Super-Kamiokande experiment of Chapter 9 has watched the protons in fifty thousand metric tons of water. Super-Kamiokande has seen no proton break up into a positron (the antimatter partner of the electron) and a pion (the lightest of the particles made of quarks), so for that way of breaking up, the proton lasts beyond the thirty-fourth floor. The proton does not decay at all, so the proton has no floor in the building. So the remains of stars keep their particles and their mass until each body ends inside a black hole, or is carried away alone, beyond the reach of all other matter.

The black holes last longest. In 1974 the physicist Stephen Hawking showed that a black hole gives off a faint glow, as a warm body does. Hawking also showed that the heavier the black hole, the colder its glow. When a black hole has the mass of the Sun, the black hole glows at about six hundredths of a millionth of a degree above absolute zero (the coldest

cold there is, which Chapter 20 met). The oldest light is far warmer than the black hole. So the black hole takes in more warmth from the oldest light than the black hole gives off. The black hole begins to shrink only after the oldest light has cooled below the black hole's own temperature. The oldest light cools that far between the eleventh and the twelfth floors. The shrinking itself then takes about ten to the sixty-seven years: a one followed by sixty-seven zeros. A black hole of the Sun's mass glows itself away on the sixty-seventh floor. The largest black holes sit in the centers of galaxies, and they last to about the hundredth floor.

Set the floors side by side. The emptying of the sky is done by the twelfth floor. Black holes of the Sun's mass are all gone fifty-five floors higher. So the emptying comes first, by an enormous margin, and the glow of the black holes changes nothing in the emptying. No floor of the building carries a falling back of the galaxies, a rip, or a change of empty space, and I give the reason for each of the three in the next three sections.

The Expansion Keeps Going

Throw a ball straight up, and the ball slows, stops at the top, and falls back into your hand. From a small enough world, a ball thrown just as hard never comes back: the ball slows forever and never stops. For most of the twentieth century, physicists pictured the expansion of the universe like the thrown ball. If the galaxies had too little speed for the amount of matter between them, gravity would win: the expansion would stop and reverse, and the whole of space would fall back together. Physicists call that falling back a *recollapse*: the expansion of the universe as a whole stopping, turning around, and contracting all of space together. The Big Crunch is the end of a recollapse.

A recollapse could come about in three ways. There could be enough matter to stop the expansion. The cosmological constant could later shrink, or turn from a push into a pull. Or the end of an epoch could itself be a collapse of all of space at once. My account has its own reason against each of the three ways.

The first way, enough matter to stop the expansion, is decided by a sum that comes from Einstein's equations of gravity. The square of the rate of expansion equals a part from the density of matter and energy, less a part from the bending of space as a whole if space is closed, plus a part from the cosmological constant. The density part is never negative, because matter and energy are never negative amounts. A recollapse needs the rate of expansion to fall to zero, since a growing universe can begin to shrink only by first standing still, like the ball at the top of its flight.

The bending part is zero. The bending of space as a whole is set by a length: the size of the ball that space would be curved like. The length that fixes the bending of space as a whole is set once, at the beginning of an epoch, and the length stays unchanged ever after. No comparer in our epoch can lay a ruler beside anything from before our epoch began. A difference that no comparison can ever register is no difference. So the beginning of our epoch carries over no length from anything before our epoch. The beginning of our epoch holds only one length, the Planck length. As Chapter 8 showed, the Planck length is the length at which the two great descriptions of physics meet: the quantum description of matter and light, and Einstein's smooth description of space and time. At the Planck length a body's gravitational size equals its quantum size, and neither description dominates the other. A space closed like a ball the size of the Planck length would close up again at once, and a space bent the other way on so small a length would fly apart before any matter could gather. Our epoch is the era in which stars, galaxies and black holes form, so the space of our epoch is *flat*, as Chapter 3 said: lines that start out side by side stay side by side. Astronomers have measured the bending of space as a whole, from the oldest light and from the patterns in which galaxies are spread, and found the bending zero to within about two thousandths of the whole.

The constant part is positive. The cosmological constant is the share of a positive energy, the energy of empty space, so the cosmological constant is positive. Two teams of astronomers showed the speeding up from distant exploding stars, in the papers of 1998 and 1999 that Chapter 3 told. Both teams found the constant positive. Put the three parts together: the

density part is never negative, the bending part is zero, and the constant part is positive. So the square of the rate of expansion is always larger than the constant part alone. The rate of expansion therefore never reaches zero, whatever the amount of matter. Gravity holds the expansion back, and it never stops it.

The second way needs a cosmological constant that changes: a constant that later shrinks, or turns from a push into a pull. Chapter 3 pictured the cosmological constant as the scale printed in one corner of a map. Chapter 3 also stated the reason, a theorem about Einstein's equations: the equations keep a strict account of energy and of momentum, and a constant term that varied from place to place, or from one time to another, would break that account. A fixed number neither shrinks nor grows, and its sign never changes. As Chapter 3 showed, the dark energy is the share of the energy of empty space that a measurement made from inside takes in, and that share enters Einstein's equations as their one constant term. The measurement made now fixes the value of the share. We piece together the history of our epoch from that measurement, and the history carries that one value at every time of the epoch, after the present as well as before it. So the expansion is not driven by a drifting field whose energy could fall with time.

The third way needs the end of an epoch to be a collapse of all of space at once. Our epoch does end in a collapse, but the collapse happens only inside the black holes, each black hole on its own clock, while the space between the black holes keeps expanding the whole time. The whole sky never rushes together on any evening. The authors write that at a Big Crunch there would be nowhere to run, because space itself would shrink (*Frequently Asked Questions About the Universe*, ch. 4, "So Are We Toast?"). Space as a whole never shrinks, and the only collapses are the collapses of matter that falls into black holes. Our epoch does not fall back.

What Is Bound Stays Bound

In August 1999 the physicist Robert Caldwell posted a paper titled "A Phantom Menace?". In the paper Caldwell asked what would follow if the dark energy were stranger than any kind of energy physicists usually allowed. In 2003 Caldwell followed that strange energy to its end with the physicists Marc Kamionkowski and Nevin Weinberg. The three physicists' paper has the words "Cosmic Doomsday" in its title. The three physicists found that the strange energy grows denser as the universe expands, without limit, and reaches an infinite density at a definite time. For one example the three physicists worked out the timetable: the end would come about twenty-two billion years from now. The Milky Way would be torn apart about sixty million years before the end. Atoms would come apart a ten-billion-billionth of a second before the end. The Big Rip is that end, with every bound thing torn apart.

Whether a rip comes depends on one number. Every kind of stuff that fills the universe has a pressure and a density. The number that matters is the pressure divided by the density, and physicists call that number the stuff's *equation of state*. For thin matter, such as the galaxies themselves, the number is zero, and for light the number is one third. For the cosmological constant the number is exactly minus one, and stuff with that number does not thin at all as space grows. When the number of a stuff lies below minus one, the stuff grows denser as space grows. Caldwell named stuff whose number lies below minus one *phantom energy*. Caldwell, Kamionkowski and Weinberg showed that a rip happens when the number lies below minus one, and only then. For a number of exactly minus one, the three physicists' own analysis shows no rip: everything bound now stays bound.

The dark energy of our epoch is the cosmological constant, one number for the whole epoch, and a density that never changes as space grows has a number of exactly minus one. So the dark energy of our epoch has the number for no rip, now and at every later time of the epoch. Nothing else in the world can supply a phantom energy alongside the cosmologic-

al constant. As Chapter 4 showed, the kinds of particle form a closed list. As Chapter 3 said, the energy of the Higgs field has been constant since long before the expansion began to speed up. A constant energy does not thin as space grows, so the number of the Higgs field's energy is exactly minus one. The Higgs field therefore supplies no phantom energy.

Picture yourself standing outside in a breeze. A steady breeze, the same every minute, makes you lean a little. You find your balance once, and you stand all night. Only one wind knocks you over in the end: a wind that keeps rising, with no limit to its strength. The cosmological constant is the steady breeze, and the phantom energy is the wind that keeps rising. Everything bound now is bound in a world that already has the cosmological constant at its present value. So the small outward push of the cosmological constant is already part of the balance of every bound thing, as the steady breeze is part of your balance, and that push never grows. The size of the push follows from the measured value of the constant and from measured masses and sizes. At the outer edge of the cloud of matter around our galaxy, the push is about seven thousandths of the pull that holds the matter there. For the Earth in its path around the Sun, the push is about eight parts in a one followed by twenty-three zeros of the Sun's pull, and for an atom the push is smaller still. The push stays the same fraction of the pull, for the edge of our galaxy, for the Earth and for an atom alike: the same tomorrow, on the twelfth floor of the building of years, and on the twenty-fifth.

The raisin bread of Chapter 23 shows a second way that the expansion tears nothing bound apart. As the dough rises, every raisin moves away from every other raisin, and no raisin swells, because each raisin holds itself together. The expansion is the rising dough between the raisins. Each bound thing is a raisin: an atom, a planet, a galaxy, a family of galaxies. Gravity acts where the matter is, while the cosmological constant is the same at every place and every time and gathers at no place. So the cosmological constant cannot build up against any one bound thing, and the expansion never tears apart anything that holds together.

Empty Space Keeps Its Nature

On 24 January 1977 the journal *Physical Review* received a paper called "Fate of the false vacuum" from Sidney Coleman, a physicist at Harvard University. Coleman asked his readers to picture a liquid heated past its boiling point and kept from boiling. In the overheated liquid the jostling of the heat keeps making tiny bubbles of steam, and most of the bubbles shrink away. Now and then one bubble forms large enough to grow, and that bubble spreads until the whole liquid has turned to steam. Coleman said that empty space could be like the overheated liquid: held in a state that is not its lowest, and waiting for one bubble. Three years later Coleman and the physicist Frank De Luccia added gravity to the picture. Coleman and De Luccia found that a bubble leading into an empty space of energy below zero collapses inside under its own gravity. Coleman and De Luccia wrote that the decay of a false vacuum (empty space held, like Coleman's liquid, in a state that is not its lowest) is "the ultimate ecological catastrophe".

Picture a hilly country with many valleys, and a ball resting at the bottom of one valley. Nudge the ball, and the ball rolls a little way up the slope and settles back. As Chapter 3 said, the *vacuum* is empty space at its lowest energy, with every field at its quietest. A vacuum is like the bottom of the lowest valley. A valley that holds the ball but is not the lowest in the country is like a *false vacuum*: a settled state of empty space that is not the lowest one. In quantum physics a ball held in a valley can pass through the ridge into a lower valley without climbing over the top. Physicists call that passing *tunneling*. For a whole world held in a false vacuum, the tunneling begins as one bubble that grows. The decay of a false vacuum always needs a second, lower valley for the bubble to lead to.

Empty space has two settled features, and each feature has one valley. The first feature is the held shape of the six small dimensions of possibility, which Chapter 11 counted: the range of what a finding could be, curved at every point far smaller than the core of an atom. The six can vary in two ways only: in their size, and in the ratio of the sizes of their

two parts. The size and the ratio are each held at one value, because every direction of the six bends by the same amount, the bending of the Planck scale. So the six are curved at one to two and a half Planck lengths. Chapter 9 met string theory: the proposal that each particle is one way a tiny string can vibrate. String theory also curls six dimensions small. In string theory, physicists thread fields through loops in the six small dimensions. A field can wind through a loop any number of times, and each count of windings gives a different valley, so string theory has a vast number of valleys. The law of gravity in all ten dimensions comes from the geometry of the ten dimensions alone. No field is threaded through the six small dimensions. So my account has no count of windings to choose. The six small dimensions have one valley, and no lower valley for a bubble to lead to.

The six small dimensions stay held while the large world of space and time is there around them, with things in it to compare against. The large world is missing in two places only: at the end of a black hole's interior (everything inside the black hole's horizon), and around a body carried away alone, with nothing left within its reach. Both places lead to the turn: the limit at which the next epoch begins. The turn is not a bubble of a lower vacuum, because in the next epoch the same six small dimensions form again with the same shape.

Empty space has a second settled feature: the settled value of the Higgs field, which Chapter 5 called the condensate. The stability of the Higgs field is the authors' worry. Picture the bottom of a wine bottle, with its raised bump in the middle and a round trough all about it. Let the height of the glass stand for the energy of the Higgs field. Let the distance from the center stand for the size of the field's value. The curve of the Higgs field's energy is derived in my account, and the curve has two parts. One part pulls the energy down as the square of the field's size, and one positive part pushes the energy up as the fourth power of the field's size. Together the two parts make a curve with one lowest place, the round trough, and the trough is the present state of the Higgs field. The closed list of kinds of particle has one field of the Higgs field's kind, and

that field has one direction in which to vary, its size. So the Higgs field has no other direction in which a lower valley could lie. My account also has the principle that every way of varying has a least state, so the energy of the Higgs field has a lowest value, below which the energy cannot fall.

The fourth-power part is set by how strongly the Higgs field acts on itself, and in quantum physics that strength changes slowly with the energy at which the strength is measured. The strength is worked out at the energies of the weak force. Physicists measure the Higgs boson, a small ripple of the Higgs field, at the energies of the weak force. At the energies of the weak force, in the two-part curve of my account, the lowest value of the energy is the present state of the Higgs field. In 2013 the physicist Dario Buttazzo and his colleagues followed the strength out to far higher energies. Buttazzo and his colleagues used the Standard Model (the established theory of the kinds of particle and of the three forces among them: the strong force, the weak force and electromagnetism), with the measured masses of the Higgs boson and of the top quark. In their calculation the strength falls to small or negative values at very high energies, and a region of energy lower than the present state appears far out beyond the trough. In the Standard Model calculation the present state is *metastable*: held, able in principle to pass by tunneling to the far region, and lasting far beyond the age of the universe. In 2018 three physicists computed a lifetime for the present state: Anders Andreassen, William Frost and Matthew Schwartz found about ten to the one hundred thirty-nine years. In the building of years that lifetime is the hundred and thirty-ninth floor. The hundred and thirty-ninth floor is far above the sixty-seventh, where the last black hole of the Sun's mass is gone.

The six small dimensions keep their one shape for as long as the large world is there around them, and the Higgs field rests in its one trough, at the lowest value of the curve I derive. The Standard Model calculation, too, has the trough holding past the hundredth floor, the last floor of the black holes.

The Emptying Ends in a Turn

Go back to Edinburgh in 1852, and to Thomson's spreading of energy. The emptying sky of this chapter is the modern form of Thomson's picture: the galaxies leave, the stars burn out, and the count of entropy rises. As Chapter 13 said, the entropy of a thing is a count of the arrangements of its small parts that look the same from outside, and the count is always made relative to some look at the thing. The cold, dark sky is real, and the cold, dark sky is how the far future looks from inside our epoch. Three grounds show that the story of the universe does not stop at the cold, dark sky, and each ground is enough by itself.

The first ground is that content cannot be without a context. Chapter 1 named the two parts of every finding: its content, what is found, and its context, where it is found (the three settings of space, time and possibility). My account has axioms, the basic statements on which the account is built. The third axiom says that content and context are held together: there is no content without a context in which it is content, and no context without a content. At the end of a black hole's interior, and for a body carried away alone, the matter and light have not ceased to be. The content is still there, and no large world is left to be its context. So a context must form again. A context can form only from the one thing left: the geometry of all ten dimensions itself. When the conditions fail, the ten-dimensional geometry restores a large outside context. It must.

The second ground is the Incommensuration Theorem of Chapter 1. The first half of the theorem says that symmetry and continuity cannot both be applied, simultaneously and fundamentally, to any event or comparison. Recall the two pictures of Chapter 1: the ramp is continuous, smooth with nothing sudden anywhere, and the staircase is symmetric, the same at every step. A final world of featureless emptiness would be the same everywhere and at every moment, like the staircase, and smooth, with no break anywhere, like the ramp. So a final world of featureless emptiness would be perfectly symmetric and perfectly continuous at once, and by the first half of the Incommensuration Theorem no event or com-

parison can be both at once. A final featureless emptiness is the one character no comparison ever finds, so the emptying cannot simply come to rest.

The third ground answers the heat death, Thomson's fear, directly. I pictured the third ground in Chapter 22 with the census of a newly founded country. Every entropy is a count of the same kind as a census. An entropy counts the arrangements that look the same to the comparisons available from one outside world, so every entropy is counted against that one outside world, as a census is counted on one country's forms. Our epoch's entropy tends toward a largest value, and that largest value is counted against our epoch's outside world. When our epoch's outside world has emptied, no world is left for the largest value to be counted against, and the next epoch begins its own count against its own outside world. The heat death would be a final maximum of entropy that holds forever. So the heat death has no outside world against which the heat death could be counted.

The three grounds come from three places: the third axiom, the Incommensuration Theorem, and what an entropy counts. The three grounds are like three strands of one rope, each strand spun from a different fiber, and each ground answers Thomson's old fear by itself.

Chapters 20 to 22 showed where the next epoch begins. The interiors of all black holes share one end, because no comparison, before that end or after it, can tell the end of one interior from the end of another. That shared end is the turn: the limit at which an epoch begins, approached from both sides and reached from neither. The next epoch begins from the turn, and, as Chapter 20 showed, the Big Bang of our own epoch is the turn, seen from our side when we trace our history back.

Two different clocks time the turn and the glow of the black holes. The glow is timed by the clock of the outside world: seen from outside, a black hole of the Sun's mass lasts and glows for ten to the sixty-seven years, and the black hole shrinks by that glow. The turn is timed by the clock of what falls in. On the clock of what falls in, the end of the interior comes at most

about fifteen millionths of a second after the falling matter crosses the horizon. As Chapter 21 showed, the end of the interior lies at no moment of the outside world's time. The building of years counts the years of the outside world, so the building has no floor for the turn. What falls in reaches the end of the interior, and so reaches the turn, within those fifteen millionths of a second of its own time, a span vastly shorter than the ten to the sixty-seven years of the glow. As Chapter 28 showed, at the turn the form of what fell in (what the matter is, and which of its possible courses it has taken) crosses into the next epoch.

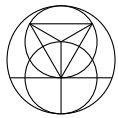
The turn comes even though the expansion keeps speeding up. Between the black holes the cosmological constant goes on carrying the galaxies apart, but black holes still form, and their interiors still share one end. The cosmological constant is a share taken in by measurement from inside an outside world. No outside world is left at the shared end of the interiors, so the cosmological constant plays no part at all there. So, as Chapter 22 showed, the history of the universe is a cycle of epochs, and not a single arc from Big Bang to heat death. Cham and Whiteson give a third picture of a Crunch, a new Big Bang joined to ours by a thread of time, and that picture has the same outcome as my account. On my account, the outcome comes with no Crunch: the next epoch begins at the shared end of the black holes' interiors, and the space between the black holes never stops expanding.

> **The short answer**
>
> Our epoch's sky empties and the emptying ends in a turn that begins the next epoch, but the expansion never turns back, nothing bound is torn apart, and empty space keeps the one settled state that my account derives for empty space.

Chapter 3 showed that the cause of the speeding up is one number for our whole epoch. So the course of the expansion is fixed from the tenth floor upward. The four endings of your question come down to one road.

Three of the endings never come: the Big Crunch, the Big Rip and the collapse of empty space. The fourth ending is the cold dark of Thomson's heat death, and that cold dark is the last view of one epoch before the next epoch begins.

When the sky is empty, does time stop?



Chapter Thirty

Will Time Ever Stop?

In which the coffee cools without a last step, Clausius's maximum leaves the order of comparison as it was, and the last watcher under an empty sky still finds things in order

Will time ever stop?

What this chapter uses

A *comparison* is the act of finding whether two things are the same or different in some respect, and every measurement is a comparison; a *finding* is the outcome of one comparison, laid down as a record; a *comparer* is whatever makes a comparison, whether or not the comparer has a mind (Chapter 1).

Every comparison goes one way, from what could be found, to the finding, to its record, and so time goes forward (Chapter 13).

The *turn* is the limit at which an epoch begins: our history, traced back, approaches the limit and shows the limit as a first moment; an *epoch* is one era of the world (Chapter 20).

On 24 April 1865, in Zürich, the physicist Rudolf Clausius read a paper to the Natural Science Society of the city. Clausius was then professor of physics at the Swiss Federal Technical Institute in Zürich, and his subject was the science of heat and work. The journal *Annalen der Physik und Chemie* printed the paper in 1865. In the paper Clausius gave a name to a quantity of his theory of heat. He called the quantity entropy, from the

Greek word for a transformation. At the very end of the paper Clausius set down two sentences, in German, about the whole universe. In English the two sentences read: "The energy of the universe is constant. The entropy of the universe tends toward a maximum".

Clausius's first sentence says that the world's store of energy neither grows nor shrinks. His second sentence says that the world's entropy climbs, and climbs toward a largest value. Clausius said nothing about time in his two sentences. If the entropy of the universe climbs toward a largest value, what becomes of time when the entropy gets there? Does time run down and stop, as a clock does?

From Cham and Whiteson's pages

What Cham and Whiteson Showed

Cham and Whiteson give a whole chapter of their book *Frequently Asked Questions About the Universe* to the question "Will time ever stop?", which is also the chapter's title, and they take the question seriously. Cham and Whiteson begin by asking what "time stopping" would even mean, and they find three answers. First, "time stopping" could mean no more laws: cause and effect lose their meaning, and the order of the world comes to an end. Second, "time stopping" could mean no more changes: the world freezes in whatever state it has reached. Third, "time stopping" could mean the end: time ends only together with the whole universe.

Then Cham and Whiteson gather what physics knows about time. Time had a beginning of sorts, since the expansion of the universe, run backward, leads to a state of infinite density where all our theories break down. Time is relative: every place has its own clock, and a clock moving fast, or sitting near a heavy mass, is seen by others to run slow, while the clock's owner always feels time pass normally. The authors write that speed cannot stop a clock: a clock on a fast ship ticks as slowly as you like, but the clock would stop only at the speed

of light, which nothing with mass can reach. And time may not be basic at all: some physicists think that time flows out of a deeper "meta-time", the way a river's flow is something water does and need not do.

The authors then weigh three ways that time could end. The first way is a Big Crunch: the universe falls back on itself. After a Big Crunch, time might be capped, as the direction north is capped at the North Pole. At the North Pole you can take no step farther north. Or time might run on through the crunch. Or a new Big Bang might start a new universe, with time running on unbroken from the old universe into the new one.

The second way is the heat death, which Chapter 29 described. The heat death is a final state of one even warmth, in which entropy has reached its largest value. Some physicists say that time flows because entropy rises, and so time would stop when entropy stops rising. The authors call that idea a big leap, for two reasons: no one knows that entropy drives time, and particles still fly around at maximum entropy. They close the thought with a joke that is also a judgment: "So while it may not be the end of time, it will definitely be the end of fun" (*Frequently Asked Questions About the Universe*, ch. 12, "The Heat Death").

The third way is a stop in the meta-time. We would never notice a stop in the meta-time, since our clocks and our thoughts would stop along with the meta-time, as a character in a paused movie never learns of the pause. The authors' last word on the matter is an admission: "It's time to admit the truth: we don't really understand time" (*Frequently Asked Questions About the Universe*, ch. 12, "The End of Our Time"). Cham and Whiteson ask the same question, "Will time ever stop?", in their earlier book, *We Have No Idea*, and together with that question they ask whether time will stop when the universe reaches maximum entropy. Cham and Whiteson close the whole question with that book's refrain: "The truth is that, as usual, we have no idea" (*We Have No Idea*, ch. 8, "Question #5: Will Time Ever Stop?").

I agree with the authors on two results, and my account has its own ground for each result. First, no clock with mass is ever brought to a stop. Second, as the authors suspected, a maximum of entropy is no end of time. On the question itself, where the authors say that they have no idea, my account has an answer: time does not stop.

Which Time?

Physics uses one word for three different times, as Chapter 12 showed. Geometric time is the time on a clock. Geometric time belongs to the shape of space and time, and a clock's geometric time runs at a rate set by where the clock is and by how the clock moves. A comparer is anything that compares one thing with another and registers the result. Evolution time is the number on the single dial in quantum theory's rule for how a quantum state changes. No one time is geometric time, event time and evolution time at once, with each of the three made perfect.

The question "will time stop?" therefore has one meaning only after someone sorts out which time the question means. The authors' three meanings of "time stopping" already do that sorting. Their meaning "no more changes" asks about clocks, because a clock is a thing that changes in a regular way. So the question becomes: will every clock come to a last tick? Their meaning "no more laws" asks about order: with cause and effect gone, will the order in which one thing is found after another come to an end, or run backward? Their meaning "the end" asks whether the universe, and time with it, comes to a last moment. The question about clocks is about geometric time, and the question about order is about event time. Evolution time belongs to the mathematics of quantum theory, and none of the authors' three meanings asks about evolution time.

The Coffee That Never Quite Reaches the Room

Pour a cup of coffee at eighty degrees Celsius and set the cup on a table in a room at twenty degrees. Check the coffee with a thermometer every ten minutes or so. A cup on a table follows Isaac Newton's rule of cooling closely. Call the difference between the coffee's warmth and the room's warmth the gap. By Newton's rule, the gap closes by about the same fraction in each equal stretch of minutes. Say that the gap halves in each stretch. You find the gap sixty degrees, then thirty, then fifteen, then seven and a half, and so on. Each time you check, you find the gap halved.

Now look at all your readings together. Every reading lies between eighty degrees and twenty, inside a finite stretch of the thermometer. The readings come closer and closer to twenty, and no reading is the last reading before twenty. Name any reading, and there is a next reading, closer still. The readings approach twenty degrees as a limit. A limit is a value that the readings come as near to as you like, and that no single reading is. Chapter 20 first gave the word "limit" its meaning, with a picture of a walker halving the distance to a wall.

The picture of halving again and again is very old. The philosopher Aristotle reports the puzzle of the philosopher Zeno in the sixth book of his *Physics*: a runner must first cover half the track, then half of what remains, then half again. The marks at the halfway points all lie within one finite track, and no mark is the last mark before the finish line.

A clock that falls into a black hole keeps a time of exactly the same shape as the coffee's readings. Chapter 21 followed the falling clock. The falling clock shows its proper time. Chapter 12 named proper time: the time a clock shows as the clock is carried along its own path. On the falling clock, the end of the interior comes soon. For a black hole of the Sun's mass, the end comes at most about fifteen millionths of a second after the clock crosses the horizon. The end of the interior is a limit for the falling clock, as twenty degrees is a limit for the coffee's readings. Physics describes the path of the falling clock for every moment short of the end and

for no moment beyond the end, and at the end the smooth description of space and time stops. The falling clock's time is finite, and that finite time has no last tick in it.

For the one who falls in, the end of the interior is the end of time on the faller's own clock. The black hole's outside world is everything outside its horizon, and for the outside world the end of the interior never happens. No signal from the end of the interior reaches any moment outside the horizon, so no clock outside can place the end of the interior before, at or after any of the outside clock's own moments. The authors themselves describe what a friend far away sees: the faller slows almost to a freeze at the horizon, and the friend never sees the faller cross the horizon at all. Time as a whole does not stop, because no clock, the falling clock included, comes to a last tick.

The clocks outside a black hole behave as the authors say. A clock on a fast ship ticks slower as the ship goes faster, and the clock still ticks on. Seen from far away, a clock near a black hole ticks slower and slower, and the clock still ticks on. On every path, then, inside a black hole or outside, the time a clock shows comes to no last tick: the falling clock comes to its end as a limit, and the clocks outside tick on. The authors' meaning "no more changes" pictured a world frozen in its last state. A clock is a thing that changes in a regular way, and no clock comes to a last tick. So the answer to that picture is no.

What Was Measured

Physicists have measured clocks slowed by motion and clocks quickened by height, and every one of those clocks ticked on. In October 1971 the physicist Joseph Hafele and Richard Keating, of the United States Naval Observatory, flew four atomic clocks twice around the world on ordinary airliners, as Chapter 12 told. The clocks flown east came home about fifty-nine billionths of a second behind the clocks of the United States Naval Observatory in Washington. The clocks flown west came home about two hundred and seventy-three billionths of a second ahead.

In 2010 Chin-Wen Chou and his colleagues raised one of two aluminum-ion clocks by thirty-three centimeters, and the higher clock ran faster. In the clocks flown around the world and in the raised clock, each change of rate was the amount that relativity predicts. The rule of relativity says that a clock on a faster ship has a slower rate, and a rate of zero only at the speed of light, which nothing with mass reaches. What we now know is that motion and height change the rate of a clock by the amounts relativity predicts, and that the rule of relativity, which the flown clocks and the raised clock confirm, brings no clock with mass to a stop.

Does Time Stop at the Maximum?

Now return to Clausius's second sentence: "The entropy of the universe tends toward a maximum". In Chapter 29 we followed Clausius's maximum to its end. Chapter 13 showed that the count of an entropy is always made relative to some look at a thing. In the far future our epoch's outside world empties: everything in it falls into a black hole or is carried out of reach by the expansion of the universe, as Chapter 29 found. When our epoch's outside world has emptied, the largest value of our epoch's entropy has nothing left to be the largest value of. So no heat death holds forever, because a heat death is a largest value of entropy that holds forever, and the emptied outside world leaves nothing to count that value against. The next epoch begins its own count. In this chapter I still have the physicists' question to answer. Where entropy does reach its largest value, in a cup or in a whole epoch, does time stop there?

The answer rests on two arrows of time, which Chapter 13 described: two different things that point the same way. The structural arrow is the one-way order of every comparison: from the range of what could be found, to the act in which one finding is made, to the record the finding lays down. The one-way order is present in one comparison made once, as in a photographer's position, click and print: the photographer's position gives the range of pictures she could take, the click is the act that takes one picture, and the print is the record. The one-way order needs no

crowd of parts and no special beginning of the world. The direction of time rests on the structural arrow, and the growth of entropy shows that direction in things of many parts.

Go back to the coffee after a whole night on the table. To every reading your thermometer can make, the coffee is at the warmth of the room. The entropy of cup and room has reached its largest value. You can still read the thermometer this morning, and again after breakfast. Each reading comes after the reading before it, and each reading leaves its record after the reading is made. The order of your readings runs as it ran while the coffee cooled. So wherever entropy reaches its largest value, the one-way order of comparison stays exactly as it was. The authors doubted that entropy drives time, and their doubt was well founded: entropy does not drive time, and the end of entropy's rise is no end of time's direction.

The Last Watcher Under the Empty Sky

The authors' meaning "no more laws" asked whether the order of things will end. Picture the far future, and someone still there, standing outside at night and looking up at a sky with nothing left in it. The watcher can be any comparer at all, the word Chapter 1 used for anything that compares one thing with another and registers what it finds: a person, an instrument, a detector, an atom.

Shut your eyes and spin around on the spot until you are dizzy. The organ of balance in your inner ear tells you that you are turning. Set a gyroscope spinning on a good mount, and the gyroscope's axis keeps pointing at the same distant stars while the Earth turns beneath the gyroscope. In both cases something registers "turning" or "not turning": your inner ear registers your turning, and the gyroscope's axis registers its own not turning. In 1883 the physicist Ernst Mach argued that to turn is always to turn relative to something, and that the something is the matter of the rest of the universe. Mach was then a professor in Prague, and he made his argument about turning in a book on the history of mechanics. In terms of differences, the principle of identity says that a difference that no

comparison can register is no difference. Where nothing is there to compare against, no comparer can tell one standard of "not turning" from another, so matter within reach, matter that a comparer can still compare with, fixes the standard of "not turning". Your sense of standing still is a comparison with the rest of the universe.

Distant matter fixes "before" and "after" in the way distant matter fixes "not turning". Picture two ships far apart at sea. Each ship keeps a log, and each ship fixes the times in its log by the same stars overhead. When the crews lay the two logs side by side in port, the crews can place the storm that one ship met before or after the squall that the other ship met, because both logs were timed against one sky. In the picture, the ships are comparers, the logs are their records, and the one sky stands for the distant matter of the universe, a shared sky for every comparer. The distant matter is a common reference. Against the common reference, comparers place events far apart from one another before or after each other, and as cause or effect. The outside world of a comparer is everything outside the comparer that the comparer can still compare with. Across the whole outside world, the order of before and after rests on the common reference.

Now take the common reference away, as the far future does. Every comparer belongs to some bound structure, a star or a galaxy or a group of galaxies held together by its own gravity, and every bound structure comes to one of two ends. A bound structure falls into a black hole, or the expansion carries the structure away alone, beyond the reach of all other matter. Each comparer has a cosmological event horizon, which Chapter 23 named: the edge beyond which nothing sent now can ever reach that comparer. Because the horizon is centered on the comparer and moves with the comparer, the comparer carried away alone never crosses its own horizon, but everything else crosses that horizon, until the comparer's only reference is the horizon itself. The comparer who falls into a black hole reaches the end of the black hole's interior. The two roads are falling into a black hole and being carried away alone, and so both roads come to one condition: no matter is left within reach to compare against.

At the end of either road, “standing still” and “turning” have nothing left to be measured against. “Before” and “after” between distant things have nothing left to be measured against either, and neither have cause and effect between distant events. In the picture of the two ships, the ships have lost their sky. The crews can no longer place the storm before or after the squall. For the comparer carried away alone, whatever happens to that comparer at the end of its road cannot be placed before, at or after any event elsewhere, because the lone comparer lies beyond the horizon of every other comparer.

Time has one direction, which Chapter 13 found in the structural arrow. Across the outside world, time’s one direction is also marked on the largest scale, in three ways. Entropy grows in the direction of time, the universe expands in the same direction, and the common reference of the distant matter orders distant events in the same direction. At the end of either road, no outside world is left within reach to carry the three marks: the growth of entropy, the expansion of the universe, and the order of distant events. So at the end of either road, time loses its large-scale direction, which is the direction of time as the outside world marks it. The structural arrow is a different thing: the structural arrow is the one-way order inside each comparison, and that order is never reversed.

Look up once more with the watcher, before the end of the road. The watcher’s look runs from what could be seen, to the seeing, to the memory of having seen, and no look runs backward. Every comparison the watcher makes runs that one way, and the end of the road reverses none of the watcher’s comparisons. So the last watcher under the empty sky still finds things in order: each finding comes after the range it was found from, and each record comes after the finding it records. Whatever is at the end of an interior does not cease. Only one thing is gone: anything outside the interior to compare with. So no further comparison is left to take its place in the one-way order. When the sky has emptied, what has ended is what a comparer can compare with, and time has not ended.

The answer to the authors' "no more laws" has two parts: one order stays, and the use of another order is lost. The authors' "no more laws" pictured cause and effect losing their meaning everywhere. What is lost is narrower: the comparers lose the common reference that lets them place distant things before or after one another, and with the common reference they lose cause and effect between distant events. The one-way order of each comparison stays untouched: the order in which anything is found and then known.

No Moment for the Turn

The third question is the authors' meaning "the end": does the universe, and time with it, come to a last moment? The authors' Big Crunch pictured a last moment for time: time capped as the direction north is capped at the North Pole. Our epoch's expansion never falls back, as Chapter 29 found, so no Crunch caps our time. The falling clock has already shown the answer for every clock: the end of an interior is a limit, and no clock comes to that limit with a last tick. One case remains: the turn itself, in which the emptying ends, as Chapter 29 found.

The turn is the limit at which an epoch begins, as Chapter 20 showed. Seen from the side of the old epoch, the turn is the one shared end of the interiors of all black holes, as Chapters 21 and 22 found. A comparer could register the turn as an event only by making a comparison across the turn, a before compared with an after. No comparison across the turn can be made, because the outside world of our epoch has no moment at the end of an interior, and the falling clock's own time ends at the limit the falling clock approaches. Three things belong to the approach on each side of the turn, and none of the three belongs to the turn itself: how long things take, how fast things change, and how hot things grow. So the word "when", which asks for a time, does not apply to the turn. The turn happens at no time, and the turn is no last moment of any clock.

The authors said that time had a beginning of sorts, and that beginning has its place at the turn too. Our history, traced backward, takes the turn for a first moment: the Big Bang, as Chapter 20 found. The authors are right that time had a beginning in one sense: the beginning that our history shows when we trace our history back. The far end of our epoch is also a turn, a limit like the turn at our epoch's beginning, and beyond that far turn the next epoch begins its own history, with its own clocks and its own counts.

A River Behind the River?

One more of the authors' pictures remains to be answered, a picture they give for an idea that some physicists hold. The idea is that time flows out of a deeper meta-time, as a river's flow comes from water that could also lie still, and that a stop in the meta-time is a stop no one would notice. I answer the river picture from two principles this book has already used: event time comes with comparison, and a difference that no comparison can register is no difference.

The first principle says how event time arises. Recall the empty universe of Chapter 12: a universe with only a head and a book in it, and nothing changing. Two moments in that empty universe cannot be told apart, because nothing is different between the two moments. Something has to change for one moment to be told from the other, and in that universe the only place the change can be found is in the perceiving, which is a comparison. Chapter 12 put the result in one sentence: time comes with the comparison, not before the comparison. Findings make the order of event time, and findings do not happen inside a time laid down before them. So no river of time runs behind the findings for the findings to float on.

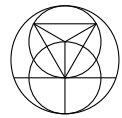
The second principle is the principle of identity, put in terms of differences: a difference that no comparison can register is no difference. The authors describe a stop in the meta-time that no clock, no thought and no record could ever register, since every clock, thought and record would

stop along with the meta-time. By the principle of identity, the authors' stop is no stop, because no comparison anywhere could ever register the authors' stop. The authors say themselves that only someone with an outside view of the flow of the meta-time would know. Every comparison is made from inside the world, and a stop that no comparison inside the world registers makes no difference to anything in the world.

> **The short answer**
>
> Time does not stop: no clock comes to a last tick, and what ends with the emptying is what a comparer can compare with, never the one-way order of comparison.

The authors gave three meanings of an end of time, and each meaning has its answer: the clocks tick on, the order of each finding stays, and the turn is no last moment. In the far future a comparer loses the common reference of the distant world, and keeps the order in which anything is found and then known.

How long will we be there to watch?



Chapter Thirty-One

How Long Will Humanity Survive?

In which the rocks of the solar system, the Sun and the long emptying are each followed to their end, and the end of every thinker is told apart from the end of thinking

How long will humanity survive, and could it last forever?

What this chapter uses

A *comparison* is the act of finding whether two things are the same or different in some respect, and every measurement is a comparison; a *finding* is the outcome of one comparison, laid down as a record; a *comparer* is whatever makes a comparison, whether or not the comparer has a mind (Chapter 1).

The *content* of a finding is what the finding finds, as the warmth of your coffee; the *context* is where the content is found, and the context has three sides, the three settings of space, time and possibility (Chapter 1).

The world has ten dimensions, one of time, three of space and six of possibility, and the six are the range of what a finding could be, present at every place and never a place themselves (Chapter 11).

The *turn* is the limit at which an epoch begins: our history, traced back, approaches the limit and shows the limit as a first moment; an *epoch* is one era of the world (Chapter 20).

Hard randomness is an outcome that no description of what came before fixes, however complete that description is, for any comparer whatsoever; one outcome that nothing fixed is chance seen from outside and choice seen from inside (Chapter 26).

In the autumn of 1978 the physicist Freeman Dyson gave four lectures at New York University. The lectures were the James Arthur Lectures on Time and its Mysteries. Dyson worked at the Institute for Advanced Study in Princeton. Dyson began with *The First Three Minutes*, a book for general readers that the physicist Steven Weinberg had published the year before. Dyson quoted one line of Weinberg's book: "The more the universe seems comprehensible, the more it also seems pointless". Dyson answered Weinberg's line in one sentence: "If Weinberg is speaking for the twentieth century, I prefer the eighteenth". Dyson set out to answer the view that Weinberg spoke for, a view that, in Dyson's words, left us "only the choice of

being fried in a closed universe or frozen in an open one". In Dyson's use, a closed universe is a universe whose expansion stops and turns into a collapse. An open universe is a universe that expands forever. Dyson leaned toward the open universe, and he asked three questions about a universe that expands forever. In his first question, Dyson asked whether an open universe freezes into a permanent quiet as the universe expands and cools. Dyson asked his second question in his own words: "Is it possible for life and intelligence to survive indefinitely?" In his third question, Dyson asked whether societies can keep sending messages to one another across ever greater distances. In the printed lectures Dyson gives his first replies to the three questions in one line: "Tentatively, I shall answer them with a no, a yes, and a maybe". The lectures appeared the next year in the journal *Reviews of Modern Physics*, under the title "Time without end".

Dyson's yes was his reply to the second question, about life and intelligence. He backed the yes with a plan for one society that keeps on thinking. Chapter 29 answered Dyson's first question: the emptying of our epoch, the long age in which the galaxies leave and the stars burn out, ends in a turn that begins the next epoch. Here I answer Dyson's third question on the way to his second.

The question of how long humanity can last has a near end and a far end. The near end is how long we have on Earth, under the Sun and among the rocks of the solar system. The far end is Dyson's second question: whether anything of us can last forever. Jorge Cham and Daniel Whiteson set out a ladder of times that runs from the near end to the far end, and in this chapter we climb their ladder, rung by rung. At the far end the question becomes two questions. The first question is whether one thinker, or one people, can go on forever. The second question is whether thinking can go on forever.

Every Danger, on Every Timescale

Cham and Whiteson give the bad news first. They say that a humanity that lasts until the end of time is highly unlikely. The authors' reason is a rule of survival. To last to the end of time, humanity would have to come through every danger the universe holds, at every scale of time: "we have to survive all of them" (*Frequently Asked Questions About the Universe*, ch. 4, opening). The authors say that humanity's chance depends on two things: how likely each danger is, and how long a time we have in mind.

Then the authors climb a ladder of times, one rung for each scale of time. Right now the nearest dangers are of our own making. The three nearest dangers are nuclear war, a changing climate, and a technology that gets away from the people who built it. Over thousands of years, asteroids and comets become dangers too, and over millions of years a wandering planet, star or black hole could pass through the solar system and scramble the orbits of the planets. Over billions of years the Sun itself grows and later leaves a cooling ember, so humans must leave the solar system to go on. Even a humanity spread across many stars and galaxies would still face, in the authors' words, "two big threats to human existence: the laws of physics and infinity" (*Frequently Asked Questions About the Universe*, ch. 4, "Beyond"). In the authors' account, the laws of physics become a threat if the Higgs field collapses. Physicists, the authors say, are not sure how stable the Higgs field is. Infinity is a threat by sheer patience: "in an infinitely old universe, anything that can happen eventually will happen" (*Frequently Asked Questions About the Universe*, ch. 4, "Infinity").

The authors end with one way through the two threats, and they call that way a technicality. If the universe stopped expanding and fell back together into a Big Crunch, time itself would end there. At the moment of the Big Crunch, the humans then alive could say they had lasted to the end of time. The authors' chapter ends with their verdict on the humans who would be alive at the Big Crunch: "We should all be so lucky" (*Frequently Asked Questions About the Universe*, ch. 4, "So Are We Toast?").

The authors' ladder is good physics, and most of its rungs are best told in the authors' own terms. This book has something of its own to say on three rungs: the rocks, together with the dangers of our own making; the Sun; and the far end, where the question is whether one humanity can last forever.

Will an Asteroid Hit Us?

On the morning of 15 February 2013 a rock about twenty meters across struck the air over Chelyabinsk, in Russia. Cham and Whiteson tell what followed. The rock came from the asteroid belt, moving at sixty thousand kilometers an hour. The light of the rock's explosion was reported brighter than the Sun, and about a thousand people were hurt. The first warning anyone had of the rock was the rock's arrival in the air.

The authors tell where the dangerous rocks come from and how the rocks came to be. They say that a killer rock most likely comes from our own neighborhood. Our neighborhood has three places that hold killer rocks: the belt of asteroids between Mars and Jupiter; the Kuiper Belt of icy bodies beyond Neptune; and the Oort cloud far beyond Pluto, from which most comets fall. The rocks in all three places are rubble left over when the solar system formed. The danger from a rock grows with the rock's size. Rocks up to a meter across burn up as shooting stars. A rock twenty meters across makes an event like the one at Chelyabinsk. Rocks a kilometer and more across endanger the human species, and the authors report that scientists believe a rock several kilometers across arrived sixty-five million years ago and may have ended the dinosaurs. The comfort is that big rocks are rare and easy to see. Astronomers have mapped most of the big rocks. In the authors' words: "The good news is that we know where 90 percent of the big rocks in the solar system are" (*Frequently Asked Questions About the Universe*, ch. 9, "How Likely Is It?"). The authors report that so far none of the mapped rocks is on a course to hit us. Comets are harder to find in time, because a comet that falls in from the Oort cloud on a long orbit may be seen for the first time on its way in,

with a year of warning at best. The authors put early detection first, because a rock found in time needs only a small nudge, given early, to miss the Earth.

A natural clock shows that the rocks are leftovers from the beginning of the solar system. Uranium turns into lead by two separate chains of radioactive decay, at rates known from the laboratory, so each chain works as a clock, and the two *uranium-lead clocks* tell how long ago a grain of rock locked its uranium in. In 1956 the geochemist Clair Patterson read the lead in meteorites, the rocks from space that reach the ground. Patterson dated the meteorites, and the Earth with them, at about four and a half billion years, to within seventy million years. In 2012 James Connelly and his colleagues read the two clocks together in the oldest grains inside meteorites, and they fixed the age of the oldest grains at a little over four and a half billion years, to within about a hundred and sixty thousand years. Meteorites are pieces of the solar system's first solids. So the authors' picture of leftover rubble is a dated fact. The rocks that might strike us are as old as the first solid grains of the solar system.

The authors close their chapter on the rocks with a caution: the universe is unpredictable, and our science has limits. The future of the orbits is open in the world itself. I show the open future with a small nudge of the same kind as the nudge that the authors propose. Wire a Geiger counter to a small rocket, so that the counter's next click launches the rocket if the click comes within one minute. In the words of the book: "The rocket nudges a small asteroid". Over the years the small asteroid passes near a larger asteroid on its new path and shifts the larger asteroid's orbit, and the larger asteroid in turn shifts a larger one still, until in principle the orbits of planets are moved. Every step after the first is ordinary gravity and motion. The first step is a click of the kind Chapter 26 called hard randomness. Hard randomness is an outcome that nothing before it fixes, however fully everything before the outcome is known. So the shape of space and time, curved by where all those masses go, differs according to an outcome that was not settled until it happened. So the future of the orbits is open in the world itself, as well as in our knowledge of

the world. Because the future of the orbits is open, an early nudge can change where a rock goes: a rock found in time can be moved, and people choose whether to move the rock.

People make the nearest dangers on the authors' ladder (nuclear war, a changing climate, and a technology that gets away from its builders), and people decide how each of the three dangers turns out, by choices of the same kind as the choice to move a rock. What task the dangers made by people belong to. Humanity first learned to live with change. Then humanity learned causation: the steady rule that the same conditions bring the same results. Humanity built its science and its machines on the rule of causation. In the book's words: "The next mastery that humanity must have is the mastery of choice". The reason: the attempt to solve all problems with the tool of causation alone has side effects, and the side effects include pollution, inequality, and the effects of applying top-down engineering to complex ecosystems. So, of the dangers on the authors' list, the nearest are the dangers whose course depends on what people choose, just as the course of a rock found in time does.

When Will the Sun Burn Out?

The Sun's life sets how long humanity has on Earth. When the Sun's ember is followed to its end, the ember also shows the two roads that every thinker comes to at the far end of the question: a fall into a black hole, or a journey away from all other matter. Cham and Whiteson tell the Sun's life period by period, with a date at the head of each period. The authors start from how a physicist sees the Sun: "To a physicist, the Sun is a constantly exploding nuclear bomb" (*Frequently Asked Questions About the Universe*, ch. 19, opening). Gravity squeezes the Sun inward, and the burning in the Sun's core pushes outward. Gravity and the burning hold each other in a stalemate that lasts about ten billion years. Through the stalemate the Sun brightens by about one percent every hundred million years, so in about four billion years the Sun is forty percent brighter than now, bright enough to boil our oceans. In about five billion years the Sun

swells to two hundred times its present size and nearly swallows the Earth. At an age of eleven point four billion years the Sun has used up the hydrogen in its core, and the core then burns helium into carbon for about a hundred million years more. The Sun is too light to burn carbon, so after the helium the Sun fizzles out. The Sun's outer layers drift away as a glowing cloud. The Sun's core is left behind as a *white dwarf*: a cooling remnant that holds, in the authors' figures, about half the Sun's mass in a ball about the size of the Earth. The white dwarf glows by its stored heat for what the authors say may be trillions of years. Then the white dwarf cools into a dark *black dwarf*. The authors end on a picture of humanity gathered around the embers of the Sun, telling stories of the days when the Sun burned.

I tell three events as the authors tell them: the Sun's brightening, the boiling of the oceans and the Sun's swelling. I add a different end for the ember, and the reasons behind four periods of the Sun's life: why the burn is slow, why the burn is steady, why the Sun stops at carbon and oxygen, and what holds the white dwarf up.

The first reason is why the Sun's burn is slow. The burning in the Sun is *fusion*, which Chapter 18 described as the joining of light nuclei into heavier ones, and in the Sun four protons are joined, step by step, into one nucleus of helium. In the first step, two protons join into a nucleus of heavy hydrogen. Chapter 19 described heavy hydrogen as one proton and one neutron bound together. For two protons to make heavy hydrogen, one of the two protons must turn into a neutron while the two protons are briefly close. Only the weak force can turn a proton into a neutron. The weak force is the force of Chapter 4 that turns one kind of particle into another. The reach of the weak force is far smaller than a proton. So the change from proton to neutron is rare, even in the crowded core of the Sun. A proton in the Sun's core waits billions of years, on average, before it joins another.

The second reason is why the Sun's burn is steady. A hot gas in a box cools as the gas loses heat. Where a ball of gas is held together by its own gravity, the ball does the opposite: when the ball loses energy by shining,

the ball shrinks a little, and the shrinking heats the ball. The heating of a shrinking ball of gas is a rule of mechanics. Suppose the core burned faster than the Sun shines: the extra energy would swell the Sun, the swelling would cool the core, and the cooler core would burn more slowly. Suppose the core burned more slowly than the Sun shines: the Sun would shrink, heat and burn faster. Either way the burning returns to the rate at which the Sun shines. The authors' stalemate between gravity and fusion is the rule of mechanics at work: a balance that puts itself right.

Physicists have watched the burning in the Sun's core directly, through the core's neutrinos: light, uncharged particles that pass through almost everything. In the first step of the chain that joins four protons into helium, neutrinos fly straight out of the Sun. In 2014 the team of the Borexino experiment reported that they had caught the neutrinos of the first step. The count was about sixty-six billion neutrinos on every square centimeter each second. The Borexino count showed that about ninety-nine percent of the Sun's power comes from the chain that begins with two protons, so we now know from the Sun's own messengers, its neutrinos, that the Sun burns by the slow chain that the weak force allows.

The third reason belongs to the Sun's helium period: why the Sun stops at carbon and oxygen. When the hydrogen in the core is spent, the same rule of mechanics applies: the core loses energy, shrinks and heats, until at about a hundred million degrees helium begins to burn. Then three helium nuclei make the long stride of Chapter 18. The three nuclei join at once into one nucleus of carbon, because no nucleus formed by a smaller step holds together. Some of the carbon takes in one more helium nucleus and becomes oxygen. So the ash of the Sun's helium is carbon and oxygen together. Two nuclei are far likelier to join when they come together fast, because the push keeps slow nuclei apart. A hotter core makes its nuclei move faster. A nucleus with more charge pushes harder, so each heavier fuel needs a hotter core to burn, and only stars many times the Sun's mass grow hot enough to burn the carbon and oxygen that helium leaves. So the authors' statement follows from the heat that each fuel needs: the Sun is not massive enough to burn carbon.

The fourth reason is what holds the white dwarf up once no fuel burns in it. Picture a theater filled from the front, one person to a seat. Take away half the rows and keep the whole crowd: the people from the rows removed must sit further back, in more expensive seats. Electrons fill their states the way the crowd fills the seats, one electron to a state: a seat stands for a state, and a more expensive seat stands for a state of higher energy. No two electrons can share the same state, and physicists call that rule *exclusion*. Squeeze a crowd of electrons into a smaller room, and each electron must take a state of higher energy. So the crowd pushes back against the squeeze. The push of the crowd is called *degeneracy pressure*: the pressure a crowd of electrons exerts because exclusion forbids them all to settle into the lowest states, and degeneracy pressure needs no heat at all. In 1930 the young physicist Subrahmanyan Chandrasekhar sailed from India to England, on his way to Cambridge. On the voyage he found that degeneracy pressure has a limit. Above about one point four times the Sun's mass, no white dwarf can hold itself up, and Chandrasekhar published the result in 1931. Every white dwarf that astronomers have weighed lies below Chandrasekhar's limit.

Astronomers have weighed one white dwarf closely. Sirius, the brightest star of the night sky, has a faint companion called Sirius B. The two stars circle each other every fifty years. The orbit of the two stars shows that Sirius B has one point zero two times the Sun's mass. The light of Sirius B is stretched as the light climbs out of the star's pull, and the stretch grows with the mass of Sirius B and with how small Sirius B is. Since the mass is known, the stretch shows the radius of Sirius B: about five thousand six hundred kilometers, smaller than the Earth. A teaspoon of the matter of Sirius B would weigh about fourteen metric tons. A metric ton is a thousand kilograms. So a star's mass can fit in less room than the Earth takes up, held up by the star's electrons alone. And the Sun itself, when it has burned its fuel, will leave a white dwarf. The commonest white dwarfs hold about six tenths of the Sun's mass in a ball about the size of the Earth, which is close to the authors' figure of about half the Sun's mass for the Sun's own ember. Degeneracy pressure, which holds the em-

ber up, does not depend on the ember's warmth, so the ember keeps its size as it cools, and the black dwarf that the ember becomes is a dark ball the size of the Earth, still holding the mass of a star.

On what comes after the black dwarf, this book's answer is different from the best known picture. In 1997 the astrophysicists Fred Adams and Gregory Laughlin set out the long future of the remnants in a review called "A dying universe". In their picture, particles of dark matter strike the nuclei of a cooled white dwarf and are caught, and inside the white dwarf the caught particles destroy one another, which keeps the white dwarf warm for a very long time. Adams and Laughlin take as their working case that the proton decays, as the theories that join three forces into one predict. If the proton decays, the white dwarf shines faintly by the energy of the decay, loses mass and swells, and at about the mass of a giant planet the white dwarf ceases to be a star at all.

My account agrees with Adams and Laughlin on what holds each remnant up. My picture is different from the picture of Adams and Laughlin at three places. The first place is the dark matter, which Chapter 2 found to touch ordinary matter only by weight: dark matter never strikes a nucleus, so dark matter gives the ember no warmth. The second place is the proton, which has no way to break up, as Chapter 9 found. The physicists of the Super-Kamiokande detector have watched fifty thousand metric tons of water for a long time and have seen no proton break. The third place is how the forms of the ember's matter, its nuclei and electrons, come to an end. In the picture of Adams and Laughlin, the forms end by slow wasting. The forms end only at the end of the road the ember travels. I also show that the rest of the ember's matter lasts. The electron is the lightest particle that carries electric charge, and charge is never lost, so the electron has nothing to decay into. Inside the ember's carbon and oxygen nuclei, the neutrons cannot decay. A decay would leave a nucleus that weighs more than the nucleus the decay started from. So I conclude: "Left to itself, a white dwarf or a neutron star loses none of its matter to decay: it keeps its mass, goes cold, and stays held up". The Sun's ember does not waste away.

The ember travels all the same, because over the long ages the ember's galaxy keeps stirring the ember. Every remnant's path ends in one of two ways. On the first road, a remnant falls into a black hole. On the second road, the remnant is flung clear, and the expansion of the universe carries the remnant beyond the reach of all other matter: the remnant is carried away alone. Chapters 29 and 30 followed every body of our epoch along the same two roads: into a black hole, or away alone.

Can a Mind Keep Thinking Forever?

Dyson's yes to his second question rested on a plan with two parts. The first part is to run colder. When a thinker is built to run at a lower temperature, the thinker thinks the same thoughts more slowly and spends less energy on each thought, but a colder body also sheds the waste heat of its thinking more slowly. Dyson found that slowing down alone does not let a society last forever. The second part is to sleep. In Dyson's plan, a society thinks in short bursts and sleeps between the bursts, radiating away the heat of each burst while the society sleeps. As the universe cools, the society makes its waking stretches a smaller and smaller share of the time. Dyson showed that the schedule of waking and sleeping can be chosen so that the society's own count of time goes on forever, while the total energy the society needs stays finite. For a society as complex as ours, Dyson put the whole store of energy at "about as much energy as the sun radiates in eight hours". Dyson's universe expands forever and has no energy of empty space. So in Dyson's universe, more and more galaxies come into view as time goes on.

Twenty years later the universe as measured had changed. As measured, the expansion of the universe speeds up, driven by the cosmological constant, which Chapter 3 found to be the share of the energy of empty space that a measurement made from inside takes in. In February 1999 the physicists Lawrence Krauss and Glenn Starkman sent out a paper. In the paper, Krauss and Starkman worked out Dyson's plan in a universe whose expansion speeds up. In a universe whose expansion speeds up, every ob-

server has an edge: the observer's horizon, which Chapter 23 called the cosmological event horizon. No signal sent today from beyond the horizon will ever reach the observer. So any civilization can gather only a fixed amount of matter and energy. Because every society has its own horizon, Dyson's third question has a plain answer: no chain of societies passes a message to a society beyond the horizon of the society that sends it. The horizon itself glows, very faintly, so empty space keeps a temperature that never falls away. Picture a room whose walls stay faintly warm forever: nothing in the room can cool below the warmth of the walls without a refrigerator, and the refrigerator costs more energy than it saves. The warm walls stand for the glowing horizon, and the things in the room stand for a thinker. Where a thinker is held at the temperature of the horizon, which is a floor, the thinker cannot keep lowering its use of energy, and so a finite store of energy pays for only a finite amount of thinking. Krauss and Starkman found that Dyson's plan of sleep fails too, because every sleep needs an alarm clock to end the sleep, and over an endless time every alarm clock fails. Krauss and Starkman published their conclusion in *The Astrophysical Journal* in 2000: "the integrated conscious lifetime of any civilization will be finite". In their sentence, integrated means added up over all of time: the whole conscious life of a civilization, summed, is a finite amount.

My account has the same answer as Krauss and Starkman, on separate ground, and the ground uses neither the store of energy nor the temperature. Picture the smallest comparison there can be. I describe the smallest comparison. Two hydrogen atoms sit some distance apart in an empty universe. The first atom gives out a particle of light. The second atom takes in the particle of light, and the second atom's electron is lifted to a higher level. Take away the first atom, and the second atom has nothing to be measured against. Take away the lasting structure of the second atom, and nothing keeps a record of what arrived. Take away the light, and nothing passes between the two atoms. The three removals show one rule: a comparison needs an actual interaction, not a possible one. A thought is a comparison like the comparison between the two atoms, made by a com-

parer (whatever makes a comparison) that is a mind: the thought is made against something actually there, and the thought is kept in a lasting structure of the thinker's own. Energy, too, has a place in my account. Energy is the capacity of a system to participate in comparisons. A store of energy, however large, is a capacity, and a capacity is used only where there is something there to compare with.

Now walk a thinker through the long emptying that Chapters 29 and 30 followed. In the long emptying, the other galaxies pass beyond every horizon, and every remnant travels one of the ember's two roads. Every thinker belongs to some bound structure, such as a planet, a star or a galaxy. Every bound structure ends on one of the two roads. On the first road the thinker falls into a black hole. On the thinker's own clock, the end of the hole's interior comes after a finite time: for a hole of the Sun's mass, the end comes at most about fifteen millionths of a second after the thinker crosses into the hole, as Chapter 21 found. The end of the interior belongs to the faller's own clock alone. So at the end of the interior, the whole outside world is beyond the thinker's reach. On the second road the thinker is carried away alone, and everything else passes beyond the thinker's horizon. Then the thinker keeps one reference only, its own horizon, which goes wherever the thinker goes, as the skyline of Chapter 29 goes wherever a walker on a wide plain goes. The thinker's horizon is set by where the thinker is, and by no other body. So at the end of either road, the thinker has nothing outside itself to compare against.

At the end of either road, the thinker also loses the structure in which the thinker compares. In our epoch, matter takes forms such as atoms, molecules and cells. Atoms, molecules and cells depend on the six small dimensions keeping their held shape. The large world has things in it to compare against. At the end of a black hole's interior, and for a body carried away alone, no large world with things to compare against is left, so the condition that holds the six fails there, and the forms of matter end with the condition. I use a picture for a form held by a condition: an ice sculpture in a cold room. The cold around the sculpture holds the sculpture's shape. When the room warms, the shape is gone, but the water of

the sculpture does not vanish. The shape stands for the forms of matter, the cold stands for the condition, and the water stands for what the matter is made of. The picture has one limit: the melted water is still water. Past the end of each road, what goes on is no longer protons, nuclei or electrons. What the matter was made of goes on, and the forms the matter took come to an end. So no thinker makes an endless run of findings. A thinker's run of findings is the series of findings the thinker makes, one after another. Every run of findings ends for a reason that depends on neither the size of the thinker's store of energy, nor the thinker's temperature, nor the speed at which the thinker thinks. Even a thinker with an endless store comes to the end of its run of findings, however cold and however slowly the thinker runs. So no one thinker thinks for ever, and no thought crosses into the next epoch.

My answer is different from the authors' verdict, because the two answers rest on different ground. Cham and Whiteson judge a humanity that lasts forever, until the end of time, highly unlikely, because a humanity that lasts forever would have to survive every danger at every scale of time. The authors' answer is a judgment of odds, and on a judgment of odds a lucky humanity is still possible. My answer uses no odds: no thinker's run of findings goes on forever, because every run of findings ends on one of the two roads, whatever dangers the thinker escapes on the way.

Thinking Begins Again

Chapter 29 found that the emptying of our epoch ends in a turn, and that the next epoch begins from the turn under the same law. The structure is the same in every epoch: the six small dimensions return with the same shape and the same size. Then the new epoch makes stars, and the stars make black holes. In the new epoch, comparison happens. Every act of comparison in the new epoch has the features that every act of comparison has in ours. So comparers, anything that compares, are present in the next epoch as comparers are present in ours.

Whatever thinking happens in the next epoch belongs to the next epoch alone. No act of comparison spans the turn. So no thinker of our epoch has a finding, record or memory that is real in the next epoch. Both halves of the answer hold together: thinking does not end, since in each epoch that follows comparison begins again, and the thinking of the next epoch continues no thinker of this one. A next epoch comes after ours, and another epoch comes after the next. So thinking goes on forever in the sense that comparison begins again in each epoch.

The authors' furthest hope is a humanity spread across the galaxies. A humanity spread across the galaxies comes to the same boundary: the turn, which no act of comparison spans. A humanity that spreads moves its people from place to place within our epoch. I show that every place a path from here can reach belongs to our own world, just as Chapter 24 found the regions beyond our horizon to be parts of our one world. What crosses into the next epoch is the form of the content, as Chapter 28 found. The form of the content is carried with everything that falls into the black holes, and the form arrives in the next epoch as one averaged form, from which the next epoch's galaxies grow as a plant grows from a seed. Nothing in the averaged form shows which body or which sender went into the averaged form. So nothing crosses into the next epoch as itself: no body, no ship, no readable message, no record and no person. The lesson for anyone who would escape: the future needs no rescue from the dark.

My account has an answer to each of the authors' two big threats, the laws of physics and infinity. The first threat was the collapse of the Higgs field, which Chapter 29 pictured with the bottom of a wine bottle, the height of the glass standing for the energy of the field. One principle of my account is that every way of varying has a least state. So the energy of the Higgs field has a lowest value, as Chapter 29 found. At the energies of the weak force, Chapter 29 worked out how strongly the Higgs field acts on itself, and in the two-part curve that Chapter 29 derived at those energies, the lowest value of the energy is the present state of the field. In the standard calculation of 2013, Dario Buttazzo and his colleagues followed

the strength with which the Higgs field acts on itself out to far higher energies, and in their calculation the present state lasts far beyond the age of the universe.

The second threat was infinity: the patience of an infinitely old universe, in which anything that can happen will happen. The argument from infinity needs one humanity that lasts through all of time, so that every fluke gets its turn against that one humanity. Within our epoch no thinker lasts through all of time, because every thinker's run of findings ends on one of the two roads. Each epoch is a domain of comparison: in the words of Chapter 8, the range within which comparisons can be made. Each epoch is a whole physical domain, coherent from inside, and the series of epochs is a series of domains of the same structure, not one totality containing them. In the sentence just quoted, a totality is one finished whole that would hold all the epochs together. No thinker of one epoch is present in another epoch. So no humanity of ours is there for the flukes of later epochs to strike.

The authors' technicality, the Big Crunch, also has a counterpart in my account. Chapter 29 found that our epoch keeps expanding and never falls back. So the Big Crunch does not come, and the Big Crunch was the authors' road to the end of time. The end of time the authors pictured is there all the same, for anyone who falls into a black hole. The end of the interior is the end of time on the faller's own clock, and the end comes after a finite time on that clock, with no last tick before it, as Chapters 21 and 30 found. When a faller reaches the end of the interior, the faller comes to the end of time, but the faller does not last forever, because the faller's run of findings is finite and ends at the end of the interior. For the one who falls in, it is the end of time, and it comes soon. The lucky humans of the authors' last line can have their wish, and for a hole of the Sun's mass the end of time comes within fifteen millionths of a second of the crossing into the hole.

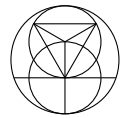
So the answer to this chapter's question has a near part and a far part. The near part is that humanity on Earth has billions of years of the Sun's steady burn. People can also find the dangerous rocks and choose to move

them. The far part has two halves. Every thinker's run of findings ends on one of the two roads, whatever the thinker is made of and however patient it is. Thinking, the act of comparison, has no end, because each epoch's dark is followed by another epoch in which comparison begins again.

> **The short answer**
>
> The Sun's steady burn gives humanity billions of years on Earth, where people can find the dangerous rocks and choose to turn them aside, and while every thinker's run of findings ends, thinking begins again in each epoch under the same law.

The authors ask about two different ends as if the two were one end: the end of every thinker, and the end of thinking. In this chapter's answer the two ends are separate: every thinker comes to an end, and thinking never comes to an end. I ask throughout how the world is found from inside. For the far future, this chapter's short answer says that in every epoch to come there are again comparers inside the world to find the world.

Before our own run of findings ends, will we have answered everything?



Chapter Thirty-Two

Will Science One Day Answer Everything?

In which every question is sorted into one of three kinds, and the asking is found never to run out

Can science answer every question we ask, even why the universe exists?

What this chapter uses

A *comparison* is the act of finding whether two things are the same or different in some respect, and every measurement is a comparison; a *finding* is the outcome of one comparison, laid down as a record; a *comparer* is whatever makes a comparison, whether or not the comparer has a mind (Chapter 1).

The *content* of a finding is what the finding finds, as the warmth of your coffee; the *context* is where the content is found, and the context has three sides, the three settings of space, time and possibility (Chapter 1).

The three *settings* in which anything is measured are space, the place of a finding; time, the moment of a finding; and possibility, the range of what could have been found instead; a setting is *bent* when one part of the setting differs from another part (Chapter 1).

Continuous: nothing is sudden, as along a ramp; *discontinuous*: something is sudden, as at the edge of a step; *symmetric*: what is found stays the same across a change of setting, as each step of a staircase is like every other; *asymmetric*: different everywhere, as the height along a ramp is (Chapter 1).

The *Incommensuration Theorem*: at the foundation of any event or comparison, symmetry and continuity cannot both be perfect together, and neither can asymmetry and discontinuity. The Incommensuration Theorem is a structural fact about the nature of knowing (Chapter 1).

Three things in nature do the bending: gravitation bends space, the cosmological constant bends time, and the dark matter bends possibility (Chapter 1).

In September 1930 two meetings of scientists followed one another in the city of Königsberg, in East Prussia. From 5 to 7 September, mathematicians, physicists and philosophers met in Königsberg at the Second Conference on the Epistemology of the Exact Sciences. *Epistemology* is the

study of knowing: how anything comes to be known, checked and held. On the conference's last day the logician Kurt Gödel mentioned a result about systems of axioms almost in passing, in a general discussion. The *axioms* of a system are the basic statements the system builds on, as in Chapter 1. In a system of mathematics, mathematicians prove everything else from the axioms. Gödel had found a gap in every system of axioms of a certain kind: a system whose axioms can be listed by a fixed rule, which is free of contradiction, and which is rich enough for ordinary arithmetic. The gap is that some statements written in the system's own language can be neither proved nor disproved in the system. Gödel published the proof of that gap the next year.

On 8 September 1930 the mathematician David Hilbert spoke in Königsberg to the congress of the Society of German Scientists and Physicians. Hilbert's address was called "Naturerkennen und Logik", logic and the knowledge of nature, and a four-minute part of the address was broadcast by radio, in a recording that survives. In 1872 the physiologist Emil du Bois-Reymond had told the same Society of German Scientists and Physicians that science must accept a hard verdict on certain riddles of nature, the verdict "ignorabimus": we shall never know. Hilbert answered du Bois-Reymond: "For us there is no ignorabimus, and in my opinion none whatever in natural science". Hilbert ended: "Wir müssen wissen. Wir werden wissen". We must know. We will know.

So in one city, on two days, Hilbert and Gödel gave your question two answers. Hilbert's answer was a hope, spoken to a hall and sent out by radio. The hope was that every question has an answer, and that we will find the answer. Gödel's answer was a proof, mentioned in a discussion. The proof showed that a system of the kind Gödel described has questions that the system's own means cannot settle. Hilbert's hope and Gödel's proof each hold a true part of the answer to your question.

Where the Authors Draw the Line

Jorge Cham and Daniel Whiteson draw a line around science, and they draw it with care. They say that scientists can answer the questions whose answers an experiment can test. They put the line in one sentence: "If a theory can't be tested with experiments, then it falls in the realm of philosophy or religion or pure speculation" (*We Have No Idea*, ch. 14, "How Can We Know Anything About the Big Bang?"). Their example is a tiny pink stuffed kitten floating in deep space between our galaxy and the Andromeda Galaxy. The claim that the kitten is there is a physical claim, and no instrument we have can check the claim, so for now, they say, the claim is no scientific idea.

The line around science moves, and the authors are glad that it moves. Thinkers held that matter is made of atoms long before any instrument could detect an atom, and once new instruments could detect atoms, the idea of atoms crossed from philosophy into science. The early moments of the universe were once a subject of pure speculation, and their study too has crossed from philosophy into science. The authors put the lesson in one line: "Today's philosophy questions are tomorrow's precision science experiments" (*We Have No Idea*, ch. 14, "The Big Finish").

The authors add two more points. The first point comes at the close of their first chapter, where they tell the history of science as a series of revolutions. In each revolution, people found that an earlier view had been skewed by our particular place in the world (*We Have No Idea*, ch. 1, closing). They hold that more revolutions of that kind are almost certainly coming, and that relativity and quantum physics might be among the ideas replaced. The second point comes in their chapter on a theory of everything, where they ask how anyone would know that a theory was the final one (*We Have No Idea*, ch. 16, "How Will We Know If We Are Done?"). They name one sign that a theory is closer to final: the theory has fewer arbitrary numbers, which are numbers the theory needs and

does not fix, so that physicists must measure them and put them in by hand. Then they conclude: "The truth is that we have no idea how to determine if a theory is the final theory".

The authors end their book with the question they call the Ultimate Mystery: "Why does the universe exist and why is it the way it is?" (*We Have No Idea*, "A Conclusion of Sorts", "The Ultimate Mystery"). Ask that question, they say, and you are soon asking why there are fundamental laws at all, and why the universe follows them; the answers to those questions may lie outside science. Yet, they write, science can test more of the universe every year, and the growth is speeding up. The authors ask whether that growth will one day take in the deepest question, and they answer with the refrain that gives their book its title, adding that the ride will be exciting.

The authors' message is clear, and I take their message as they give it. Science is bounded by what experiment can test; the boundary moves outward, faster every year; and the authors leave unanswered whether the boundary will ever take in the question of why there is a universe.

The Edge of the Map

Picture explorers drawing the map of a coast as they sail along it. Each day the drawn part of the map grows. Behind the ship lies the stretch of coast already drawn; ahead lies the stretch not yet reached; and the edge of the drawing moves forward with every day of sailing.

Names to the two parts of that picture, the coast already drawn and the coast ahead. Every measurement is a comparison.) The *known* is what earlier comparisons have laid down as structure: patterns found, values measured, results anyone can state, repeat and share. The *unknown* is what further comparisons can reach and have not reached yet: the coast ahead of the ship. The line between the known and the unknown moves with every investigation, and I call that line the *soft boundary*: "The soft boundary is the site of epistemic progress".

On this point the authors and this book arrive at one result, each on separate ground. The authors call the part of the universe that science can test the testable universe, and it grows year by year. In the terms of the Immanent Metaphysics, the account from which this book answers, that growth is the known spreading into the unknown across the soft boundary. The authors arrive at the result from the history of science, from atoms and the Big Bang. I arrive at the same result from what knowing is. Every known fact was once unknown, and the act of knowing is the act of bringing the unknown into the known. So the unknown is the source of all knowledge, and the known is what the source produces. Therefore the soft boundary moves wherever anyone compares. On the ground of the account, the authors' "tomorrow's precision science experiments" are just what one should expect.

The story of one question shows how a question crosses from philosophy into science. In 1964 the physicist John Bell took up a question about what kind of world we live in: could the outcomes of quantum measurements be fixed in advance, by causes carried along with the particles, with no influence passing between places faster than light? Bell looked at pairs of particles made together, whose outcomes agree in a pattern when the two particles are measured far apart, and he defined a score, a measure of how strongly the paired outcomes agree. He showed that if hidden local causes, carried along with the particles and acting no faster than light, fix every outcome, the score must be two or below. Quantum theory predicts a score of up to a little more than two point eight. What was done, then, was this: Bell turned the question into a number that an instrument could measure. In 2015 the physicist Bas Hensen and colleagues made the measurement at Delft, in the Netherlands, with two electrons one point three kilometers apart. The team chose that distance so that no signal at the speed of light could pass between the two measurements while they were being made. What was found was a score of about two point four, above the ceiling of two, and in the same year two

other groups also found the ceiling broken, one in Vienna and one in Boulder, Colorado. What we now know is this: no account in which hidden local causes fix every outcome matches the world.

Bell's work follows the order of my own argument: a structural result first, then predictions that can fail. Before any experiment was run, Bell settled what a world of local causes could show. Then measurement decided whether our world is a world of local causes.

The authors draw their line around science by asking one question of every claim: can an experiment test the claim? I answer their question by first sorting claims by what each kind of claim does. A claim that explains why something happens, or predicts how it will happen, forbids some observation. A law that says why the apple falls forbids the apple to rise. So an experiment can test a claim that explains or predicts, and testing is the right way to judge such a claim. A description says what something is, and a description forbids nothing. Chapter 1 described what comparing is: every comparison has a content (what a finding finds) and a context (where the content is found). Every observation agrees with that description, because every observation is a comparison that has both a content and a context. A description is judged in another way, by asking whether it describes what is there, whether it leaves out nothing that matters, and whether it bears on what one wanted to understand. The description of comparing holds in every act of comparison and is checked in each one. So the description of comparing can be known with no experiment to test it. The authors place every untested claim in philosophy, religion or speculation; in the account, the descriptions of comparing belong to knowledge, and every claim about what will be found belongs to experiment.

Questions That Name Nothing

In 1865 the physicist James Clerk Maxwell wrote down the laws of electricity, magnetism and light, which physicists call *Maxwell's equations*. In Maxwell's equations light is a wave. Every wave then known was the motion of some material, as sound is a motion of the air. So physicists

asked what material light was a motion of, and they named that material the *ether*. Physicists built careful models of the ether. In 1887 the scientists Albert Michelson and Edward Morley set out to measure the motion of the Earth through the ether. They split a beam of light, sent the two halves along two arms set at right angles, and brought the two halves back together. Michelson and Morley saw no motion of the Earth through the ether, and whatever motion remained was too small for their instrument to show, less than a sixth of the Earth's speed in its orbit. In 1905 Albert Einstein showed that the field of light needs no material to carry it. The field of light is a thing of its own kind. What we now know is stated: "The question about the ether was not answered. It was dissolved, and Maxwell's equations for light, the real finding behind it, stood unchanged".

The ether question shows a second kind of question, beside the kind that a measurement answers. One example is a question about the color of the number seven. A person settles a question that names nothing, with no measurement at all, by seeing that it names nothing. Chapter 8 called the mistake behind a question that names nothing a *category error*: applying a concept where the concept does not belong, so that the question is badly formed, which is a different thing from being hard to answer. In this book we have met two more questions that name nothing. Chapter 14 found that the question of travel to an earlier time names nothing, because a finding once made stays made. Chapter 15 found that the question of a signal faster than light names nothing, because the speed of light is the outer edge of comparison itself. When someone sees which category each word belongs to, a question that names nothing is dissolved, and nothing real is lost: light still obeys Maxwell's equations, and every measurement Michelson and Morley made still holds.

Now we can read the authors' revolutions again. The authors are right that theories will keep being replaced, and I give the reason on my own ground. Think again of the explorers' map. The map holds every line, name and sounding (each measured depth of water) that the explorers set down. The coast holds every rock and every turn of the tide. A better map holds more, and the coast still holds more than the better map. Every

theory has three parts that match parts of that picture. The first part is the world the theory is about, like the coast. The second part is the model in which the theory describes the world, like the map. The third part is the set of links between the world and the model, made by measurement, like the sightings that tie each line of the map to a stretch of shore. A model is a specification: everything in a model was set down by someone, and a model shows only what was set down. The world is what goes beyond every specification: whatever has been set down, the world holds more. So every model leaves out some of the world it describes, and somewhere a measurement will fail to fit the model. A theory is replaced when a measurement fails to fit its model. Newtonian mechanics is as good as it ever was where its correspondences hold. A revolution moves the edge of the region where a model holds. Yet the measurements remain, and the replaced theory stays good wherever its links to measurement hold.

Some knowledge survives every revolution, because that knowledge rests on comparison alone and on no particular theory. Chapter 15 found that nothing travels faster than light because the speed of light is the outer edge of comparison itself. The outer edge of comparison rests on three things only: that every interaction is a comparison, that comparison has limits set by its own structure, and that the speed of light marks the outer limit. So the edge stays when a theory changes: the edge of the domain would remain if quantum theory were modified or replaced. The domain in that sentence is the domain of comparison, the range within which comparisons can be made.

The Ruler and the Coffee

Listen to a child who has just learned the word "why". Why did the apple fall? Because heavy bodies pull on each other. Why do heavy bodies pull on each other? Because mass bends space and time. Why does mass bend space and time? Because the equations of gravity say so. Why do the

equations of gravity hold? At this last question the answers change kind. Each earlier answer named a wider law, and the last question asks why there are laws at all.

Look at the form of the answers that came easily. Each easy answer says that the case asked about is one case of a wider pattern: the apple falls because there is a law of attraction, and the apple's fall is one instance of the law. My books call that kind of why the *shallow why*: the why that asks for the law of which this is a case, and is answered by naming the law. The word 'shallow' names the form of the answer. Nearly all the explaining that science does is done at the level of the shallow why. Physicists answer the shallow why. They also answer what is there, where it is, how it comes about and when, sometimes with great precision.

The child's last question is of another kind. The child is asking why the laws hold at all, and why there is a world with laws instead of no world. The philosopher Gottfried Wilhelm Leibniz asked that question in its clearest form in 1714: why is there something rather than nothing? My books call that kind of why the *deep why*: the why that asks for the possibility from which a whole world is chosen.

Lay a ruler beside the cup. The ruler tells you the height of the cup, exactly, and nothing at all about how warm the coffee is. You do not send the ruler back to the shop. The ruler lacks nothing: a ruler measures length, and warmth is another kind of thing.

Measurement is to the deep why as the ruler is to the warmth of the coffee. Chapter 1 found that the context of every finding has three sides, called its settings, and that one of the three settings is possibility: the range of what could have been found instead, as your coffee could have been cold, or spilled, or tea. The range of what could have been found belongs to one world, and every finding is made inside that world. The deep why asks for something wider: the possibility of there being a world at all, against which our whole world is one alternative. No world holds the possibility of there being a world. A measurement is an interaction between things that share a world. So physicists find every what, where, how and

when inside the world they measure. Every shallow why is a law of that world. From inside a world, there is nothing against which to compare the possibility of a world. So no measurement returns the possibility of a world, just as a ruler returns no warmth: in each case the thing asked for is of another kind than what the instrument measures.

Some physicists have said that physics has already answered the deep why: the physicists Stephen Hawking and Leonard Mlodinow said so in 2010, and the physicist Lawrence Krauss said so in 2012. They argued that physics has shown how a world can arise from empty space, or from a law such as gravity acting on nothing. In their accounts the answers are a how and a what: how a world of a given kind grows from a starting state of a given kind, under laws of a given kind. Hawking, Mlodinow and Krauss take the starting state and the laws as given. Yet the deep why asks about exactly the starting state and the laws. Chapter 22 answered where our epoch (one era of the world, in which stars, galaxies and black holes form) came from: the shared end of the black holes of the epoch before ours. The answer of Chapter 22 is of the same kind as the answers of Hawking, Mlodinow and Krauss, a how and a what inside the one world, and it leaves the deep why as a separate question.

The deep why is a well-formed question. The deep why asks for possibility, and possibility is one side of the context of every finding, a side that every measurement already takes for granted; so the deep why has meaning, and it is no confusion of words. The deep why is no question that physics has failed to answer and might yet answer with better instruments. The deep why belongs to metaphysics, which the Preface called the study of what must be so for anything at all to be known. Metaphysics asks how a world is related to its possibility, and it asks by a method other than measurement. Metaphysics says what kind of answer the deep why would have: an answer shaped like a principle, which says what makes a world the kind of thing that could be at all.

On the deep why, the authors' answer and this book's answer differ, and each answer has its own ground. The authors find that the answers to why the universe exists may lie outside science. They leave open whether

science will one day find those answers. They come to that view from the shape of the question: first why the universe, then why the laws, then why the universe obeys the laws. I answer the question that the authors leave open: no measurement answers the deep why. I come to that answer from the shape of measurement: every measurement is made inside a world, and the deep why asks about the world from outside.

What Never Runs Out

Return to Königsberg, and to Gödel's remark. Hilbert had called for a foundation of mathematics from which every mathematical question could be settled, a system both consistent and complete. A system is *consistent* when it never proves a statement both true and false. A system is *complete* when every true statement in its language can be proved in it. Picture every statement a system can write as a town, and every proof as a road from the axioms to a town. Chapter 1 met two characters of every comparison: symmetry, which is what is found staying the same across a change of setting, and continuity, which means that nothing is sudden, so that a small change of setting brings only a small change of what is found. Consistency is a symmetry: two roads that reach the same town must agree about what holds there, whichever road was taken. Completeness is a continuity: every true town is reached by some road, so no true town is an island. So when a system is of the kind Gödel studied, rich enough to compare its own proofs with its own statements, the system cannot be perfectly consistent and perfectly complete at once. I set out the match between Gödel's theorem and the Incommensuration Theorem term by term, and shows that Gödel's theorem is one case of the Incommensuration Theorem, the case found first in mathematics. Mathematicians keep consistency and live with incompleteness, and so mathematics stays open: a study pursued from many sides, never closed into one finished body.

Gödel's result is a finding, something learned about mathematics. The edge of knowing in the world is a finding of the same kind as Gödel's result. A picture shows the shape of the edge of knowing in the world.

Chapter 15 compared the edge of comparison to a walker's horizon, which goes wherever the walker goes. When the walker walks on across open ground, each mile brings into view land that was hidden, so any one horizon can be passed. Yet the horizon goes with the walker everywhere, and the curve of the ground itself makes the horizon. The horizon is no fence standing at the end of a flat meadow. The land the walker will see tomorrow is like the unknown, and each mile walked is like a move of the soft boundary. A second fact about the walk is of another kind: from every place there is a line past which the walker cannot see, and that line belongs to the shape of the ground, so however far the walker goes, there is always such a line.

I name a third class beyond the known and the unknown. The *unknowable* is what no comparison could reach, even in principle, for a reason in what knowing is, which no effort and no instrument changes. The edge of the unknowable is fixed by the principle of identity of Chapter 24: what no comparison can tell apart, in any way at all, is one thing and not two. So what cannot be compared even in principle cannot be told apart from anything, and no statement at all can rest on what cannot be compared. I call the edge of the unknowable the *hard boundary*. If a being had unlimited intelligence, unlimited time and unlimited resources, that being would still meet the hard boundary, because the structure of the act of knowing sets the boundary, and no lack of power does. The limit the theorem draws is the curvature of the field itself. The field in that sentence is the domain of comparison, which Chapter 8 called the range within which comparisons can be made. In the walker's picture, the field is the open ground. The curvature of the field is the bend of that ground, the shape of the domain itself, and that curvature is a different thing from the bending of space by gravitation.

The unknowable is present wherever anyone compares, as the shape of the domain itself. The unknowable gives the unknown its depth: because the unknowable is permanent, the unknown is never used up, and no investigation ever reaches a state in which everything has been mapped. There will always be real surprises in a real world.

People come to the unknowable by knowing. Ignorance yields only the unknown, and it takes knowing enough to see the shape of what knowing cannot take. So the deepest sense of mystery is reported by those who have gone furthest into a subject. Hilbert's "we will know" is true of the soft boundary, and since 1930 physicists have borne out his hope at the soft boundary again and again. Du Bois-Reymond's "we shall never know" points toward the hard boundary, which is real and fixed. So the two answers stand together, each at its own boundary: Hilbert's hope holds at the soft boundary, and du Bois-Reymond's verdict holds at the hard boundary.

I find limits in the account as well, and I can say where each one lies. A description of comparing is itself a set of comparisons, so what the account says about theories holds of the account too. The account describes the structure of every finding. The account leaves the particular values and events of a world for measurement to find: physics finds the particular. The account marks where the unknowable begins, without stepping past that edge. And a person who discovers the account, works through it and uses it is living a process. In the account I can point toward that process, show it by example and suggest it by story. But a description hands over structure, while the process is lived. Physics cannot reach its own basis, and metaphysics cannot reach its own practice. Physics and metaphysics each reach to where the other stops, and the two meet in the act of comparison, which is where physics is done. So there is an answer to the authors' question of how anyone would know that a theory was final. The answer is that every theory, my account included, holds less than the whole of its world. Whoever locates the limit of a theory has found something about the theory, and lost nothing.

Three Kinds of Question

You can now sort any question this book has met, and any question to come, into three kinds.

Questions of the first kind are answered by measurement. Questions of this first kind include what the universe is made of, how old it is, how fast it expands, and whether local causes fix the outcomes of quantum measurements. Each is answered by comparing the world with a standard, and each answer moves the soft boundary. For questions of this kind the authors are right that "the grand scientific mysteries have real, hard answers" (*We Have No Idea*, ch. 1, closing), and right that today's philosophy can be tomorrow's experiment.

Questions of the second kind name nothing, and they are dissolved: the ether, a trip to an earlier time, a signal faster than light. For questions of this second kind no instrument is needed, and none would help. Seeing which category each word belongs to is the answer, and every finding remains.

The third kind holds one question, the deep why, which asks for the possibility of a world. That possibility is inside no world, so no measurement answers the deep why.

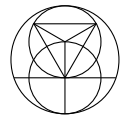
In this book I have used the description of comparing at every step, and the description of comparing lies under all three kinds of question. Every act of comparison checks the description, and no experiment tests it. The unknowable lies beside the three kinds: people reach the unknowable through knowing, and it is never used up.

> **The short answer**
>
> Measurement answers some questions; some questions name nothing and are dissolved; no measurement answers the deep why; and the asking never runs out, because no investigation moves the edge of the unknowable.

The short answer gathers the three kinds of answer this book has given: answers found by measurement, answers found by seeing that a question names nothing, and the deep why, placed beyond what any measure-

ment answers. With the three kinds in hand you can tell which kind of answer any question can have, and because the unknowable is never used up, there will always be more to find from inside the universe.

What, then, do you now hold that you did not hold before?



Chapter Thirty-Three

What Does That Even Mean?

In which the answers of the book are gathered, and the question that follows every answer is answered

What does that even mean?

What this chapter uses

A *comparison* is the act of finding whether two things are the same or different in some respect, and every measurement is a comparison; a *finding* is the outcome of one comparison, laid down as a record; a *comparer* is whatever makes a comparison, whether or not the comparer has a mind (Chapter 1).

The *content* of a finding is what the finding finds, as the warmth of your coffee; the *context* is where the content is found, and the context has three sides, the three settings of space, time and possibility (Chapter 1).

The three *settings* in which anything is measured are space, the place of a finding; time, the moment of a finding; and possibility, the range of what could have been found instead; a setting is *bent* when one part of the setting differs from another part (Chapter 1).

Three things in nature do the bending: gravitation bends space, the cosmological constant bends time, and the dark matter bends possibility (Chapter 1).

The *cosmological constant* is the share of the energy of empty space that a measurement made from inside takes in, one number for our whole epoch (Chapter 3).

Gravity is the *arena*, the stage of space and time on which the three forces act, and so gravity stands beside the three forces and is not a fourth force (Chapter 7).

In 2021 Jorge Cham and Daniel Whiteson published *Frequently Asked Questions About the Universe*, a book made from the questions that listeners sent to the authors' twice-weekly podcast, *Daniel and Jorge Explain the Universe*. The authors write that nothing brightened their day more than opening their in-box and finding a thoughtful question from a curious listener, and that the askers ran in age from nine to ninety-nine (*Frequently Asked Questions About the Universe*, Introduction).

In the book's last chapter, Cham and Whiteson report what they found in the letters. A listener would ask a question and then add a second question. The authors guess that most of the letter writers were not even expecting to ask the second question. The authors' first example reads: "Hey, Daniel and Jorge, is the universe really fourteen billion years old? And what does that even mean?" (*Frequently Asked Questions About the Universe*, ch. 20). The authors' second example reads: "Say, where does the energy to expand the universe come from? Can it really come from nothing? What does that even mean?" (*Frequently Asked Questions About the Universe*, ch. 20). The authors write that the added question is probably the question they are asked most often. They saved the added question for the end of their book, because they think it is the most important question they get about the universe.

The added question is the question after the answer. In the question after the answer, the listener asks what the answer changes for the one who asked. At the end of this book, the question after the answer has two parts for you: what you now hold that you did not hold before, and what the answers you now hold mean for you.

The Question After the Answer

Cham and Whiteson explain why people add a second question. They say that a person asks about the age of the universe. As soon as the question is sent, the asker wonders what to do with the answer. Then, they say, a small voice whispers the second question. The authors hold that the specifics of an answer matter less than the answer's significance for how you live. An answer about where the universe came from may change nothing in the details of your day, and yet, in the authors' words, "it can change something even more important: the context of your life" (*Frequently Asked Questions About the Universe*, ch. 20). The authors' example is the discovery that the Earth is not the center of the cosmos. The discovery showed that humanity is a small part of something larger.

The authors hold two further things in their last chapter. First, they write that each of the questions in their book, and every question of science, has an answer, though the answer may be hidden, or far away, or too small to see for now. Second, they write that the meaning of an answer is the one question they cannot answer for their reader, because the meaning of an answer is different for each of us. In their words: "We all get to define our own context and find our own significance in this universe" (*Frequently Asked Questions About the Universe*, ch. 20). So Cham and Whiteson end their book, a book that opened with a promise of answers, by asking their reader a question: "So what are your frequently asked questions?" (*Frequently Asked Questions About the Universe*, ch. 20).

Their earlier book, *We Have No Idea*, ends in a matching way. *We Have No Idea* says of itself in its closing pages: "This book is not so much about answers but about questions" (*We Have No Idea*, "A Conclusion of Sorts", "The Ultimate Mystery"). The authors write that the main lesson of the book is that we should be excited about all the things we do not know, because so many discoveries are still ahead. They put the lesson in one line: "The age of human exploration and discovery is far from over" (*We Have No Idea*, "A Conclusion of Sorts", "The Ultimate Mystery"). Then the authors raise what they call the Ultimate Mystery: why the universe exists, and why the universe is the way it is, and they ask whether science will one day answer questions that deep. They answer the question with their refrain: "We have no idea" (*We Have No Idea*, "A Conclusion of Sorts", "The Testable Universe"). Their next line is the last line of the book: "But it will certainly be an exciting ride".

The authors give one message in the last chapters of their two books, and the message has four parts. Answers matter for the context they give a life. The mysteries have real answers, and the range of what science can test keeps growing. The meaning of every answer belongs to the one who asks. Asking is itself worth doing.

I take the authors' message as they give it. I answer the authors' last question, whether science will one day answer the deepest questions, on separate ground. The authors use the word *context* for how you see your-

self and how you relate to the wider universe. In Chapter 1 I gave the word context a narrower sense: the context of a finding is where the content of the finding is found, and the context has three sides, the three settings of space, time and possibility. The two senses of the word differ, and in the answers of this book I join the two senses. The answers of this book say what the wider universe is in relation to you, a comparer inside the universe, and so the answers change the context of your life in the authors' sense.

What You Now Hold

Picture the authors' in-box once more, full of letters, each letter with its second question. Below I set out the answers that this book has given, Part by Part, in the order you met them, and for each Part I say what its answers mean for the one who asked.

The first letters asked what the universe is made of. Two bendings make up about ninety-five percent of the universe's energy (Chapter 1). The two bendings are the bending of time by the cosmological constant and the bending of possibility by the dark matter (Chapter 1). The other five percent, the stuff, comes from a closed list of kinds of particle (Chapter 1). Gravitation, the bending of space, has no slice of its own in the authors' pie (Chapter 1). The dark matter is real energy, located where the dark matter pulls and made of lasting vibrations of the six small dimensions of possibility, and so no instrument will ever find the dark matter except by its weight (Chapter 2). Dark energy is the cosmological constant: the share of the energy of empty space that a measurement made from inside takes in, one number for our whole epoch (Chapter 3). The smallness of the cosmological constant is the largeness of what we can see: the constant is small because the part of the world we can see is large (Chapter 3). The basic elements of matter are a closed list of kinds, and the kinds are few because every comparison has three positions (Chapter 4). There are three of each kind of matter because the content turns three ways, with no fourth way (Chapter 4). No smaller pieces lie below the

known kinds (Chapter 4). The charges of the particles are forced: they are the one solution that keeps the description of the forces consistent (Chapter 5). The masses sit on a counted ladder beneath a ceiling, a mass that no particle of matter can exceed, and the structure of comparison sets the ceiling, while measurement supplies the last values of the masses (Chapter 5). Mass is the measure of one relation of a thing to its context (Chapter 6). The relation is found three ways: as the thing's pattern, its inertia and its weight (Chapter 6). Mass and energy at rest are one currency, one quantity counted in two units (Chapter 6). Most of your weight is the energy that binds quarks together (Chapter 6). For the one who asked, the answers about what the universe is made of mean that most of what the universe weighs is the shape of the settings in which you find anything at all. The rest is a few kinds of piece, each kind with a reason.

The next letters asked about gravity and space. Gravity is the arena: the stage of space and time on which the three forces act (Chapter 7). The three forces are electromagnetism, the strong force and the weak force. So everything falls alike, and nothing shields gravity (Chapter 7). Gravity is feeble on the electron because the electron is very light compared with the Planck mass (Chapter 7). The Planck mass is about the mass of a grain of sand a quarter of a millimeter across (Chapter 7). Gravity and the quantum are two descriptions of one world, joined side by side, with one smooth geometry of space and time for each alternative of the matter, and neither description has to be given up or quantized (Chapter 8). There is one account of everything: electromagnetism, the strong force, the weak force and the arena, joined side by side, with no single larger force or theory from which the forces and the arena follow (Chapter 9). The ground of the one account of everything is known, because the account describes how the account itself is found (Chapter 9). Space is the pattern of which events can affect which (Chapter 10). Space bends smoothly wherever there is something to be found, and space has no smallest step (Chapter 10). The world has ten dimensions: one of time, three of space and six of possibility (Chapter 11). The six dimensions of possibility are the range of what a finding could be, present at every place and never a place them-

selves (Chapter 11). For the one who asked, the answers about gravity and space mean that the ground under you and the sky over you are found in a space and a time that have a definite shape.

Then came the letters about time. Time comes with comparison (Chapter 12). Physicists use one word for three times: the time on your clock, the order of your findings and the time of quantum change (Chapter 12). No one time is all three times with each made perfect (Chapter 12). Time goes forward because every comparison goes one way: from what could be found, to the finding, to the record of the finding (Chapter 13). The order of comparison needs no special beginning of the world (Chapter 13). Travel to an earlier time names nothing, because a finding once made stays made, and any loop in space and time brings a traveler only to the traveler's own later findings (Chapter 14). The coffee stays spilled: in the first chapter of the authors' second book, the coffee spilled on your pants is the small mistake that a trip back in time would undo. The speed of light is the outer edge of comparison itself, and the speed of light is the same for every comparer (Chapter 15). The number we give the speed of light shows only the size of our units (Chapter 15). Every journey and every message stays within the speed of light (Chapter 15). For the one who asked, the answers about time mean that what you have found and what you have done stay found and done.

The letters about the stars came next, and the first of those letters asked who is shooting superfast particles at the Earth. Whoever is shooting the particles is in our own region of the cosmos and is built of the known kinds of particle (Chapter 16). The arena has no least step: light of every energy from distant gamma-ray bursts arrives together, which shows that any grain of space that would slow light is smaller than the Planck scale (Chapter 16). Two things keep anyone from the stars: the years that the distances take, and the energy that the engines need (Chapter 17). The structure of comparison limits every traveler and every signal to the reach of light (Chapter 17). Within the reach of light, the structure of comparison rules out no journey (Chapter 17). Life has been found in one place: here, on the Earth (Chapter 18). Life is made of the

same materials at every star, and the same rules join those materials at every star (Chapter 18). Whether life is anywhere else is set by each place's history, and each place's history can be read only by finding life there (Chapter 18). For the one who asked, the answers about the stars mean that the sky is made of what you are made of, under the same law that you are under.

Then came the letters about the beginning. We are made of matter because our epoch began with an excess of matter (Chapter 19). The excess is a residue that every change since has kept (Chapter 19). The excess has one sign everywhere: everywhere the excess is of matter, not of antimatter (Chapter 19). Antimatter exists because comparing produces every state together with its mirror, the same state with every label reversed (Chapter 19). The Big Bang is the turn, the limit at which our epoch begins (Chapter 20). When we trace our history back, we draw the turn as a first moment (Chapter 20). Our world began even and flat, with no long inflation (Chapter 20). The first ripples of our world show the form of the epoch before ours (Chapter 20). The whole new world came from one origin, and so regions of the sky that no signal ever connected are alike (Chapter 20). You can fall into a large black hole intact, and your friends outside never see you cross (Chapter 21). On your own watch you soon reach the end inside the black hole: the end is a moment, ahead of every path inside, and every black hole of our epoch shares that one end (Chapter 21). Before the Big Bang came the collapse of the interiors of the black holes of the epoch before ours, and at the one end that those interiors share, a new large world formed, in a cycle of epochs with no first turn (Chapter 22). Space is flat, with no short loop anywhere (Chapter 23). For every measurement made from inside, our space is the same as a space without end, since no comparer can tell our space from a space without end (Chapter 23). Every comparer stands at the center of its own horizon, the edge of everything whose light has reached the comparer (Chapter 23). For the one who asked, the answers about the beginning mean that

the beginning had a before, and that the place where you stand is the center of your own horizon, as every comparer's place is the center of its own horizon.

Then came the letters about you. A copy of you, wherever the copy stood, would be a second person (Chapter 24). I exclude the other universes that would hold copies of you, but the regions beyond our horizon are parts of our one world (Chapter 24). A quantum state can be moved without being copied, and never faster than light (Chapter 25). A person is not information, so a description of you, sent and rebuilt, is a map of you (Chapter 25). You are not in the map of you. People are fairly predictable and never completely predictable, today or ever: the future is open (Chapter 26). One outcome that nothing fixed is chance seen from outside and choice seen from inside (Chapter 26). The world is not a computer program (Chapter 27). A simulated world that held real people would be a fenced region of this one world, and the fenced region would share this world's open outcomes, its arrow of time and its people (Chapter 27). The form of everything you are and do is never destroyed (Chapter 28). When part of that form ends inside a black hole, that part is kept as a share of the form from which the next world grows, and nothing of you crosses into the next world as you (Chapter 28). For the one who asked, the answers about you mean that you are one person, no description contains you, and your choices are yours.

The last letters asked about the far future. The sky of our epoch empties, but the expansion never turns back, and nothing bound by gravity is torn apart (Chapter 29). Empty space keeps the one settled state that I derive for empty space in my account (Chapter 29). The emptying of the sky ends in a turn, at which the next epoch begins (Chapter 29). Time does not stop: no clock comes to a last tick (Chapter 30). What ends with the emptying of the sky is what a comparer can compare with, but the one-way order of comparison never ends (Chapter 30). Because the Sun burns steadily, humanity has billions of years on the Earth (Chapter 31). On the Earth, people can find the rocks from space that could strike the Earth, and choose to turn those rocks aside (Chapter 31). Every thinker's run of

findings ends, and in each epoch thinking begins again under the same law as in ours (Chapter 31). Some questions are answered by measurement, some questions name nothing and are dissolved, and the deepest why lies past every measurement (Chapter 32). Because the unknowable has an edge that no investigation moves, the asking never runs out (Chapter 32). For the one who asked, the answers about the far future mean that after the emptying of our sky there are again comparers inside the world to find the world.

Three Kinds of Answer

Look back over the answers, and you can see that the answers come in three kinds, as I sorted them in Chapter 32.

A measurement answers some questions. Questions that a measurement answers include how much matter there is, how old our epoch is and how fast light goes. In the chapters on those questions, I told what was done, what was found, and what we now know. For questions that a measurement answers, the authors are right that there is an answer. In the chapter of *We Have No Idea* on life elsewhere, the authors say that the question of life on other planets has an answer: "Either there is (or was or will be) life on other planets or there is not" (*We Have No Idea*, ch. 17, "Are We Alone?"). The authors write of the two possible answers: "Either answer is mind-blowing and one of them is true" (*We Have No Idea*, ch. 17, "Are We Alone?"). In Chapter 18 I found that whether life is anywhere else is set by each place's history, which can be read only by finding life there. So the question of life elsewhere is a question of the first kind, a question that a measurement answers.

Some questions name nothing. In Chapter 14 I took a plain example: a request for the color of the number seven. The answer is neither hidden nor hard to find, because the request puts the word "color" where the meaning of "color" does not reach: a number is not a thing that has a color. The question of what light is a motion of, a trip to an earlier time, and a signal faster than light are requests of the same kind as the request for the

color of seven. In Chapter 32 I showed each of the three requests dissolved. When this book says that something cannot be, it means that the request names nothing. No future machine can satisfy a request that names nothing, so whatever is excluded in principle is excluded, for that reason, in all future practice. Each answer of the second kind, to a question that names nothing, is a thing you now know about the world. You know where the world's edges are, and why the edges are where they are.

No measurement can answer one question: why there is a world at all. In Chapter 32 I laid a ruler beside the cup: the ruler tells you the height of the cup and nothing of the coffee's warmth, and nothing is missing from the ruler. In that picture, measurement is the ruler, and the question of why there is a world is the warmth. The question is well formed, and the question is of another kind than the questions a measurement answers: the question is about the possibility of there being a world, and every measurement is made inside a world. Of the question why there is a world that it "is not a question physics has failed to answer". The method of physics does not apply to the question, for the same reason that a ruler does not measure temperature.

The three kinds of answer are a measured answer, a request found to name nothing, and one question found to lie past every measurement. Beside the three kinds of answer is the unknowable, and on my account the unknowable is the ground of the authors' excitement. The authors draw their excitement from the history of discovery: each new instrument has let science test more questions. I find the same excitement as the authors in the structure of knowing itself: in what every act of knowing must contain. I sort what is not known into two classes. The unknown is what comparers can reach by further comparison and have not reached yet, and the edge of the unknown moves with every investigation. The unknowable is what no comparer could reach by any comparison, even in principle, and the edge of the unknowable does not move. The depth of the unknown comes from the unknowable: It is what ensures that the act of investigation never runs out of territory. The unknowable is reached through

knowing: a person reaches the unknowable by knowing enough to see the shape of what knowing cannot take. So those who have gone furthest into a subject report the deepest sense of mystery.

The authors' last question in *We Have No Idea* was whether we will one day answer the deepest questions about the universe. I answer that question in two parts. First, no measurement will answer why there is a world at all, because every measurement is made inside a world. Second, the asking never runs out, because the unknowable has an edge that no investigation moves, and so the unknown is never used up. The authors hold that the age of human exploration and discovery is far from over, and on my account the age never ends.

The authors also say in the introduction to their second book that "asking questions supposes that it's possible to find the answers, which we believe is an act of hope" (*Frequently Asked Questions About the Universe*, Introduction). I agree that asking is an act of hope, on my own ground. In Chapter 5 I found that a number that agrees with measurement before its reason is known is a question, "why does it land?", a question about why the number agrees with what is measured. To call the agreement a "coincidence" is to claim something more: that the agreement has no reason at all. A question states what would settle the matter, and so a question contains the instruction for the next step. I call a label such as "coincidence" a *grade*: a label recording how sure a checker is of a step. A grade contains no instruction for the next step. The grade closes the inquiry, and the question opens it. I opened every chapter of this book on a question, and with every answer I reached, I handed on the next question.

Whose Meaning Is It?

The authors leave the meaning of each answer to the one who asks, and I come to the same result on separate ground. In Chapter 26 I found that one outcome that nothing before it fixed is described from two sides. From outside, the outcome is chance: no one can tell the outcome apart

from a random event by any measurement. From inside, the outcome is choice: the outcome has the character of the one from whom the outcome came. For meaning, it follows that the meaning of a choice cannot be extracted, passed on in its particulars, or reproduced by any process other than the one that is the choice. So no book, this book included, can hand you the meaning of its answers. The authors leave the meaning of an answer to the asker because the meaning of an answer is different for each of us. I leave the meaning of an answer to the asker because a choice is one event described from two sides, and the meaning of a choice belongs to the one who chose.

On meaning I go a step further than the authors go. The authors speak of meaning as something each of us defines and finds. I show that meaning is also already present: "Meaning belongs to the structure of the residual, and nothing can remove it". In the quoted sentence, the residual is the part of each event that no law fixes, the part that is choice when seen from inside. As in Chapter 26, "meaningful" means significant to the process an outcome came from. A meaningful outcome has the character of the process it came from, and I add that the outcome has a share in value. The argument that meaning is already present has three steps. First, to draw a line where meaning stops is to compare from a point of view, which is a meaningful act. So no line where meaning stops can be drawn from outside meaning. Second, the idea that choice is meaningful is itself a meaningful idea, so the idea is a case of the very thing the idea is about, and that case stays a case under every description. Third, every attempt to define meaninglessness is meaningful, so meaninglessness has no case of its own. The meaning that cannot be removed is the mark that each outcome has of the process the outcome came from. The meaning that cannot be removed is a different thing from a significance that someone could write down for every event. *Nihilism* is the view that nothing means anything. Nihilism would need a case of meaninglessness that is a case of itself, and there is no such case. To declare that nothing matters is to weigh

worth, and so the declaration is itself a case of mattering. So you define your own significance, as the authors say, and you always begin from a world that already has meaning.

One more thing belongs to you alone: your asking. The *formalism* of physics is its written equations and rules, and the formalism cannot contain the doing of physics. The doing of physics is judging which measurement to make, seeing the moment when a model has been exceeded, and choosing to follow one oddity rather than another. No model contains the judging, the seeing or the choosing, and no model could contain them. The blind spot of a theory is where its practice lives. Your asking is part of the doing of physics. No answer in this book contains the one who asked, and asking is the part of the work that only the asker does.

What It Means

Now take the two letters that the authors quote. One letter is about the age of the universe, and the other is about the energy that expands the universe. I answer each letter whole: its first question and its second.

The first letter asks whether the universe is really fourteen billion years old. Our epoch is about 13.8 billion years old, as we find by tracing our history back, and the listener rounded 13.8 billion to fourteen billion. The listener also asked what that age even means. The age is the age of our epoch, counted from the turn: the limit that we approach when we trace our history back, and that we take for a first moment. The turn had an epoch before it, and our epoch will be followed by a next epoch.

The second letter asks where the energy to expand the universe comes from, and whether the energy can really come from nothing. The energy that speeds up the expansion is the cosmological constant, which comes from empty space, the thing we call nothing in everyday life. In Chapter 3 I found that the energy of empty space is real, that a measurement made from inside takes in a share of the energy of empty space, one number for our whole epoch, and that the share bends time. So the expansion speeds

up because time, one of the three settings (space, time and possibility) in which you find anything, is bent, and a measurement made from inside weighs the bend of time.

In the authors' sense of context, how you see yourself and how you relate to the wider universe, the answers of this book say three things about where you stand. You are inside the universe as a comparer, and you find the universe from where you stand. Your findings are real, and once made they stay made. What you choose is chance from outside and choice from inside, and the meaning of what you choose is yours and cannot be removed.

The Cup on the Table

Put your hand around the cup on your table. The coffee is warm.

The warmth of the coffee is one finding, and everything I have said in this book about findings is in that one finding. In the finding there is your noticing, there is the warmth you found, and there is where you found the warmth: here, now, among the ways the cup could have been. The warmth is content, what the finding finds, and the content is made of the kinds on the closed list of kinds of particle. The table is the place, the moment is the time, and the ways the cup could have been, cold, spilled or tea, are the possibility. Together the place, the time and the possibility are the context of the finding, in its three settings, and each setting has its bend. Your noticing came before your memory of the noticing, and the order from noticing to memory runs one way. The finding, once made, stays made. You make the finding from the center of your own horizon, as every comparer makes its findings from the center of its own horizon. No description of you is you, and the noticing is yours.

At another table, someone else puts a hand around a cup and finds the cup warm, and that finding is theirs. After the long emptying of our sky, in the epoch that follows ours and in every epoch after it, comparison be-

gins again, and the comparers in those epochs make findings that are their own. The world is found from inside, here and now and in every epoch, by comparers like you.

> **The short answer**
>
> What you now hold is a world whose largest part is the bending of the settings in which every finding is made, found from inside it by comparers like you, whose findings are real and whose questions never run out.

The short answer is the book's question answered whole: the universe is made mostly of the bending of the settings in which everything is found, and our place in the universe is the place of a comparer inside it, where every answer is found. In the authors' own sense of the word context, the short answer is the context of your life as the answers of this book describe that context, and what that context means for you stays yours to find.

Put your hand on the cup once more. The coffee is still warm, and you are the one who found it so.

Reading Beside Cham and Whiteson

This table sets each chapter of this book beside the chapters and sections of *We Have No Idea* and *Frequently Asked Questions About the Universe* that the chapter cites or takes a picture from. It also names the pictures the chapter uses, with the cup's step first wherever the cup returns. With the table, the three books can be read side by side.

This book	Cham and Whiteson	The pictures here
Preface: A Frequently Asked Preface	*We Have No Idea*, Introduction; ch. 1, "What Is the Universe Made Of?"; ch. 13, "What Happened to Chapter 13?"; "A Conclusion of Sorts", "The Testable Universe". *Frequently Asked Questions About the Universe*, Introduction; ch. 1, "Practical Versus Possible Versus Not Impossible"; ch. 20, "Why Do We Ask Questions?".	the cup: your own cup of coffee, set on the table beside this book before Chapter 1; the two books set side by side; the authors' pie; the telescope and the collider beside the act of finding out; a cupful of the sea
1. What Is the Universe Made Of?	*We Have No Idea*, ch. 1, "What Is the Universe Made Of?"; ch. 3, "The Pie Chart".	the cup: noticing that the coffee is still warm, every finding has a content and a context, and the context has three sides, the three settings; the Planck briefing in Paris, 2013; the authors' pie; a ramp and a staircase; a ball on a rubber sheet; a drum's favored notes; a thermometer, a ruler and a satellite; a map, a push and a forecast of rain

This book	Cham and Whiteson	The pictures here
2. What Is Dark Matter?	*We Have No Idea*, ch. 2, opening, "Ways We Know Dark Matter Is There", "How Dark Matter Interacts", "How Can We Study Dark Matter?", "What We Know about Dark Matter" and "Why This Matters"; ch. 15, "Gravity Versus Pressure".	the cup: with your eyes closed, you find it by its weight alone, and a thing can be found through one channel only; the glowing clouds of Andromeda; the planets around the Sun; the authors' merry-go-round, galaxy seen twice and colliding clusters; a ringing crystal; the surface of a balloon, each point paired with the point opposite it; a globe whose points are blends of two answers; the ringing early gas; the halos as scaffolding

This book	Cham and Whiteson	The pictures here
3. What Is Dark Energy?	*We Have No Idea*, ch. 3, opening and "What Could Dark Energy Be?"; ch. 15, "How Did It Get This Way?". *Frequently Asked Questions About the Universe*, ch. 12, "The Big Crunch"; ch. 18, "Space-Bending Warp Drives".	the cup: dipped in the sea, it holds a cupful, and a measurement made from inside what it measures holds a share; Einstein's still universe, 1917; the authors' building of a hundred floors; a ball thrown upward; a lamp of known brightness down a road; a jar pumped empty; two metal plates; two dancers in a close dance; a rock on a shelf; a coil of spring steel; one tree measured by a tape and by its shadow; the strings of a piano; tiles on a floor; a cake cut into equal slices; a page and a word; a map and its printed scale; a deck of fifty-two cards
4. What Is the Most Basic Element of Matter?	*We Have No Idea*, ch. 1; ch. 4, "What Are All These Particles For?" and "What Is the Most Basic Element of Matter?"; ch. 16, "The Smallest Particles" and "What Is a Theory of Everything?". *Frequently Asked Questions About the Universe*, ch. 13, "A You Beyond You".	the cup: light passes from the coffee to you, you take in its color, and the cup holds more than you see, so every finding has three positions; Thomson's tube of four gases, 1897; the authors' toy blocks, cake with nine unused ingredients and onion; a snowflake beside an electron; a letter saved twice under one name; two stones, a thermometer and a color card; a three-faced pencil in a groove; the hand of a clock

This book	Cham and Whiteson	The pictures here
5. Are the Particles' Numbers Just Arbitrary?	*We Have No Idea*, ch. 4, "What's the Pattern of the Masses of the Particles?" and "What's Up with Those 1/3 Electric Charges?"; ch. 5, "The Higgs Boson"; ch. 16, "How Will We Know If We Are Done?".	Balmer's four lines of hydrogen, 1885; the authors' lost and found two thousand dollars, and their tinyon; a ledger and its clerk; a guessing game of yes-or-no questions; a strip of paper folded in halves; three houses on a road that runs downhill; a hand closed around a ball; a ruler laid against itself; an arrow from the corner of a room; a tailor's pattern; Millikan's drops of oil
6. What Is Mass?	*We Have No Idea*, ch. 5, "The Stuff of Stuff" and "Particularly Confusing Particle Masses". *Frequently Asked Questions About the Universe*, ch. 15, "Mass and Energy" and "A Massive Conclusion".	the cup: lidded and lifted hot, then lifted cold, it weighs a little less cold, so mass measures a relation and energy has weight; the CERN seminar of 4 July 2012; a bathroom scale; a box of mirrors filled with light; a rubber band stretched until it snaps; the authors' bag of beans, and their dollars and euros; one spacecraft in an empty universe; a wound spring; a stone on a hill

This book	Cham and Whiteson	The pictures here
7. Why Is Gravity So Different from the Other Forces?	*We Have No Idea*, ch. 6, opening, "Gravity's Weakness" and "Maybe Gravity Is Special"; ch. 5, "Gravitational Mass" and "Are the Two Kinds of Mass the Same?"; ch. 2, "How Matter Interacts".	the cup: let go together with a spoon, it lands with the spoon, so weight and resistance to motion are one relation to the context; the hammer and the feather on the Moon, 1971; the authors' magnet and nail; a play, its actors and its stage; a phone in a metal elevator; Einstein's falling man and his room pulled by a rope; Newton's pendulums; a mountain and a valley
8. How Does Gravity Meet the Quantum?	*We Have No Idea*, ch. 6, "The Quantum Conundrum" to "So Much for That", and "Black Hole Colliders"; ch. 16, "Joining Gravity and Quantum Mechanics". *Frequently Asked Questions About the Universe*, ch. 11, "Who's Right?".	the chirp that reached Hannover, 2015; Ryle's visitor looking for the University; Feynman's ball in two places; an architect's two drawings of one house; the torsion balance of Page and Geilker; a struck crystal; a light microscope and a cell; the hot oven of 1900; the laser light and the arms of the LIGO detector

This book	Cham and Whiteson	The pictures here
9. Is There a Theory of Everything?	*We Have No Idea*, ch. 16, "What Is a Theory of Everything?", "Baboons All the Way Down" and "The Most Fundamental Forces".	Georgi's evening of 1974, and a proton with a door to leave by; the authors' onion and baboons; a railway's timetable and track; blue and yellow paint stirred to green; a triangle; the three knobs of a stove; a puzzle cube whose faces turn; a tank of water; three cars on one road; a country of many valleys; a kitchen on a Sunday afternoon, with honey tasted, a loaf of bread baking, a recipe and a photograph; the last turtle; a computer and its programs
10. What Is Space?	*We Have No Idea*, ch. 7, "The Mysteries of Space", "Which Space Is the Place?", "Space, It's a Thing", "This Sounds Ridic-goo-lous. Are You Sure?" and "Space Goo, You're Swimming in It". *Frequently Asked Questions About the Universe*, ch. 18, "Wormhole Warp Drives".	the cup: its warmth reaches your hand now, and nothing it does now reaches the Moon now, so space is the pattern of which events can affect which; the letters of Leibniz and Clarke, 1716; the authors' warehouse and goo; a pan balance; a handshake across a table; two witnesses; the eclipse of 1919; two clocks a third of a meter apart; the authors' air and its molecules; a microscope and a cell; the light of a gamma-ray burst arriving together

This book	Cham and Whiteson	The pictures here
11. How Many Dimensions Are There?	*We Have No Idea*, ch. 9, "What Exactly Is a Dimension?" and "Wrapping Up These New Directions". *Frequently Asked Questions About the Universe*, ch. 6, "Options for Teleportation"; ch. 18, "A Hyperspace (or Subspace, or Superspace) Warp Drive".	the cup: slid along the table, across it and lifted, it cannot be moved to the cup of tea it could have been; Kaluza's fifth direction and a garden hose; the authors' mailing address; a city map; a thermometer, morning and evening; a recipe and its ingredients; a street and a wall; two towns on a map; a page and the direction straight up; a particle counter before it clicks; a small staircase of one, three and six; a diary and the next room; the grain of a sculptor's stone
12. What Is Time?	*We Have No Idea*, ch. 8, "A Definition of Time" to "Question #1: How Is Time Different from Space (and Why)?", with "So Tell Us Already: What Is Time?", and "Question #4: Do We All Feel Time the Same Way?"; ch. 10, "History Is History". *Frequently Asked Questions About the Universe*, ch. 1, "Practical Versus Possible Versus Not Impossible"; ch. 12, "Time Is Relative".	the cup: hot at seven and warm at eight, two findings in order, and in a still room no two moments could be told apart; four clocks flown around the world, 1971; the authors' snapshots, pizza, and race of a llama and a ferret; a head and a book in an empty universe; two hydrogen atoms; a laboratory bench with a lump of ore, a counter and a clock; two clocks of single aluminum ions

This book	Cham and Whiteson	The pictures here
13. Why Does Time Only Go Forward?	*We Have No Idea*, ch. 8, "Question #3: Why Does Time Move Forward?" to "Time and Particles", with "Does Entropy Help Us Understand Time?". *Frequently Asked Questions About the Universe*, ch. 1, "Going with the Flow"; ch. 12, "The Heat Death".	the cup: the cream spreads through the coffee and never gathers again, and your noticing comes before your memory of it; Eddington's arrow, 1927; the authors' kitchen and bouncing ball; a deck of cards in its factory order; a photographer's position, click and print; a footprint and its step
14. Why Can't I Travel Back in Time?	*Frequently Asked Questions About the Universe*, ch. 1, "Practical Versus Possible Versus Not Impossible", "You Can't Go Back to the Future", "No Do-overs?" and "Going with the Flow". *We Have No Idea*, ch. 8, "Question #2: Can We Travel Back in Time?".	the cup: the coffee spills, and a finding once made stays made; Gödel's universe, 1949; the authors' spinning cylinder, wormhole and eddy in a river; a country of roads and a drive back to a birthplace; the largest prime number; the color of the number seven; the tops of the spin echo

This book	Cham and Whiteson	The pictures here
15. Can We Travel Faster Than Light?	*We Have No Idea*, ch. 10, opening, "The Speed Limit of the Universe", "But Why This Speed?", "Summary" and "Past and Future". *Frequently Asked Questions About the Universe*, ch. 6, "Options for Teleportation" and "Getting There at Light Speed"; ch. 18, opening.	the cup: a cup on a table on Mars, whose news reaches you no sooner than light allows, and whose "now" is no fact for you; Rømer's late moon, 1676; the authors' hamster, astronaut and cat; a walker on a globe and the antipode; better boots; a firework's flash drawn as a cone; a ball thrown in a train; a walker's horizon; muons in the air and in ice; two linked electrons in Delft; a rate of exchange
16. Who Is Shooting Superfast Particles at the Earth?	*We Have No Idea*, ch. 11, opening, "What Are Cosmic Rays?", "Where Are They Coming From?", "What Could They Be?" and "Cosmic Messengers".	Hess's balloon, 1912; the authors' house sprayed with bullets, and their messengers; a baseball; a swing pushed in time; a drizzle that strikes harder as you run; a gun made of metal; runners on a smooth road and on gravel; a photograph's smallest dot

This book	Cham and Whiteson	The pictures here
17. What's Stopping Anyone from Traveling Between the Stars?	*Frequently Asked Questions About the Universe*, ch. 8, "So What Are We Waiting For?"; ch. 2, "Scenario #4: Or Have They?"; ch. 18, "Space-Bending Warp Drives", "Wormhole Warp Drives" and "A Hyperspace (or Subspace, or Superspace) Warp Drive". *We Have No Idea*, ch. 10, "But Maybe We Can Visit Other Stars"; ch. 17, "So Where Are They?", "Where Is Everyone?" and "Could We Learn Physics from Them?".	Fermi's walk to lunch at Los Alamos, 1950, and the cartoon of the saucers; a ship inside the cone of its own departure; a rate of exchange; muons reaching the ground; Voyager 1; the authors' moving walkway; a country of roads, with new roads and faster cars; the authors' mailing address; the "WOW!" signal
18. Are We Alone?	*We Have No Idea*, ch. 17, opening, "Number of Habitable Planets with Life (flife)" and "Are We Alone?". *Frequently Asked Questions About the Universe*, ch. 7, "Cosmic Neighbors", "Planets Beyond Our Solar System" and "Oh Yeah, an Atmosphere".	Drake's listening telescope, 1960; the authors' traveler abroad; sunlight through a prism; the iron in blood and the oxygen in a breath; a footbridge with one plank missing; the mountainside of the elements; the authors' best house on the block; a lake that freezes from the top down; notes and a sonata; a person choosing a gift for a friend; a bacterium swimming toward its food

This book	Cham and Whiteson	The pictures here
19. Why Are We Made of Matter, Not Antimatter?	*We Have No Idea*, ch. 12, "Mirror Particles", "Antiparticle Annihilation", "The Mysteries of Antimatter", "Neutral Matters", "Why the Universe, Not the Antiuniverse?" and "Curious Matters". *Frequently Asked Questions About the Universe*, ch. 8, "Antimatter".	Anderson's curved track, 1932, and a jet's white trail; zero written as plus one and minus one; the authors' raisin and antiraisin; an alphabet and a library; a ratchet with a paddle; boiling water and cooling honey; two tally counters in a factory; a marble in a bowl; a line of shells after the tide; the end of a party of couples; a can of paint mixed before the painting; the authors' flying cars
20. What Happened During the Big Bang?	*We Have No Idea*, ch. 14, "Big Mystery #1: Quantum Gravity", "Are We Done?", "An Inflated Answer" and "What Caused Inflation?"; ch. 7, "Straight Thinking about Bent Space"; ch. 15, "How Did It Get This Way?".	the horn at Holmdel and its noise, 1965; a walker halving the distance to a wall, and a map drawn from the footprints; the edge of a map of a country; two towns that share an accent; an ant on a marble and on a ball the size of the Earth; the worn steps of an old church; a quilt and a woven cloth; children on a trampoline; a sled on an almost level hill

This book	Cham and Whiteson	The pictures here
21. What Happens If I Fall into a Black Hole?	*Frequently Asked Questions About the Universe*, ch. 5, opening, "Getting Closer", "The Shadow of the Black Hole", "What Your Friends Will See" and "What's Inside?". *We Have No Idea*, ch. 6, "Let's Get Realistic and Visit a Black Hole".	the two clocks of Oppenheimer and Snyder, 1939; the authors' picnic blanket; the authors' picture of standing on the Earth, the feet pulled slightly harder than the head; light cones that lean toward the center; a ball that holds the hole's whole mass out to a given depth; a friend watching from far away; moving toward tomorrow; the densities of the early universe passed in reverse; the edge of a map; funnels whose ends meet; the photograph of a black hole's shadow
22. What Came Before the Big Bang?	*We Have No Idea*, ch. 14, "And What Happened before the Big Bang?". *Frequently Asked Questions About the Universe*, ch. 11, its three answers, with "Relativity Is Mostly Right" and "How Can Something Come from Nothing?".	the Vatican study week, 1981; a family tree drawn from the records of one parish; the same rates read the other way in time; a film of a balloon letting out its air, run backward; a bundle of undated letters; the census of a new country; Hawking's North Pole, as the authors report it

This book	Cham and Whiteson	The pictures here
23. How Big Is the Universe?	*We Have No Idea*, ch. 15, opening, "Our Address in the Cosmos", "The Size of the Universe", "A Finite Universe in Infinite Space", "A Finite Universe in Finite Space", "An Infinite Universe" and "And Why Is the Universe So Empty?". *Frequently Asked Questions About the Universe*, ch. 16, "What Can We See?", "Hints from the Movements of Galaxies", "Finding the Crust of the Universe", "The Central Point", "The Universe Is Infinite" and "The Universe Has a Funny Shape"; ch. 3, "Another You in Our Universe".	the cup: your cup stands at the center of all you can ever see, and so does every cup on every table; Hubble's plate, 1923; a lamp of known brightness down a road; a skyline; a ring of ripples around a stone in a pond; a traveler on a wide plain; the authors' rising loaf; the raisin bread of *What Comes After the Dark*; a ball the size of the Earth beside a marble; an old video-game screen and the authors' donut; matched rings of hot and cold spots; a ladder from the Planck length to the edge of all we can see
24. Is There Another You?	*Frequently Asked Questions About the Universe*, ch. 3, "The Odds of You", "Unlikely but Not Impossible?", "The Different Universes Multiverse", "The Quantum Multiverse", "Another You in Our Universe", "An Infinite Universe", "Is the Multiverse Real?" and "Wrapping It Up". *We Have No Idea*, ch. 14, "Maybe There Are Lots of Universes"; ch. 16, "How Will We Know If We Are Done?".	the cup: two identical cups on two tables are two cups; Everett's branching observer, 1957; the authors' die with a quadrillion sides, and their soap opera; two coins, one in each hand; a country of roads

This book	Cham and Whiteson	The pictures here
25. Why Can't We Teleport?	*Frequently Asked Questions About the Universe*, ch. 6, opening, "Options for Teleportation", "You Are Information", "You're Not That Quantum", "You're Totally Quantum", "Too Many Yous", "Getting There at Light Speed", "Making a Quantum Copy" and "Beam There, Done That"; ch. 13, "A You Beyond You".	the cup: the recipe for your coffee, read over the radio, brews a second cup across the sea, and a description of a person is a map with no person in it; the photons of Innsbruck, 1997; polarizing sunglasses; a filter and a photon leaning at forty-five degrees; two friends and two bits; the authors' toy bricks; a ramp and a staircase of identical steps
26. Are Humans Predictable?	*Frequently Asked Questions About the Universe*, ch. 10, opening, "Physics in Your Brain", "A Chaotic Brain", "Your Quantum Brain", "The Randomness of Quantum Particles Is Very Small", "The Quantum Randomness Tends to Average Out" and "Did We Get It Right?".	the cup: you reach for it or you do not, and the one outcome is chance seen from outside and choice seen from inside; Lorenz's two weathers; the authors' dare to look away; a Geiger counter beside a lump of ore; Laplace's intellect; a player piano and the hiss of a radio; two laboratories with dials; a cable stronger than any one of its strands; a snowy slope; an old friend's usual order at a familiar restaurant; a program that shrinks files; a hand on a light switch

This book	Cham and Whiteson	The pictures here
27. Do We Live in a Computer Simulation?	*Frequently Asked Questions About the Universe*, ch. 14, "Why Even Consider This?", "Brain in a Vat", "Shortcut #3", "Could You Tell?" and "Why Build It?"; ch. 10, "Physics in Your Brain".	the cup: a cup on a screen cools only as the program says; Bostrom's count of minds, 2003; the authors' video game, brain in a vat and traffic simulation; curls of steam that repeat; a printed list of numbers read from its last line up; a friend telling you a story you have never heard; the Geiger counter of Chapter 26, beside a click timed by a rule; a prison cell; the digits of pi and a list that misses a number; an orrery; two pebbles dropped into a still pond; three slits
28. Is an Afterlife Possible?	*Frequently Asked Questions About the Universe*, ch. 13, "The Physics of Heaven", "Transporting You to Another Location", "Existing in Another Location Forever", "Heaven on Earth", "A You Beyond You" and "Ripples Through Time".	the cup: its warmth goes into the room, kept whole and never found again as the cup's; Hawking's encyclopedia, Dublin, 2004; the sorting bins of a post office; a road that runs off the edge of a map; children's hopscotch, its chalk court washed away each night and the game played again by the same rules; a stadium's roar heard from a hill; a house that would hold every world as a room; pi and a wheel

This book	Cham and Whiteson	The pictures here
29. How Will the Universe End?	*We Have No Idea*, ch. 3, "What This Means about the Future". *Frequently Asked Questions About the Universe*, ch. 12, "The Big Crunch" and "The Heat Death"; ch. 4, "Higgs Field Collapse" and "So Are We Toast?".	Thomson's paper, Edinburgh, 1852; the night sky far from town; a walker who carries a skyline; a building of years; a ball thrown upward; a steady breeze and a rising wind; raisin bread; a liquid kept from boiling; a hilly country of valleys; the bottom of a wine bottle; the census of a new country; three strands of one rope
30. Will Time Ever Stop?	*Frequently Asked Questions About the Universe*, ch. 12, the chapter as a whole, with "The Heat Death" and "The End of Our Time". *We Have No Idea*, ch. 8, "Question #5: Will Time Ever Stop?".	the cup: it cools toward the warmth of the room, halving the difference again and again, with no last step; Clausius's two sentences, Zürich, 1865; Zeno's runner; the authors' river of meta-time and paused film; spinning until dizzy, and a gyroscope; a watcher under an empty sky; a head and a book in an empty universe

This book	Cham and Whiteson	The pictures here
31. How Long Will Humanity Survive?	*Frequently Asked Questions About the Universe*, ch. 4, opening, "Immediate Threats" to "Higgs Field Collapse", "Infinity" and "So Are We Toast?"; ch. 9, "Rocks in Space" and "How Likely Is It?"; ch. 19, opening, and the stages from "Fusion Pushes Back" to "The End (Trillions of Years from Now)".	Dyson's lectures, 1978; the authors' ladder of dangers; the rock over Chelyabinsk, 2013; the uranium-lead clocks; a Geiger counter wired to a rocket; a theater filled from the front; Sirius B and a teaspoon of fourteen metric tons; the authors' embers; a room whose walls stay faintly warm; two hydrogen atoms and one particle of light; an ice sculpture in a cold room
32. Will Science One Day Answer Everything?	*We Have No Idea*, ch. 14, "How Can We Know Anything About the Big Bang?" and "The Big Finish"; ch. 16, "How Will We Know If We Are Done?"; ch. 1, closing; "A Conclusion of Sorts", "The Ultimate Mystery".	the cup: a ruler beside it tells you nothing of the coffee's warmth, and nothing is missing from the ruler; Königsberg, September 1930; the authors' pink stuffed kitten; explorers mapping a coast; Bell's score and the electrons of Delft; the ether and two arms at right angles; a child's chain of whys; a walker's horizon, made by the curve of the ground, and no fence at the end of a flat meadow

This book	Cham and Whiteson	The pictures here
33. What Does That Even Mean?	*Frequently Asked Questions About the Universe*, Introduction; ch. 20, "Why Do We Ask Questions?". *We Have No Idea*, ch. 17, "Are We Alone?"; "A Conclusion of Sorts", "The Ultimate Mystery" and "The Testable Universe".	the cup, the last picture of the book: someone at a table finds the coffee warm, here, now and in every epoch where comparison begins again; the authors' in-box of letters; the color of the number seven; a ruler beside the coffee

Where to Go from Here

Each step of this book is worked out in full in another of my books. These are the books the chapters and "For the Specialist" draw on most, the most used first; every book of the collection that I cite in this book is listed under "Books of the Physics Collection" in the References. Each entry says what the book gives the reader of this book and how it reads: in plain words, with some mathematics, or for the specialist.

What Cannot Be; Signals Faster Than Light, Time Travel, Simulation and Determinism, in Plain Words. The requests that name nothing, each walked in full: a signal faster than light, a trip to an earlier time, a world that is a program, and a world fixed in every outcome. It also gives the edge of comparison, the person who is no file, the meaning that cannot be removed from a choice, and the deep why that no measurement reaches. How it reads: plain words.

At the Edge of Reality; From Black Holes to the Big Bang in Ten Dimensions. Chapters 20 to 22 in full: the fall into a black hole to the end of its interior, why the ends of all interiors are one end, and how that end is the turn from which a new epoch begins. It also counts the ten dimensions from what every comparison contains. How it reads: plain words.

The Gravitational Passage; Deriving General Relativity from the Immanent Metaphysics. The derivation of Einstein's theory of gravity from the structure of comparison, with the identity that sets the share of the cosmological constant, the emptying of every observer's sky and the cycle of epochs. How it reads: for the specialist.

What Comes After the Dark; The Far Future of the Universe, in Plain Words. Chapters 29 to 31 at full length: the long emptying of the sky, what becomes of the stars and their ashes, what crosses into the next epoch and what stays behind, and why thinking begins again. How it reads: plain words.

The Story of the Particles; Why Every Particle Is Required, and Why There Are No More. The kinds of particle, level by level: the three carriers, the three generations, the three forces and the arena, the antiparticles, and the reason the list of kinds is closed. How it reads: plain words.

Two Theories, One World; Gravity, the Quantum and the Mistake Behind the Search for One Theory. Chapters 8 and 9 in full: the two great theories as two descriptions of one world, joined side by side, the category error in asking the arena of space and time to come in steps, and why the arena has no least step. It also defines the gravitational size that Chapters 8 and 10 use. How it reads: plain words.

Why These Numbers; The Strengths, Masses and Mixings of the Particles, in Plain Words. Chapter 5 in full: the ladder of halvings, the ceiling on the masses, Koide's relation and the standing of every number the particles carry, with the weakness of gravity read as a distance. How it reads: plain words.

What the Beginning Left Behind; The First Ripples, the First Waves and the One Vacuum, in Plain Words. Chapter 20 in full: the first ripples as the averaged form of the epoch before ours, the flatness of space, and why there was no long inflation, with the shares of the universe set out one by one. How it reads: plain words.

The Unquantized Arena; A Structural Diagnosis of Quantum Gravity and the Measurement Problem. The case, proposition by proposition, that gravitation is not quantized, that each alternative of the matter carries its own smooth geometry, and that physics uses one word for three times. How it reads: for the specialist.

The View from Inside; On the Cosmological Constant and Why Empty Space Weighs So Little. Chapter 3 in full: the cupful of the sea that gives this book its title, and the share of the energy of empty space that a measurement made from inside takes in. How it reads: plain words.

The Weight of Possibility; Dark Matter as a Vibration of Context. The dark matter as a lasting vibration of the six small dimensions of possibility, worked out, with the count that gives six less two divided by pi for the dark matter beside the ordinary. The six of that count are six kinds of shape, and not the six dimensions. How it reads: some mathematics.

The Matter We Know; From the First Atoms to the End of the Periodic Table, in two volumes, *Wholes* and *Gatherings*. Atoms, nuclei and stars built from the kinds of particle: why every electron is found alike, why the levels of every atom are the same in every star, how the stars made the elements of life, and what holds a white dwarf up. How it reads: plain words.

The Basis of Physics; Nineteen Essays on the Structural Limits of Physical Law. Essays that read the physics already established through the structure of comparison, among them the edge of comparison, what physics cannot reach, and the deep why. How it reads: plain words.

Side by Side; Twenty-Four Models of the Universe, in two volumes. This book's account set beside twenty-four other accounts of the universe, among them those of Niels Bohr, Roger Penrose and Max Tegmark, each with a register of where the two agree and where they part, and the dated record of the account's predictions. How it reads: some mathematics.

Causality Without Determinism; Free Will, Measurement and Mind. Chapter 26 in full: causation without determinism, the free will theorem, and the one event that is chance seen from outside and choice seen from inside. It also gives the bound triple of Chapter 27. How it reads: plain words.

The Weight of the Unseen; Dark Matter in Questions and Answers. Chapters 1 and 2 as questions and answers: what the dark matter is, why only its weight shows it, and how the shares of the universe are weighed. How it reads: plain words.

Measurement; The Steps from Comparison to Physics. How the act of comparison becomes the units and measures of physics, and why a simulated world with someone in it is a region of the one world. How it reads: plain words in its first part, and for the specialist in its second.

The Last Turtle; Essays from Comparison and the Incommensuration Theorem to Causation, the Arena and the Limits of Computation. Essays that carry the act of comparison to time, causation, the arena, the line between the classical and the quantum, and the limits of computation, among them the essay on what a copy of a person cannot carry. How it reads: plain words.

The Coming of the Kinds; How the Particles Came to Be After the Big Bang. Chapter 19 in full: why the laws of the kinds hold matter and antimatter even, why no process among the kinds makes the excess of matter, and why the excess is a residue with one sign everywhere. How it reads: plain words.

The Compactification; Initial Conditions, the Perturbation Spectrum, and the Gravitational Wave Signature. The state that the turn sets, and the first ripples it carries, worked out in full. How it reads: for the specialist.

Physics Is Not Math; Metaphysics, Physics, Computation and Mathematics, and Why Their Order Cannot Be Otherwise. The order in which metaphysics, physics, computation and mathematics rest on one another, with the value that lands, the grade that closes an inquiry, and the orrery that is not the solar system. How it reads: plain words.

Why Time Travel Is Not a Concept; A Meditation on the Three Times and the Cauchy Horizon. Chapter 14 in full: the three readings of a trip back in time, and why, in the sense in which the phrase is used, it names no concept. How it reads: some mathematics.

An Immanent Metaphysics. The whole system, in aphorisms, from which every chapter of this book is drawn. How it reads: for the specialist.

Home in the World; The Immanent Metaphysics for Readers of Carlo Rovelli. The companion of this book, on the same ground, for readers of Carlo Rovelli: comparison, the floor beneath it, and a life that is rare in the universe and is here. How it reads: plain words.

Jorge Cham and Daniel Whiteson close *We Have No Idea* with a bibliography, "How Do You Know This Stuff? And Where Can I Learn More?", which gives, chapter by chapter, the measurements and papers behind

their numbers. For further reading they recommend three books: Max Tegmark's *Our Mathematical Universe* (Knopf, 2014), Sean Carroll's *From Eternity to Here* (Dutton, 2010), which they also name for the arrow of time, and Carlo Rovelli's *Seven Brief Lessons on Physics* (Riverhead, 2015).

What the Coming Measurements Will Find

In this appendix I gather the measurements still to come that bear on the account of this book. For each coming measurement, the appendix says what will be measured and what this account says the measurement will find. The predictions of this account are published together in one dated record, *The Registered Predictions of Physics from Comparison; A Dated Record*, of 1 November 2026, under the DOI https://doi.org/10.67291/RQQS3025. The record is reproduced whole as Appendix B of my book *Side by Side*, Volume One. The record states forty-two predictions. Each prediction is argued in one of my physics books. For each prediction, the record names the book, chapter and section where the prediction is argued. Each entry below carries the number that the record gives the prediction. Each entry is placed under the chapter of this book whose question the prediction bears on, and the chapters come in their order. Where a chapter's question bears only on predictions already placed under an earlier chapter, the entry for that chapter names those predictions by number and says what each prediction states. The appendix "For the Specialist" gives the measurements made so far, each with the paper that reported the measurement.

The record fixes in advance when a measured result counts. When two independent kinds of measurement both establish a result at five standard deviations, the result counts. A *standard deviation* is the usual measure of the uncertainty of a measurement. A standard deviation is the typical distance by which chance puts a measurement off the true value. Chance alone would put a result five standard deviations from the true value less than once in a million tries. The record asks for a second, independent kind of measurement because any one method can have an error of its own. When a measurement differs from a prediction by less than five

standard deviations, the measurement does not count by the rule of the record. The record reports the measurement as, in the record's words, a measurement of interest. Where a prediction says that something will not be found, every search for that thing bears on the prediction, and this account says that no search will find the thing. The sign $\pm$, read "give or take", gives the uncertainty of a value.

Chapter 1. What Is the Universe Made Of?

Prediction 7. The matter fraction is 0.311

This account says that, in the present epoch (the era of the world in which we live), matter makes up a fraction 0.311 ± 0.001 of the energy of a universe whose space is flat, with no overall bending. The cosmological constant carries the remaining 0.689 of the energy. The cosmological constant is the one constant term in Einstein's equations of gravity, and Cham and Whiteson call the cosmological constant dark energy. The fraction 0.311 is the *matter fraction*: the share of the energy of the universe that matter, ordinary and dark together, carries today. The value 0.311 comes from an identity, an exact equation, between two quantities: the particle horizon, which is the edge of everything whose light has reached us, and the energy of the vacuum, which is empty space at its lowest energy. Two quantities cancel from the identity, the Hubble constant (the present rate at which the universe grows) and the Planck mass (the mass set by the strength of gravity), so the identity fixes a pure number, a number with no unit. The ± 0.001 is the spread that comes from the measured density of radiation. The record states the same prediction in three more ways, each through one more measured quantity. The first way is the age of the universe at which the cosmological constant is measured: 0.792, in the unit of time that the cosmological constant sets (the de Sitter time). The second way is a Hubble constant of 67.8 ± 0.3 kilometers per second per megaparsec, computed with the matter density measured from the microwave background, where a megaparsec is about 3.26 million light-years. The microwave background is the oldest light in the sky. The third

way is a vacuum energy density of 2.56×10^{-47} GeV^4. The vacuum energy density is computed with the measured radius of the particle horizon. An electron volt is the energy one electron gains in crossing one volt. A GeV is a billion electron volts, a little more than the mass of one proton. Particle physics uses the GeV as its unit of energy and of mass. Particle physics states an energy per volume in GeV^4, read "GeV to the fourth". In the record's words, "These are one test, stated four ways".

Four instruments will make the coming measurements of the matter fraction: the Dark Energy Spectroscopic Instrument (DESI), the Euclid space telescope, the Vera C. Rubin Observatory and the Nancy Grace Roman Space Telescope. This account says that all four instruments will find 0.311. Two measurements made so far lie on either side of 0.311. The microwave background gives a value above 0.311, and the baryon acoustic oscillations measured by DESI give a value below 0.311. The *baryon acoustic oscillations* are the preferred spacing between clumps of galaxies that sound waves left in the young universe. The predicted 0.311 lies between the two measured values, and this account says that the coming surveys will converge on 0.311. This account predicts the Hubble constant only through the matter fraction. So the coming measurements of the matter fraction also decide the value of the Hubble constant. This account says that the coming measurements of the matter fraction will find a Hubble constant of 67.8 ± 0.3. Astronomers also measure the Hubble constant with the distance ladder of Cepheid variable stars. The distance ladder is a chain of distances built outward, step by step, from pulsing stars of known brightness. The distance ladder gives a value of the Hubble constant that differs from 67.8, and the coming measurements of the matter fraction will decide between 67.8 and the value from the distance ladder.

Prediction 16. The ratio of the dark matter to the ordinary matter is $6 - 2/\pi$

This account says that the density of the dark matter is $6 - 2/\pi = 5.3634$ times the density of the ordinary matter. This account also says that the ratio of the two densities is the same at every time since helium formed. The symbol π, read "pi", is the ratio of a circle's circumference to

its diameter. Prediction 16 also gives the share of the ordinary matter in the cold matter as $1/(7 - 2/\pi) = 0.15715$. The cold matter is the ordinary and the dark matter together. In all the matter, the lightest neutrinos included, the ordinary matter has a share of 0.15644. When the matter fraction of Prediction 7 is used, the ordinary matter carries 0.0486 of the energy of the universe. The dark matter carries 0.2608. The record names the measurement that will decide Prediction 16: "A second, independent kind of measurement of the two densities, at the precision of the microwave background". The Simons Observatory is a telescope in Chile that maps the microwave background, and the observatory's maps, together with the maps of the Planck satellite, would measure the ratio of the two densities to about 0.6 percent. This account says that the two sets of maps will find 5.3634. Some analyses add the baryon acoustic oscillations of DESI to the microwave background and give a ratio that differs from 5.3634. The combined analyses come from one kind of measurement. The measurement that decides Prediction 16 is the second, independent kind of measurement that the record asks for.

Prediction 17. The coefficient shared with the cosmological constant is 1

This account says that one coefficient enters both the identity of Prediction 7 and the ratio of Prediction 16: how sharply the six small dimensions of possibility bend, stated in Planck units. The six small dimensions of possibility are six further dimensions of the world, beyond the three of space and the one of time. The six small dimensions are held far too small to see. *Planck units* are the units that the strength of gravity, the speed of light and the quantum of action set. This account says that both measurements, of the matter fraction and of the ratio, will find the coefficient equal to 1. The six small dimensions have two pieces, each with its own radius. My book *The Gravitational Passage* gives the ratio of the two radii as the square root of 6, about 2.45, and with the radii in that ratio the coefficient is 1 and the ratio of Prediction 16 is exactly $6 - 2/\pi$. Two measurements together decide Prediction 17: the measurement of Prediction 16, and an independent measurement of the matter fraction.

Prediction 18. The amplitude of clustering is 0.823

The amplitude of clustering is a measure of how strongly the matter of today's universe is gathered into clumps. This account computes the amplitude of clustering today from the matter fraction of Prediction 7 and the ratio of Prediction 16. The computed amplitude is 0.823 ± 0.006. The calculation also uses two values that the Planck satellite measured. The two values are the strength of the first ripples of density and the slight tilt of the ripples. The first ripples of density are the faint departures from evenness with which an epoch begins, and their tilt is a slight leaning of their strength toward long or toward short lengths. If the calculation takes a Hubble constant of 67.8, the amplitude is 0.827 ± 0.007. In this account the dark matter is made of gyrations: lasting vibrations of the six small dimensions of possibility. The gyrations cluster exactly as cold dark matter clusters in the standard account, the account of the universe that most astronomers use. Four kinds of measurement give the amplitude. The first kind is the lensing of the microwave background: the bending of the background's light by the matter the light passes. The second kind is the surveys of the shapes of distant galaxies, such as the Kilo-Degree Survey and the Dark Energy Survey. The third kind is the motions of galaxies. The fourth kind is the counts of clusters of galaxies, such as the counts made with the eROSITA X-ray telescope. This account says that each of the four kinds of measurement will find 0.823. Three measurements made so far agree with 0.823: the lensing of the microwave background, the complete Kilo-Degree Survey and the motions of galaxies. Two measurements made so far differ from 0.823. The two are the final analysis of clustering and lensing by the Dark Energy Survey, and the clusters counted by eROSITA. The two measurements lie on opposite sides of 0.823, and the two differ from each other. This account says that finer measurements of all four kinds will find 0.823.

Prediction 19. The dark matter acts only through gravity

This account says that the dark matter acts on everything else only through gravity, so every search for any other effect of the dark matter will find nothing, at any sensitivity. No underground detector will find dark matter scattering. No search will find light or particles given off by the dark matter, and no collider will make dark matter.

Prediction 20. The dark matter does not decay

I say that the dark matter lasts. As the universe grows, the density of the dark matter falls exactly as the density of matter falls, and the ratio of Prediction 16 is the same now as when the microwave background was released. The gyrations of each epoch are made at that epoch's own turn, the limit at which the epoch begins. No gyration passes from one epoch into the next. The history of the expansion will be measured more closely by coming maps of the microwave background, such as the maps of the Simons Observatory, and by coming surveys of galaxies, such as DESI and Euclid. The history of the expansion shows how long the dark matter lasts, so the maps and surveys will also measure the lifetime of the dark matter (*What Comes After the Dark*, Appendix B). I say that, at every lifetime that the maps and surveys can measure, the dark matter will be found stable. The physicist Roger Penrose describes the universe, in his conformal cyclic cosmology, as an endless sequence of eras, which he calls aeons. Penrose joins the remote future of each aeon to the beginning of the next aeon by a change of scale. When a change of scale keeps the shapes of things while every size changes, the change of scale is *conformal* (*What Comes After the Dark*, Chapter 11). The shapes kept include every angle and every path of light. In Penrose's account the dark matter of each aeon must decay within that aeon, so the measured lifetime of the dark matter will also tell this account and Penrose's account apart.

Prediction 21. The dark matter is perfectly cold

This account says that the dark matter clumps on every small scale: the dark matter's own motion sets no smallest scale of structure. The faintest satellite galaxies of our Galaxy are the small galaxies that orbit our Galaxy, and counts of the faintest satellite galaxies measure the smallest scale on which the dark matter clumps. *Strong lensing* is the bending of a distant galaxy's light into arcs and several images by the mass in front of the galaxy. Strong lensing shows small clumps of mass, and the small clumps also measure the smallest scale on which the dark matter clumps. This account says that each finer count of the faint satellite galaxies, and each finer map of strong lensing, will find clumps on every smaller scale that the count or the map can measure.

Prediction 22. The gyrations have about the Planck mass

This account says that the dark matter comes in gyrations whose mass is of the order of the Planck mass. A small sphere of two dimensions is one of the two pieces of the six small dimensions. The parity of the sphere is the sign that a vibration takes when each point of the sphere trades places with the opposite point. When the vibration of a gyration reverses sign under the exchange of opposite points, the gyration is called *odd*. The lightest odd gyration does not decay, because of the parity of the sphere. When a calculation is carried in powers of a small number, terms *of first order* hold the small number once, and terms *of second order* hold the small number multiplied by itself. First order is the order of the calculation that includes the first quantum correction. To first order, the lightest odd gyration has about 0.6 Planck masses. At the classical level, with no quantum correction, the lightest odd gyration has the square root of 2 Planck masses, about 1.7×10^{19} GeV. Since the dark matter is 5.3634 times as dense as the ordinary matter (Prediction 16), the two calculated masses give about one gyration for every 1.5 to 3.4×10^{18} baryons. Baryons are the particles of three quarks, such as the proton and the neutron. The re-

cord states that Prediction 21, perfectly cold dark matter, depends on the mass of the gyrations, so the measurements of the smallest clumps of dark matter also bear on the mass of the gyrations.

Prediction 24. A galaxy feels the field of a larger one only through its tide

Picture a galaxy falling freely in the gravity of a larger galaxy. I say that the smaller galaxy feels the gravity of the larger galaxy only through the tide of the larger galaxy. The tide is the difference of the larger galaxy's pull from one side of the smaller galaxy to the other. Modified Newtonian dynamics is a proposed change to the law of gravity at small accelerations. Modified Newtonian dynamics predicts an external field effect: a change, beyond the tide, in how the stars of the smaller galaxy move. I say that the external field effect will not be found. The motions of stars and gas test Prediction 24: inside a galaxy that falls in the field of a larger galaxy, the motions of stars and gas show how the larger galaxy's gravity acts on the smaller galaxy.

Chapter 3. What Is Dark Energy?

Prediction 8. The equation of state of the vacuum energy is exactly −1

This account says that the energy of the vacuum has an equation of state of exactly -1, at every epoch. The *equation of state* of a kind of energy is the ratio of the energy's pressure to its energy density, and an energy that does not change as the universe grows has an equation of state of exactly -1. So the vacuum energy has an equation of state of -1 today, and the rate at which the equation of state changes is 0. The horizon of the measurement fixes the cosmological constant once, as the constant term of one geometry, and Einstein's field equations do not let a constant term vary from place to place or from epoch to epoch. No changing field drives the speeding up of the expansion. Quintessence is one proposed kind of changing field, and neither quintessence nor a field of any other kind drives the speeding up.

The Euclid space telescope, the Vera C. Rubin Observatory and the Nancy Grace Roman Space Telescope will measure the history of the expansion and the growth of structure. DESI continues its survey of galaxies (*What Comes After the Dark*, Appendix B). This account says that the three telescopes and DESI will find the equation of state to be exactly −1. One family of combined analyses reports a departure from −1: the final analysis of the Dark Energy Survey, combined with DESI and the microwave background. The record says of the reported departure: "The reported departure from −1 will not be confirmed".

Chapter 4. What Is the Most Basic Element of Matter?

Prediction 26. What is found of color, charge and spin

This account says that color, the charge of the strong force, is found only in singlets: combinations of particles whose colors cancel. In quantum theory's description, a superposition is a combination of alternatives. No superposition of states of different electric charge is ever found. Weak isospin, the charge of the weak force, is free on both counts. Unlike color, weak isospin is found outside singlets, and unlike the states of electric charge, the states of weak isospin mix in superpositions. A spinor is the state of a particle of half-whole spin, such as the electron. When a spinor is turned through a full circle of 360°, the spinor reverses its sign, and when the spinor is turned through two full circles, 720°, the spinor is restored. Fermions are particles of matter, such as electrons and quarks, and two fermions of one kind never share a state, while any number of bosons, such as the particles of light, can share one state. Every particle has an antiparticle. The octonions are a number system of eight dimensions, and the exceptional Jordan algebra is an algebra built on the octonions. No physical system has a sector described by the octonions or by the exceptional Jordan algebra. This account says that every measurement of color, charge and spin will find the properties that Prediction 26 lists.

Prediction 30. No kind of particle beyond the closed list

This account says that the kinds of particle form a closed list: the kinds of the Standard Model, the established theory of the kinds of particle and of the three forces among them (the strong, the weak and the electromagnetic), with a right-handed neutrino in each generation. Every kind of matter occurs three times, alike in charge and in every force and differing in mass. Physicists call each of the three instances of a kind of matter a generation. So no further kind of particle will be found. The record names eleven proposals beyond the closed list. This account says that none of the eleven will be found. The first three proposals are a fourth generation, a partner particle of supersymmetry (a proposed symmetry that gives every known particle a partner), and an X or Y boson or a leptoquark (proposed particles that join quarks to leptons). The next three proposals are a W′ or a Z′ (heavier copies of the W and the Z), a second Higgs boson, and an axion (a proposed light particle). The seventh proposal is a species of dark matter, and the eighth is a sterile neutrino (a neutrino the weak force does not touch) beyond the right-handed component of each neutrino. The last three proposals are a dark photon, a mirror particle and a hidden sector. All three are proposed additions that would touch ordinary matter weakly or not at all. In the record's words, "The next collider will not find a new species". At higher energies, colliders can find heavier composites (bound states of the known kinds), but no new kind. The searches that bear on Prediction 30 are made at colliders, in underground detectors and in astrophysics.

Prediction 31. Exactly three generations

This account says that there are exactly three generations, and that no fourth generation exists at any mass. Every search for a fourth generation bears on Prediction 31. This account says that each search will find no fourth generation.

Prediction 35. No new particle in any loop

This account says that no new particle enters any loop, because no particle exists beyond the Standard Model. A loop is the brief passing presence of particles inside a process, which shifts the rate or the strength of the process. The anomalous magnetic moment of the muon (the electron's heavier copy) is the small excess of the muon's magnetism over its simplest value. A new sector would be a set of particles beyond the closed list. No new sector contributes to the anomalous magnetic moment of the muon. In the decay of a bottom quark into a strange quark and a pair of charged leptons, the coefficients that a new sector would add are zero. Physicists analyze all the measured decays of the bottom quark together in global fits. The global fits report tensions: differences from the Standard Model. This account says that the tensions will resolve within the Standard Model. The charged leptons are the electron, the muon and the tau. The charged leptons change flavor, turning from one into another, only through loops of the three light neutrinos. Each of the three light neutrinos has a Dirac mass, a mass that joins two components of one state. The *branching ratio* of a muon into an electron and a photon is the fraction of muon decays that take that path. So a muon decays into an electron and a photon with a branching ratio of order 10^{-55}. A tau decays into a muon and a photon with a branching ratio of order 10^{-54}. A muon decays into three electrons with a branching ratio of order 10^{-55}. Inside a nucleus, a muon converts to an electron at a rate of order 10^{-52} to 10^{-51} of the rate at which the nucleus captures muons. In the record's words, "No signal of charged-lepton flavor violation will be seen at any foreseeable experiment".

Chapter 5. Are the Particles' Numbers Just Arbitrary?

Prediction 37. Ceilings and relations among the masses

This account says that every particle of matter has a mass at or below a ceiling of 174.1036 GeV, which is the vacuum value of the Higgs field divided by the square root of 2. The Higgs field is the one field that fills all

of space with a settled value and gives the particles their masses. The vacuum value of the Higgs field is the strength that the Higgs field keeps everywhere in empty space. The condensate is the one steady value into which the Higgs field settles everywhere in space. Each particle has a coupling to the condensate, a number that measures how much of the particle the settled Higgs field takes hold of. The ceiling holds because every coupling to the condensate lies between 0 and 1. The charged leptons obey Yoshio Koide's relation: the sum of their three masses is two thirds of the square of the sum of the square roots of the masses. The quarks carry color and the charged leptons do not, so this account says that the quark masses in general will not obey Koide's relation. The neutrino masses are in the normal order. In the normal order, the lighter pair of neutrinos is the pair that shares the electron's flavor most. Three experiments will measure the order of the neutrino masses: JUNO, the Jiangmen Underground Neutrino Observatory in China, and the neutrino-beam experiments T2K in Japan and NOvA in the United States. I say that the three experiments, JUNO, T2K and NOvA, will find the normal order of the neutrino masses.

Prediction 38. The neutrino masses: two readings, decided by their sum

This account has two routes to the three neutrino masses, and my book *The Measures of the Kinds* sets out both routes. Chapter 5 introduced the ladder of halvings. The ladder places each particle of matter a counted number of halvings, or factors of two in mass, below the top quark. On the count route, the neutrinos step down the ladder of halvings by the charged leptons' step, two and a quarter halvings per generation. On the Koide route, the neutrinos step down by one and a half halvings per generation. The count route is placed on the ladder from the measured mass of the tau alone, and on the count route the three masses are 15.149, 17.433 and 52.366 meV, with a sum of 84.95 meV. An meV is a thousandth of an electron volt. The splittings are the differences of the squares of the masses, the quantities that oscillation experiments measure. The count route also predicts both splittings: 7.441×10^{-5} eV^2 and 2.5127×10^{-3}

eV^2. The unit eV^2 is read "electron volts squared". The Koide route takes both splittings as inputs. On the Koide route, the three masses are 0.370, 8.726 and 50.211 meV, with a sum of 59.31 $\pm$ 0.25 meV. A variant of the Koide route takes the larger splitting as input and fixes the lightest mass at 0.362 meV: the electron's mass times the fourth power of the strength of light, divided by four. The variant predicts the smaller splitting as (7.470 $\pm$ 0.040) $\times$ 10^{-5} eV^2. The variant gives a sum of the masses of 59.22 meV. The beta decay mass is the effective mass of the electron neutrino, which the energy spectrum of beta decay measures directly. The beta decay mass is about 17.6 meV on the count route and about 9 meV on the Koide route. Both routes give the normal order, three nonzero Dirac masses, and no neutrinoless double beta decay.

The sum of the neutrino masses decides between the two routes. The sum is to be measured at the matter fraction and Hubble constant of Prediction 7, with an equation of state of -1. A measurement of the beta decay mass needs no cosmological analysis. If a measurement of the beta decay mass has an uncertainty of about 3 meV, the measurement separates the two routes by about three standard deviations.

Prediction 39. Lepton mixing: two families, decided by the quadrant of the lepton phase

Lepton mixing is the way the three neutrinos of definite mass combine into the three neutrinos of definite flavor, the neutrinos that go with the electron, the muon and the tau. Lepton mixing is described by three mixing angles and by the lepton phase. The three mixing angles are θ_{12}, θ_{23} and θ_{13} (read "theta one two", and so on). The lepton phase is an angle that measures how differently neutrinos and antineutrinos mix. This account has two families of lepton mixing, and *The Measures of the Kinds* sets out both families. The carry family carries over to the mixing of the leptons the right angle that Prediction 41 gives the triangle of quark mixing. The segment family ties the lepton phase to the quark phase, the angle that measures how differently quarks and antiquarks mix. When the carry family is computed at the measured θ_{13}, the lepton phase lies in the

fourth quadrant (between 270° and 360°), at 281.37° ± 0.16°, and from the carry alone the lepton phase is 281.96° ± 0.59°. On the carry family, the square of the sine of θ_{12} is 0.3185 ± 0.0005, and the square of the sine of θ_{23} is 0.5444, in the upper octant (above 45°). The Jarlskog invariant is the single measure of the difference between matter and antimatter in the mixing. On the carry family, the Jarlskog invariant has magnitude 0.0328. On the segment family, the lepton phase lies in the third quadrant (between 180° and 270°), at 203.88° ± 1.43°, with θ_{23} = 43.34° in the lower octant and a Jarlskog invariant of magnitude 0.0134. The kernel triangle is the right triangle of sides three, four and five, whose numbers Chapter 5 found in the ladder of masses. The kernel triangle gives the square of the sine of θ_{13} as 1/45. *The Measures of the Kinds* counts 1/45 as a measured agreement. When the value 1/45 is used, the carry family gives the square of the sine of θ_{12} as 7/22.

If the lepton phase is measured with a resolution of 25.8°, the measurement separates the two families at three standard deviations. Hyper-Kamiokande, a large water detector in Japan, achieves a resolution of 25.8° after ten years of running from the end of 2027. The Deep Underground Neutrino Experiment (DUNE) in the United States achieves a resolution of 25.8° at an exposure of 600 kiloton megawatt years. The exposure is the mass of the detector times the power of the beam times the time of running. JUNO tests directly the value 0.3185 that the carry family gives for the square of the sine of θ_{12}. The kernel triangle also gives a second value for the square of the sine of θ_{13}, 1/48, and both 1/45 and 1/48 lie within two standard deviations of the measured value. If the square of the sine of θ_{13} is measured to ±0.0003, the measurement separates 1/45 from 1/48 at 4.6 standard deviations.

Prediction 40. The mass of the tau: two readings

Koide's relation gives the mass of the tau, the heaviest charged lepton, as 1776.969 MeV, from the measured masses of the electron and the muon, where an MeV is a million electron volts. The step of the ladder is the number of halvings taken once for each generation down. The tau mass

can also be read back from the measured vacuum value of the Higgs field, with the step of the ladder written as a product (the product step of *The Measures of the Kinds*). When the tau mass is read back from the Higgs field with the product step, the tau mass is 1776.9691 $\pm$ 0.0004 MeV. Chapter 5 placed each charged particle of matter on a ladder of masses, a counted number of halvings below the top quark, and the ladder of masses gives a second reading of the tau mass, 1777.146 MeV. A precision of $\pm$0.045 MeV is stated for the tau mass at the Belle II experiment in Japan. A tau mass measured to $\pm$0.045 MeV separates Koide's relation from the ladder at 3.9 standard deviations.

Prediction 41. The quark unitarity triangle has a right angle

The mixing of the three generations of quarks can be drawn as a triangle, called the unitarity triangle. The angles of the unitarity triangle are named α, β and γ ("alpha", "beta" and "gamma"). This account says that the unitarity triangle has a right angle: $\alpha = 90°$, with $\beta = 22.5°$ ($\pi/8$) and $\gamma = 67.5°$ ($3\pi/8$). If the triangle has a right angle, the quark phase (the angle that measures how differently quarks and antiquarks mix) is 67.15° $\pm$ 0.70°, twice as precise as the present measurement of the quark phase. *The Measures of the Kinds* gives two further readings of the triangle beside the right angle, from a family of mass textures (patterns among the quark masses) that *The Measures of the Kinds* holds as a hypothesis. One further reading has $\alpha = 92.0°$ with $\gamma = 65.2°$, and the other has $\alpha = 94.0°$ with $\gamma = 63.5°$. All three readings agree on β within 0.3°. The Cabibbo angle is the largest mixing between the first two generations. The Cabibbo angle has two laws, which give the size of the mixing of the up quark with the strange quark as 0.22495 or 0.22410, and at most one of the two laws is exact. If α is measured directly to about 2°, or γ to about 1°, the measurement tells the three readings of the triangle apart. The two Cabibbo laws can be told apart by a measurement of the size of the mixing of the up quark with the strange quark to $\pm$0.00043.

Prediction 42. The strength of color, the W and Z, the Higgs and the top

The strength of color is the coupling of the strong force at the mass of the Z boson. My book *The Strengths of the Kinds* solves the laws of the forces without taking the strength of any force from measurement. *The Strengths of the Kinds* calls the solution the second closure. The second closure gives the strength of color as 0.11888 ± 0.00011. The value 0.11888 rests on two values that the second closure takes. The first value is $169/4$, for the level of the couplings. An inverse strength is one divided by the strength of a force. The second value is $21/4$, for the ratio of the two gaps between the inverse strengths of the three forces at the reduced Planck mass. The *reduced Planck mass* is the Planck mass divided by the square root of eight times π, and the span of halvings that starts at the electron's mass ends at the reduced Planck mass. *The Strengths of the Kinds* also gives the value 5 for the ratio of the two gaps, beside $21/4$. On this account, the W boson, a charged carrier of the weak force, has a mass of 80.3538 ± 0.0045 GeV. The Z boson, the uncharged carrier of the weak force, has a mass of 91.1888 ± 0.0009 GeV. The weak mixing angle is the angle by which two neutral carriers of force mix to give the photon and the Z boson. On this account, the weak mixing angle at the mass of the Z has a sine whose square is 0.231164 ± 0.000036. At the simplest order of the calculation, the Higgs field acts on itself with a strength of $1/8$. The value $1/8$ is derived given an identification that my physics books state. The next order of the calculation comes in four forms, which give the Higgs mass as 125.1715, 125.1888, 125.2064 and 125.2245 GeV. Six readings of the top quark's mass lie between 172.417 and 172.657 GeV. Counted from the electron's mass up to the reduced Planck mass, the number of halvings is a whole number and a small remainder. This account writes the remainder in powers of one small number, about 0.0139. *The Strengths of the Kinds* calls the small number the one mismatch. The remainder is the small number less a term of second order. The term of second order is the small number multiplied by itself and by a coefficient. The ladder of the leptons

gives the coefficient as 3.7160 $\pm$ 0.0012. A *halving* is a factor of two in mass. The ladder of the leptons also gives the gap from the muon to the strange quark as 0.1744 halvings.

A W mass measured to about $\pm$3 MeV tests the second closure. The test of the second closure needs one matching: the calculation that joins the measured masses to the couplings of the theory. The matching must be computed in one computer program, with the W mass as an input. The six readings of the top mass can be told apart by a Higgs mass measured to $\pm$0.03 GeV, or by a top mass measured to 0.02 GeV. A Higgs mass measured to about $\pm$0.005 GeV separates the four forms of the next order of the calculation. Newton's constant is the measured number that sets how strongly gravity acts, and a measurement of Newton's constant makes the count of halvings from the electron to the reduced Planck mass more exact.

Chapter 6. What Is Mass?

The question of mass bears on two predictions placed under Chapter 5. Prediction 37 says that no particle of matter is heavier than 174.1036 GeV, since every coupling to the condensate lies between 0 and 1. Prediction 42 gives the masses of the W, the Z, the Higgs and the top.

Chapter 7. Why Is Gravity So Different from the Other Forces?

Prediction 4. Free fall is universal and nothing shields gravity

This account says that every pair of materials falls alike, at every precision. The Eötvös parameter is the fractional difference in the free fall of two materials. I say that the Eötvös parameter is zero. Antimatter falls with the acceleration of matter. No arrangement of matter shields gravity, and nothing will be found that gravity leaves untouched. Three kinds of coming test bear on the three statements of Prediction 4: tests of the Eötvös parameter, tests of the free fall of antimatter, and searches for a shield against gravity. The proposed Satellite Test of the Equivalence Prin-

ciple (STEP) aims to measure the Eötvös parameter to one part in 10^{18}. This account says that each test and each search will find what the three statements of Prediction 4 say.

Chapter 8. How Does Gravity Meet the Quantum?

Prediction 1. Gravitation entangles two masses

This account says that two masses become entangled when two conditions hold: each mass is held in a superposition of two places, and the two masses are related only through gravitation. A *superposition* of two places is a state in which a body is in two places at once, as quantum theory allows. Two bodies are *entangled* when their states are linked, so that each can be described only together with the other. The entangling phase is the shift that the pull between the masses gives to the timing of their quantum state. The entangling phase equals the phase of the Newtonian interaction of the two masses. In 2017 Bose and colleagues proposed an experiment with two masses of 10^{-14} kilograms. In the proposed experiment, each mass is held in two places 250 micrometers apart, the centers of the two masses are 450 micrometers apart, and the masses are held for 2.5 seconds. For the design of Bose and colleagues, the entangling phase is 0.314 radians. The concurrence is a measure of entanglement that runs from 0 for none to 1 for the most. On the state that the design of Bose and colleagues produces, the concurrence is 0.156. An entanglement witness is a quantity whose negative value shows entanglement, and on the state of the design of Bose and colleagues, the entanglement witness of Chevalier, Paige and Kim is -0.22. For any other design, the entangling phase is the phase that the Newtonian interaction gives for the masses, distances and time of that design.

Ordinary decoherence is the loss of a superposition through contact with the surroundings. An experiment decides Prediction 1 when the experiment holds two masses in superpositions of two places and isolates the masses so well that ordinary decoherence stays well below the entangling phase. I say that an experiment that decides Prediction 1 will find

the two masses entangled. Two rival accounts use one geometry for all the alternatives of the matter: the account of Christian Møller and Léon Rosenfeld, and the classical gravity coupled at random of Oppenheim (2023). The result of the experiment separates this account from both rival accounts. The result also separates this account from collapse driven by gravity (Diósi, 1987; Penrose, 1996), in which gravity itself ends a superposition. The three rival accounts each predict no entanglement. The Planck scale is the scale at which gravity and the quantum meet on equal terms: the scale at which a body's gravitational size equals its quantum size. Linearized quantum gravity is the description of the small waves of the geometry of space and time by quanta. Below the Planck scale, linearized quantum gravity gives the same entangling phase as this account.

Prediction 2. Gravitation alone ends no superposition

This account says that a superposition ends only through a finding, an interaction that registers which alternative is the case. So a superposition does not end of its own accord, however large the mass, however wide the separation of the two placements, and however long the time. There is no decoherence beyond the ordinary kind, and ordinary decoherence is a comparison (an act of finding whether two things are the same or different in some respect) made by some environment. For the masses of Prediction 1, collapse driven by gravity, in the version of Diósi and Penrose, ends the superposition after about 0.012 seconds, while the entangling phase needs 2.5 seconds. Some versions of collapse driven by gravity have a larger effective size, and those versions are still under test. The experiment of Prediction 1 tests the versions with a larger effective size in a new regime, and the experiment also sets a direct bound on any extra way for a superposition to be lost. I say that the experiment of Prediction 1 will find no loss of the superposition beyond ordinary decoherence.

Prediction 3. Gravitation is not quantized

This account says that the geometry has no quantum degrees of freedom of its own beyond the degrees of freedom tied to the alternatives of the matter, where a quantum degree of freedom is an independent way to vary as a quantum system. The Planck curvature is the bending of space at which quantum corrections grow as large as the effects they correct, and below the Planck curvature the small waves of the geometry can be described by quanta. The arena is space and time together: two of the three sides of the setting of every finding. In the description of the small waves by quanta, the quanta are quanta of the description, never quanta of the arena. The *effective theory of gravity* is the description of the small waves by quanta, used below the Planck curvature. The *metric* is the geometry of space and time, and gravitational waves are the small waves of the metric. A cross section is a rate of scattering. Where a measured cross section for gravitational waves departs from the effective theory, this account says that the cross section will not agree with a calculation that quantizes the metric beyond the effective theory. In the record's words, "A detector that registers a gravitational wave in single clicks agrees with the account and does not show gravitation quantized". Every detector of gravitational waves bears on Prediction 3, and so does every measurement of the scattering of gravitational waves.

Prediction 6. Gravitational waves have two polarizations and travel at the speed of light

This account says that gravitational waves travel at the speed of light and carry the two polarizations of a massless field of spin two. The two polarizations are the two patterns in which a gravitational wave stretches and squeezes space across its path. No further polarization and no other speed will be found. When a network of detectors detects gravitational waves, the detection measures the polarizations and the speed of the waves.

Prediction 33. The proton does not decay

This account says that no carrier of force joins color to the weak charge, so no transformation turns a quark into a lepton, and the proton has no route to decay. Baryon number counts each baryon as one and each antibaryon as minus one. The proton is stable because the proton is the lightest whole of baryon number one. Measurement shows that the proton is the lightest whole of baryon number one. The weak force allows rare changes of baryon number, called sphaleron changes, which at zero temperature have a rate of order 10^{-161} and cause no decay of a single proton. A *unifying group* would be a single larger symmetry joining the strong, the weak and the electromagnetic forces into one. No unifying group exists at any scale. The measured strengths of the three forces do not meet at any scale: at no scale do the three strengths become equal.

In the coming searches for proton decay, physicists watch an enormous number of protons for years, in large tanks deep underground. The physicists look for the flash or the track of a proton breaking into lighter particles (*What Comes After the Dark*, Appendix B). A pion is a light particle made of a quark and an antiquark. A kaon is also made of a quark and an antiquark, and one of the two is strange: a strange quark with a lighter antiquark, or a strange antiquark with a lighter quark. If one tank of Hyper-Kamiokande sees no decay in ten years, Hyper-Kamiokande will set the proton's lifetime for the decay into a positron (the electron's antiparticle) and a neutral pion above 7.8×10^{34} years. If one tank of Hyper-Kamiokande sees no decay in ten years, Hyper-Kamiokande will also set the lifetime for the decay into a kaon and an antineutrino above 3.2×10^{34} years. DUNE watches tanks of liquid argon. DUNE will set the lifetime for the decay into a kaon and an antineutrino above about 1.3×10^{34} years if DUNE sees no decay in an exposure of 400 thousand metric tons of argon watched for a year. Each of the three bounds is set at 90 percent confidence, which means that a bound set at 90 percent confidence is too high in at most one search in ten. This account says that Hyper-Kamiokande and

DUNE will both find the proton stable at every lifetime that the two experiments can measure, and that the searches for the carriers of a unifying group will find no such carrier.

Prediction 36. The running of the couplings changes only at known masses

The strengths of the three forces (the strong, the weak and the electromagnetic) change with the energy at which the strengths are measured, and physicists call the change of the strengths with energy the running of the strengths. This account says that the closed list of kinds fixes the rates of the running, and that the rates change only at the masses of the known kinds and of the W and Z. Every measurement of the running bears on Prediction 36, and this account says that each measurement will find the rates changing only at the masses of the known kinds and of the W and Z.

Chapter 10. What Is Space?

Prediction 5. The arena has no least length, area or duration

This account says that the speed of light in vacuum does not depend on the energy of the light through any least step of space and time. A discrete spectrum of area or volume would be a set of separate allowed sizes, with nothing between them. No discrete spectrum of area or volume will be observed, in the echoes of gravitational waves from merging black holes or anywhere else. In the record's words, "Discreteness belongs to the content, the charges and the kinds of particle, and the account predicts it there". Astronomers decide Prediction 5 by timing photons of different energies from many sources, and the astronomers tell a delay made on the way apart from effects at the source because the delay made on the way grows with distance. Prediction 5 is also decided by every observation of the spectrum of area or volume.

Chapter 11. How Many Dimensions Are There?

The six small dimensions of possibility bear on the coming measurements through two predictions. One prediction is placed under Chapter 1, and one under Chapter 2. Prediction 17 says that how sharply the six small dimensions bend is a coefficient equal to 1, shared by the matter fraction and by the ratio of the dark matter to the ordinary matter. Prediction 22 says that the gyrations have about the Planck mass. Prediction 6, placed under Chapter 8, states that the gravitational waves of the arena carry the two polarizations and travel at the speed of light.

Chapter 13. Why Does Time Only Go Forward?

Prediction 28. No world is perfectly deterministic, and no process is perfectly reversible

This account says that some asymmetry of time exists in the laws, and that no process at any scale is perfectly reversible. Reversing an evolution does not remove a finding from the order of findings, whether the evolution is reversed by an inverse in a formalism (the written equations and rules of physics) or by a pulse in a laboratory. No world is purely and completely deterministic. A superdeterministic completion of quantum mechanics would be a theory in which every outcome, the choice of what to measure included, was fixed in advance, and no such theory will be found. The statements of Prediction 28 are exclusions that follow from the structure of comparison, which is what every comparison must contain. A search for departures from the quantum predictions bears on Prediction 25 (the statistics of quantum theory hold), placed under Chapter 26.

Prediction 34. The strong force breaks no reversal; no axion

CP is the exchange of particles with antiparticles together with a mirror reflection. I say that the strong force's own angle of CP violation is zero. The structure needs no axion to cancel the measured angle. That no axion exists is a statement about the list of kinds, and the statement holds for any value of the angle. The kinds break CP through two phases only,

one phase in the mixing of the quarks and one phase in the mixing of the leptons. The list of kinds holds one Higgs field and no other field of its sort. CPT is the exchange of CP with a reversal of time added. CPT holds: a particle and its antiparticle have equal mass, equal lifetime, and equal and opposite magnetic moments. The photon and the gluons are massless. An electric dipole moment is a slight separation of the positive and the negative charge of a particle or an atom along its spin. Two kinds of search bear on Prediction 34: the searches for the electric dipole moments of the neutron and of atoms, and the searches for the axion. This account says that the searches for the axion will find no axion.

Chapter 14. Why Can't I Travel Back in Time?

The question of travel into the past bears on two predictions. The first prediction is Prediction 27, placed under Chapter 15: no signal travels faster than light, and no signal travels backward in time. The second prediction is Prediction 28, placed under Chapter 13: no process is perfectly reversible, and no reversal removes a finding from the order of findings.

Chapter 15. Can We Travel Faster Than Light?

Prediction 27. No signal faster than light, and none backward in time

This account says that a finding changes no geometry, at the place of the finding or anywhere else. The future light cone of a finding is the set of all the later events that can be causally joined to the finding. News of a distant finding enters a record only at an event on or within the future light cone of the finding. Until the news of a distant finding arrives, every local statistic follows quantum theory unchanged, whatever measurement was chosen far away. The boundary of comparison is the edge that the speed of light sets to the events a finding can be compared with. No signal crosses the boundary of comparison, and no body arrives anywhere outside its own light cone. The probabilities of the outcomes of a preparation do not depend on which test is chosen later. No later finding comes to pre-

cede an earlier finding. On this account, travel within the light cone is not excluded. On this account, nothing excludes the recession of distant galaxies faster than light, because the recession of distant galaxies is a growth of the arena between the galaxies and not a signal across the arena. Every experiment that compares findings made far apart bears on Prediction 27. This account says that each experiment will find what Prediction 27 states.

Chapter 16. Who Is Shooting Superfast Particles at the Earth?

The question of the most energetic particles bears on three predictions. The first prediction is Prediction 5, placed under Chapter 10: the speed of light does not depend on the energy of the light. The second prediction is Prediction 15, placed under Chapter 19: the observable universe holds no regions of antimatter. The third prediction is Prediction 30, placed under Chapter 4: no kind of particle exists beyond the closed list.

Chapter 17. What's Stopping Anyone from Traveling Between the Stars?

The question of travel between the stars bears on Prediction 27, placed under Chapter 15: no signal and no body passes outside the light cone, and travel within the cone is not excluded. The question of travel between the stars bears also on the record's statement that this account claims nothing either way about whether travel within the light cone can be built.

Chapter 19. Why Are We Made of Matter, Not Antimatter?

Prediction 15. The excess of matter has one sign everywhere

This account says that matter outnumbers antimatter everywhere in the observable universe, which is everything whose light has reached us. Nowhere do antibaryons outnumber baryons, and the observable universe holds no regions of antimatter. Astronomers search for stars, galaxies or domains made of antimatter. Physicists also search for antihelium

among the cosmic rays, the particles that arrive at the Earth from space. Each of the searches bears on Prediction 15. This account says that each search will find no antimatter.

Prediction 32. The neutrinos are Dirac particles; no neutrinoless double beta decay

This account says that every neutrino mass is a Dirac mass, a mass that joins two components of one state. This account also says that no state of content is its own antiparticle, where the content is what a finding finds. Every neutrino has a mass that is not zero. In neutrinoless double beta decay a nucleus would give off two electrons and no neutrinos, and this account says that neutrinoless double beta decay will not be observed at any sensitivity. The *effective Majorana mass* is the combination of neutrino masses that sets the rate of neutrinoless double beta decay. The effective Majorana mass is exactly zero, whatever the order of the masses. A Majorana mass is a mass that makes a particle its own antiparticle. The seesaw is the proposed mechanism by which a heavy Majorana mass would make the neutrino masses small. There is no seesaw scale and no heavy neutrino. Lepton mixing has one phase and no Majorana phases. The Standard Model has twenty-six parameters, not twenty-eight. The coming searches for neutrinoless double beta decay decide Prediction 32. In the inverted order of the neutrino masses, the heavier pair is the pair that shares the electron's flavor most. The inverted order would give an effective Majorana mass of 15 to 50 meV. This account says that the coming searches will find a null result in the band of 15 to 50 meV and below the band.

Chapter 20. What Happened During the Big Bang?

Prediction 9. Space is flat to the size of the primordial departures

I say that the epoch begins with space flat. This account also says that the curvature of space measured within one horizon is the curvature of the first departures from uniformity, of order 10^{-5}. The first departures from uniformity are the slight unevenness of density with which the

epoch begins. DESI and Euclid measure the curvature of space together with the matter fraction. A curvature of order 10^{-5} is far too small for DESI and Euclid to measure. The *curvature share* is the share that curvature takes in the budget that sets how fast the universe grows. So, for DESI and Euclid, the statement of this account is a curvature share of zero. This account says that the measurements of DESI and Euclid will close in on a curvature share of zero (*What Comes After the Dark*, Appendix B).

Prediction 10. No primordial gravitational waves

A *scalar* departure has one size at each place and no direction. This account says that the first departures of the geometry are scalar, sourced by departures of density, and that waves of the geometry arise from the scalar departures only at second order. In this calculation, the small number is the size of the departures. So a term of second order comes from the departures acting on one another. Chapter 20 pictures the departures acting on one another as ripples acting on ripples. The waves of the geometry stretch and squeeze space across their path, and the waves are called *tensor* departures. The ratio of tensor to scalar power is the power of primordial gravitational waves relative to the power of the first departures of density. Because the waves of the geometry arise only at second order, the ratio of tensor to scalar power is far below 10^{-6}. The polarization of the microwave background is the direction in which the background's light vibrates, and primordial gravitational waves leave a faint twist in the pattern of the polarization of the microwave background. The Simons Observatory and LiteBIRD, a Japanese satellite, will measure the polarization of the microwave background. The record says that the two instruments "will find no primordial tensor signal".

Prediction 11. The primordial departures are adiabatic

This account says that the departures pass from one epoch to the next as one form for every component of the content. So every component departs from uniformity together: the departures are adiabatic. An iso-

curvature mode would be a departure of one component against another. No isocurvature mode separates one component from another, and the dark matter carries no separate pattern of primordial departures of its own. Every finer map of the microwave background bears on Prediction 11.

Prediction 12. The departures are one pattern across the whole sky

I say that the first departures from uniformity are correlated across the whole sky, with nearly the same strength at every length. Independent, unconnected pieces would leave a pattern called white noise, and this account says that the first departures show no white noise. The tilt of the departures is the slight leaning of their strength toward long or toward short lengths. This account fixes neither the amplitude of the departures nor the sign of their tilt. The record names what decides Prediction 12: "Every finer map of the microwave sky".

Prediction 13. No long inflationary phase

Inflation is the brief burst of expansion at the beginning that the standard account uses. This account says that the sky is the same in every direction, and space is flat, because of the turn from the previous epoch, with no inflation. No inflationary phase occurred that was long enough to stretch the lengths observed today from within the early horizon, the greatest distance a signal could have crossed since the turn, to beyond that horizon. Prediction 13 is decided by the measurements of Predictions 9 to 12 together.

Prediction 14. The gravitational waves of an epoch, and their absence where others expect them

The internal space is the six small dimensions taken together as one shape, and this account says that the internal space, settling at the turn, leaves a background of gravitational waves. The background peaks today above about 5×10^{11} hertz (cycles per second), with an energy fraction below about 5×10^{-7}. The energy fraction is stated in the usual measure,

the share of the energy of the universe times the square of the Hubble constant in units of 100 kilometers per second per megaparsec. The count of light species is the number of kinds of light particle that the early universe held, as counted from the microwave background. The ceiling on the energy fraction corresponds to an addition below about 0.09 to the count of light species. In the record's words, "this is a ceiling with no floor, and no existing or proposed instrument reaches that frequency". If the measured scalar power continues to short lengths, the scalar departures induce a second-order background of gravitational waves by acting on one another at second order. In the usual measure, the energy fraction of the second-order background is about 6×10^{-23} to 1.5×10^{-22}. No planned instrument detects the second-order background. LISA, the Laser Interferometer Space Antenna, will find no background from a cosmological phase transition, because the electroweak and strong transitions are crossovers (smooth changes, with no sudden step), and because no further kind of particle exists. Pulsar-timing arrays are networks of radio telescopes that time the steady pulses of distant spinning stars. The pulsar-timing arrays have found a background of gravitational waves. If the scalar power on short lengths is near the measured power, the background found by the pulsar-timing arrays is of astrophysical origin, from pairs of supermassive black holes. The history of the content makes no stable network of cosmic strings, and no domain walls or monopoles from the electroweak breaking, which are defects proposed to form as the early universe cooled. So no background of gravitational waves comes from cosmic strings, domain walls or monopoles. Prediction 14 will be decided by LISA, by the pulsar-timing arrays, and by the count of light species measured from the microwave background.

Chapter 22. What Came Before the Big Bang?

The question of what came before bears on Predictions 9 to 14, placed under Chapter 20: a flat beginning, no primordial gravitational waves, one form for every component, one pattern across the sky, no long inflation,

and the gravitational waves of the turn. The question of what came before bears also on Prediction 20, placed under Chapter 2: the gyrations of each epoch are made at the epoch's own turn, and no gyration passes into the next epoch.

Chapter 23. How Big Is the Universe?

Prediction 23. No short loop exists anywhere in space

This account says that, at every location, every closed path that goes around the universe is at least as long as the diameter of the horizon. A path that goes around the universe cannot be shrunk to a point. The ratio of Prediction 16 rests on a count of one class of closed path in space: the class of the paths that can be shrunk to a point. If a region held a path that cannot be shrunk, the count would be at least two classes, and the ratio of Prediction 16 would be $6 - 1/\pi = 5.682$ or larger. Astronomers search the microwave background for paths around the universe, and each search bears on Prediction 23. This account says that each search will find no path around the universe shorter than the diameter of the horizon.

Chapter 24. Is There Another You?

The question of another you bears on Prediction 10 (no primordial gravitational waves) and Prediction 13 (no long inflationary phase), both placed under Chapter 20, and on Prediction 23 (no short loop anywhere in space, placed under Chapter 23).

Chapter 25. Why Can't We Teleport?

The question of teleporting bears on Prediction 25 (the statistics of quantum theory hold, placed under Chapter 26) and Prediction 27 (no signal faster than light, placed under Chapter 15).

Chapter 26. Are Humans Predictable?

Prediction 25. The statistics of quantum theory hold

This account says that repeated measurements on systems prepared alike settle to the weights of the Born rule, the rule that the probability of a finding is the square of the size of its amplitude. The Born weights hold in every part of the space of states and on the whole of that space. The Born weights hold also in the tests proposed for superdeterminism, which look for departures from those weights. The pairs of paths account for every term of the interference among three paths. The physicists Clauser, Horne, Shimony and Holt wrote the CHSH inequality, which is named for their initials. In a local account of hidden variables, every outcome is settled in advance by properties each particle carries with it. For any local account of hidden variables, the CHSH inequality bounds a sum of four correlations between two parties at 2. Tests of the CHSH inequality reach 2 times the square root of 2 and go no further. Each party has two observables: the two quantities that the party can choose to measure. When two observables give the same result measured in either order, the two observables commute. Whenever either party's two observables commute, the tests stay at 2 or below. Experiments with independent sources find the complex composition of independent systems, which uses the complex numbers (numbers built with a square root of minus one), and not the real composition, which uses the real numbers alone. Every test of the Born weights, of the interference among three paths, of the CHSH inequality and of the composition of independent systems bears on Prediction 25. This account says that each test will show what Prediction 25 states.

Chapter 27. Do We Live in a Computer Simulation?

Prediction 29. A discrete rule shows itself to a fine enough measurement

This account says that, for any one fixed discrete rule offered as the foundation of physics, a sensitive enough measurement tells the statistics of the rule from the statistics of the world. A sensitive enough measurement is one finer than the least step of the rule. Only a theory of the conjugate kind reproduces the established findings of physics at the foundation. A theory of the conjugate kind is a theory whose rules and whose findings have opposite characters, such as a continuous evolution paired with discrete findings. Every measurement finer than the least step of a proposed rule bears on Prediction 29.

Chapter 28. Is an Afterlife Possible?

The question of what remains bears on Prediction 28 (no process perfectly reversible, and no reversal that removes a finding from the order of findings, placed under Chapter 13).

Chapter 29. How Will the Universe End?

The course of the far future bears on five predictions placed under earlier chapters. The five are Prediction 7 (the matter fraction, 0.311), Prediction 8 (the equation of state, exactly -1, at every epoch), Prediction 9 (space flat), Prediction 20 (the dark matter does not decay) and Prediction 33 (the proton does not decay).

Chapter 30. Will Time Ever Stop?

The question of the end of time bears on Prediction 28 (some asymmetry of time exists in the laws, and no process is perfectly reversible, placed under Chapter 13).

Chapter 31. How Long Will Humanity Survive?

The question of how long anything lasts bears on Prediction 19 (the dark matter acts only through gravity, placed under Chapter 2) and Prediction 33 (the proton does not decay, placed under Chapter 9).

Chapter 32. Will Science One Day Answer Everything?

The question of what science can answer bears on the record's rule of decision, stated at the head of this appendix: a result counts when it is established at five standard deviations by at least two independent kinds of measurement.

What the Record Covers

The record also states the scope of its predictions, so that each measurement is counted where this account makes a claim. This account has four measured inputs: Newton's constant, the strength of light, the strength of color and the vacuum value of the Higgs field. The cosmology of this account also uses the measured density of radiation. The record states the values of the particles in two accounts, the working account and the closure account, and both accounts are true. In the working account, the measured inputs also include the mass of the electron, which is the unit, and two starting places on the ladder of halvings. A starting place is where the heaviest member of a family stands on the ladder, and the two starting places are found from the measured masses of the bottom quark and the tau. In the closure account, the chain of values runs from the mass of the electron alone to the vacuum value of the Higgs field, the mass of the top quark and the mass of the Higgs boson. The measured strength of color is an input of the working account. The second closure solves the laws of the forces without the measured strength of color, and the second closure gives the value 0.11888 of Prediction 42. This account predicts the Hubble constant through the matter fraction of Prediction 7. The Hubble constant cancels from the identity that gives the matter fraction. Measurement supplies the amplitude of the first departures from uniformity, the

slight unevenness with which an epoch begins, and the sign of the tilt of the first departures. The running of the tilt is the change of the tilt from one length to another. The running of the tilt lies outside the record, because my physics books state the running of the tilt only on a condition that I do not adopt. The kinds of particle fix how much of the excess of matter over antimatter is held as baryons. The size of the excess is a residue present from the start, and no process among the kinds makes the excess. The books that derive the structure fix the kinds of particle, but not the values of the particles. The masses, mixings and strengths are set out in *The Strengths of the Kinds* and *The Measures of the Kinds*, and the two books state where measurement has not yet chosen between two readings. This account predicts that an asymmetry of time exists (Prediction 28). The size of the asymmetry of time lies outside the record. Below the Planck curvature, this account and the effective field theory of gravity predict the same result for every experiment now proposed. A graviton would be a particle that carries gravity, as the photon carries light. If single gravitons were detected, or a primordial background of gravitational waves, the detection would not show gravitation quantized. My book *The Gravitational Passage* says that the information that falls into a black hole is not destroyed, and that the information re-emerges in the initial conditions of the next epoch. For a black hole formed from a star, this account asserts neither that the information returns to the outside world nor that the information is lost to the outside world. On this account, travel within the light cone is not excluded. This account claims nothing either way about whether travel within the light cone can be built.

For the Specialist

This appendix is for the reader who wants the sources and the exact values.

For each chapter it gives, for every claim the chapter takes from the physics collection, the book, chapter and section that carries the claim, and the standing that book gives it.

It also gives the exact values behind the numbers the chapters state in words, and the measured values the chapters tell, each with its primary paper.

The ground of every chapter is the Incommensuration Theorem: "Symmetry and continuity cannot both be applied, simultaneously and fundamentally, to any event or comparison; and neither can asymmetry and discontinuity".

The Incommensuration Theorem is a structural fact about the nature of knowing.

Preface. A Frequently Asked Preface

The Preface states the message of Jorge Cham and Daniel Whiteson in their own terms, says who this book is for and how to read it, and gives the sense of the title. It makes six statements drawn from the physics collection, listed here with the book, chapter and section that carry each one, and the standing each book gives it. It tells no measurement of its own;

the shares of the universe it gives (about 5, 27 and 68 percent) are the authors' figures, given as theirs, and their primary paper is given under Chapter 1. It has no mathematics and no exact value.

Claim in the Preface	Where the collection carries it	Standing as the book states it
The name Immanent Metaphysics means the study of what must be so for anything at all to be known, worked from inside the act of knowing and from no place outside the world.	*Home in the World*, Prelude, "Two Crews, One Tunnel", section "The Crew from Knowing" ("Metaphysics here means the study of what must be so for anything at all to be known; immanent means within: it works from inside the act of knowing, here and now, as it happens, and never from a place outside the world").	A definition of the name.
The question of what every act of finding out must contain has an answer that is exact (each thing it must contain is fixed precisely), rich (the answer holds a great deal), and the same everywhere (it holds for every act of finding out).	*Home in the World*, Prelude, section "The Crew from Knowing" ("The question has an answer, and the answer turns out to be exact, and rich, and the same everywhere"), where the question is "what must every comparison contain, whatever is compared, and whoever or whatever does the comparing?"; the Preface says "act of finding out" for "comparison".	Stated as the account's result; working that answer out is, in the Prelude's words, the Immanent Metaphysics, and the working is in the foundational books the Prelude names.

Claim in the Preface	Where the collection carries it	Standing as the book states it
The ground of the account is the act of knowing alone, and takes nothing from physics; the physics is worked out from that ground and set beside what has been measured.	*Home in the World*, Prelude, section "The Crew from Knowing" ("Its ground takes nothing from physics: no measurement, no law, no result of any experiment"); *The View from Inside*, Chapter 7, "Three Roles, and What Is Real" (each passage from structure to the world is stated as an identification, and its results are checked against measurement).	A statement of the method.

Claim in the Preface	Where the collection carries it	Standing as the book states it
The world has three settings in which anything is measured: space, time and possibility; each can be bent out of its plain shape, and three things in nature do the bending: gravitation bends space, the constant that drives the expansion (dark energy) bends time, and the dark matter bends possibility.	*The Weight of the Unseen*, "About This Book" ("Each setting can be bent out of its plain shape, and three things in nature do the bending"); the idea is explained in its Chapter 2 (questions 2.1 to 2.8). *The Weight of Possibility*, Chapter 2, Section I ("Each column therefore carries a distortion that is not zero: in space, gravitation; in time, the cosmological constant; in possibility, the dark matter").	In *The Weight of Possibility*, that each of the three settings carries a distortion of its own, and that the three distortions are gravitation, the cosmological constant and the dark matter, is derived from the Incommensuration Theorem and the three axioms of the modalities (Chapter 2, Section I; Appendix A). That the dark matter is a conserved excitation of the internal space is an identification, argued (Chapter 1, Section IV, "This statement is an identification, and this section gives its argument").

Claim in the Preface	Where the collection carries it	Standing as the book states it
The authors' 95 percent is two of the three bendings: the bending of time and the bending of possibility.	The statement of the row above, set beside the authors' pie (dark matter about 27 percent, dark energy about 68 percent, *We Have No Idea*, ch. 1); *The Weight of the Unseen*, answer 2.7 (gravitation "is not an item in the budget of the universe at all").	Follows from the two statements cited: the two shares of the pie besides ordinary matter are the dark matter and the dark energy, and gravitation holds no share. Chapter 1 gives it in full.

Claim in the Preface	Where the collection carries it	Standing as the book states it
The title names the position of a measurement made from inside the world it measures. Every finding in science is made from inside the world it finds, by instruments and observers that are part of that world; for most measurements being inside changes almost nothing; a measurement of the energy of empty space is a cupful of the sea trying to know the rest of the sea, because its instrument is made of the very fields it measures, and it holds a share of that energy, never the whole.	*The View from Inside*, "On the Purpose of This Book" ("Every finding in science is made by a comparison, made from inside the world it finds"); Chapter 1, "The Emptiest Space Is Not Empty", section "A Different Kind of Question" ("Every measurement is made from inside the world it measures, but in most measurements being inside costs almost nothing", with the thermometer in a room as its example); Chapter 7, "Three Roles, and What Is Real", Key idea ("Every measurement of the universe is made from inside it"); Chapter 10, "Why the 10^{123} Never Arises", section "A Cup from the Sea" and Figure 15 ("A measurement of the vacuum is in that position, and more so. The instrument is made of the very fields whose hum it is measuring. It is not a cup dipped into the sea from a boat; it is a cupful of the sea, trying to know the rest of the sea").	The first part is a stated premise of the account. The picture of the cupful is drawn in *The View from Inside* for a measurement of the vacuum's energy. The identification made in that section (what a measurement receives of the vacuum's energy is what is held by the degrees of freedom it engages) belongs to Chapter 3 of this book and is given there.

Measured values told in the Preface: none.

Chapter 1. What Is the Universe Made Of?

Every comparison has a content (what it finds) and a context (where it finds it), and the context has three columns: space, time and possibility. Source: *The Weight of the Unseen*, answer 2.1; *The Weight of Possibility*, Chapter 2, Section II, which takes the grid of six measures from *The Gravitational Passage*, Chapter 7. Standing: the grid is derived, as the product of two rows (content and context) and three columns (*The Gravitational Passage*, Chapter 7, Section III). The six measures are pattern in space, force in time, and probability in possibility. The modal character of each column (omniscient for pattern and space, immanent for force and time, transcendent for probability and possibility) is an assignment, which the Passage makes in the first person, "by the roles that the modalities play", and gives its reasons for: "The reasons are the roles the axioms define" (*The Gravitational Passage*, Chapter 7, Section II).

The Incommensuration Theorem, in its exact wording: "Symmetry and continuity cannot both be applied, simultaneously and fundamentally, to any event or comparison; and neither can asymmetry and discontinuity. Any comparison, perfected at its foundation, is either continuously asymmetric or discontinuously symmetric" (*Incommensuration*, Chapter 2, Section VI). *The Gravitational Passage* states and proves the same theorem in its Chapter 3, Section IV. Standing: a theorem, proved in the Passage by exhaustive enumeration of the ten candidate pairings under three rejection criteria; it has no physical premise. The ramp and the staircase of the chapter are the two survivors: continuously asymmetric, and discontinuously symmetric. The chapter's step from "a small move in a setting brings only a small change of what is found" to "where the setting does not change, what is found does not change" is the Passage's definition of continuity, "sameness of content within a sameness of context", reached as the limit of the first; symmetry is "sameness of content across a difference of context" (*The Gravitational Passage*, Chapter 4, Section IV, as *The Weight of Possibility*, Chapter 2, Section VI, quotes it).

Content is discontinuously symmetric, so context, which carries the continuity, is continuously asymmetric; an asymmetry of context is a departure from uniformity, which *The Weight of Possibility* calls a distortion and this book calls a bend. Source: *The Weight of Possibility*, Chapter 2, Section I. Standing: derived from the theorem and the content and context partition.

Each of the three columns of context carries a bend that is not zero: gravitation in space, the cosmological constant in time, the dark matter in possibility. Source: *The Weight of Possibility*, Chapter 2, Section I (the theorem applied to each column, with the three clauses of Axiom III: the columns are inseparable, non-interchangeable and distinct); full argument in its Appendix A, Sections I to X. Axiom III, as *The Weight of Possibility*, Chapter 2, Section V, quotes it from the Passage: "The (classes/instances) of the immanent, omniscient, and transcendent are distinct, inseparable, and non-interchangeable". Standing, in two parts. That each column carries a distortion of its own that is not zero is derived from the Incommensuration Theorem and the three axioms of the modalities (*The Gravitational Passage*, Chapter 3, Section IV, and Chapter 4, Section V; *The Weight of Possibility*, "The argument at a glance", first row). That the distortion of possibility is the measured dark matter rests on the identification of the dark matter as a conserved excitation of the internal space (*The Weight of Possibility*, Chapter 1, Section IV), which Chapter 2 of this book states. The chapter's plain reasons for the three clauses are those of *The Weight of the Unseen*, answer 2.7: distinct, because each behaves differently; inseparable, because all three appear together in the one equation of the expansion; not interchangeable, because none can do another's work.

Gravitation has no share of its own in the budget of the energy: in a flat epoch the term for the large-scale bending of space, the spatial curvature, is zero, so the bending of space is all local. Gravitation is the response of space to matter (*The Weight of the Unseen*, answer 2.7), in the more exact words of *The Weight of Possibility* "the arena's response to content", while "the cosmological constant is the arena's own constant term, and the dark matter is a distortion of another arena, the internal one,

which the open arena feels as mass" (Chapter 2, Questions). In the field equations the cosmological constant and the dark matter are both sources of curvature, and each is a distortion of a different context (the same passage). Source: *The Weight of Possibility*, Chapter 2, Section VII ("The Budget Is the Grid") and Questions; *The Weight of the Unseen*, answer 2.7. Standing: derived; the measured spatial curvature, 0.0007 ± 0.0019, is consistent with zero (Aghanim and others 2020).

The shares of the present energy of the universe on the account: cosmological constant $\Omega_\Lambda = 0.689$; cold dark matter $\Omega_c = 0.2608$; ordinary matter $\Omega_b = 0.0486$; lightest neutrinos $\Omega_\nu = 0.0014$; radiation $\Omega_r \approx 9 \times 10^{-5}$ (measured input). Read aloud: omega lambda, the share of the cosmological constant; omega c, the share of cold dark matter; omega b, the share of ordinary matter (baryons); omega nu, the share of neutrinos; omega r, the share of radiation. The two distortions of context that carry a share, Ω_Λ and Ω_c, sum to 0.950, the chapter's "about ninety-five percent". Source: *The Weight of Possibility*, Chapter 3, Section V; *The Weight of the Unseen*, answer 5.9.

The matter share comes from the self-consistency identity of *The Gravitational Passage*, Chapter 13, Section III. In words: the square of the particle horizon measured in Hubble radii, times the share of the cosmological constant, equals eight less three divided by pi. In symbols, $I^2\Omega_\Lambda = 8 - 3/\pi$, where $I = \int_0^\infty dz \,/\, E(z)$ is the comoving distance light has traveled over the whole expansion, in units of the Hubble distance (read: I, the integral from redshift zero to infinity of one over E of z), and $E(z) = \sqrt{(\Omega_\Lambda + \Omega_m(1+z)^3 + \Omega_r(1+z)^4)}$ is the expansion rate at redshift z in units of the present rate. With $\Omega_\Lambda = 1 - \Omega_m - \Omega_r$ (flat), the identity is one equation in one unknown and gives $\Omega_m = 0.311$ (more exactly 0.3108), $\Omega_\Lambda = 0.689$, $I = 3.20$. Scope: the identity is a statement about the present measurement, made from inside the universe, and about the epoch of that measurement and no other: "it is a statement about the one act that is real, and the identity of Section III is a statement about the epoch of that act and no other" (*The Gravitational Passage*, Chapter 13, Section VI). Standing: identification; computed (the identification is that the

cosmological constant is the share of the vacuum's energy accessible to an observer inside it, three degrees of freedom among the count of the particle horizon; this book states it in Chapter 3). *What the Beginning Left Behind*, Chapter 14, "The Ledger of the Sky", section "One Number Set: The Matter Share", writes the matter share in the column "set by the structure", with the margin note "identification; computed". The standard model of cosmology fits the matter share to the sky; this account sets it (the same section).

The ratio of dark matter to ordinary matter is $\Omega_c/\Omega_b = 6 - 2/\pi = 5.3634$ (read: six minus two over pi), a little more than five and a third. The count: six independent classes of the internal space $\mathbb{C}P^2 \times S^2$ (three of the complex projective plane times two of the sphere; the chapter's six "kinds of shape") against one class of the visible space within the horizon, less the share $2/\pi$ of the curvature of $\mathbb{C}P^2$ that abides. The six independent classes are a different count from the six internal dimensions: four and two dimensions make six by adding, while three and two classes make six by multiplying (*The Weight of the Unseen*, answer 5.2). Source: *The Weight of Possibility*, Chapter 3, Sections I to V; *The Weight of the Unseen*, answers 5.1 to 5.4. Standing: a registered ratio, a standing of its own (*What the Beginning Left Behind*, Chapter 14, "The Sixth Through One Ratio"): set by what the present measurement registers, not by a mechanism at the turn; the counting principle and the rule are the account's own principles; the form of the rule is the account's own, and the measurement fixes which member of the family holds. *What the Beginning Left Behind* files the registered ratio under none of the five standings it lists, "set by the structure" among them. The share of ordinary matter in the cold matter is $1/(7 - 2/\pi) = 0.15715$; with the lightest neutrinos taken in, the share of ordinary matter in all the matter is 0.15644.

The microwave background measures the ordinary and the dark densities separately, from the heights of its acoustic peaks, which depend on the dark matter only through its gravitation and through its taking no part in the sound of the plasma of photons and ordinary matter. Source:

The Weight of the Unseen, answers 1.5 and A.4; *The Weight of Possibility*, Chapter 5, Section I. Standing: reported (established physics of the microwave background).

The dark matter is registered only by its weight because detectors register content and the dark matter is a distortion of context. Source: *The Weight of the Unseen*, answers 3.3 and A.10. Standing: derived, given the identification of the dark matter (Chapter 2 of this book).

A second, independent kind of measurement guards against an error of method that a single kind of measurement can carry without its stated uncertainty showing it. Source: *The Weight of the Unseen*, answer A.3. Standing: the account's stated method (the rule of decision of *The Gravitational Passage*, which the appendix "What the Coming Measurements Will Find" states). The routes that do not use the microwave background are less precise than it: the most precise of them about five times less, and the cluster gas about thirty times less (*The Weight of Possibility*, Chapter 5, Section II; *The Weight of the Unseen*, answer A.7).

The kinds of particle form a closed list: "The zoo is closed: the kinds of particle are complete and the list admits no further species". Source: *The Branches of the Kinds*, Chapter 4, Section III; *The Story of the Particles*, Level 9, Section IV, "What the Zoo Does Not Contain" (a new kind would need a fourth label, an old label toward the wrong term, a fourth generation or a fourth field kind, and the structure of comparison has none of the four). The structure of comparison is, in the words of *The Story of the Particles*, "the structure of comparison, with its three positions, its six intrinsics, its three axioms, and the algebra they require", and "Every aspect of that structure now has its physical counterpart" (What the Scientists Learned, Section I, "Everything"). Standing: an argument from the structure of comparison; "The argument is not empirical" (*The Story of the Particles*, What the Scientists Learned, Section I, "Everything"); Chapter 4 of this book walks it.

Measured values told in the chapter, with their primary papers.

Quantity	Account	Measured	Primary paper
Shares announced 21 March 2013		ordinary 4.9 percent; dark matter 26.8 percent; age 13.82 billion years	Planck Collaboration, "Planck 2013 results. XVI. Cosmological parameters", *Astronomy and Astrophysics* 571 (2014) A16; ESA press release "Planck reveals an almost perfect Universe", 21 March 2013
Matter share Ω_m	0.311 ± 0.001	0.315 ± 0.007	Aghanim, N. and others (Planck Collaboration), "Planck 2018 results. VI. Cosmological parameters", *Astronomy and Astrophysics* 641 (2020) A6
Vacuum share Ω_Λ	0.689	0.685 ± 0.007	the same
Ratio Ω_c / Ω_b	5.3634	5.364 ± 0.065 (Planck alone; computed from the two published densities, treated as uncorrelated)	Aghanim and others 2020
Ratio Ω_c / Ω_b	5.3634	5.370 ± 0.048 (South Pole Telescope, Planck and Atacama Cosmology Telescope)	Camphuis, E. and others, *Physical Review D* 113 (2026) 083504
Ordinary share of all matter	0.15644	0.1587 ± 0.0066 (light elements with the distances of the Dark Energy Spectroscopic Instrument, DESI)	Schöneberg, N., *Journal of Cosmology and Astroparticle Physics* 06 (2024) 006, with DESI Collaboration 2025

Quantity	Account	Measured	Primary paper
Ordinary share of all matter	0.15644	0.156 ± 0.034 (gas in galaxy clusters)	Mantz, A. B. and others, *Monthly Notices of the Royal Astronomical Society* 510 (2022) 131

The chapter's words for these values: "four and nine tenths percent" and "twenty-six and eight tenths percent" (2013); "about 13.8 billion years" for 13.82; "within about a hundredth of a percent" for 5.364 against 5.3634; "about a tenth of a percent above" for 5.370; "a little over thirty-one percent" for 0.311; "a little above fifteen and a half percent" for 0.15644.

Later analyses that add the baryon acoustic oscillations measured by DESI to the matter share and to the ratio, and what the account says they will find, are given in the appendix "What the Coming Measurements Will Find", under Chapter 1.

Chapter 2. What Is Dark Matter?

Each paragraph below gives one claim of Chapter 2, the book and place that carry its argument, its standing as that book states it, and its exact values.

The dark matter is real energy, located where it pulls, and it pulls by the ordinary law of gravity. *The Weight of the Unseen*, answers 1.1, 1.7 and 3.8; *The Weight of Possibility*, Chapter 1, Section I. Standing: the measured facts the account takes as given, with the law of gravity as *The Gravitational Passage* derives it (general relativity, exact throughout the domain of the smooth description, below the Planck curvature).

A changed law of gravity leaves clusters short of mass, predicts too low a third acoustic peak, and is not followed by wide binary stars. *The Weight of Possibility*, Chapter 5, Section V; *Side by Side*, Volume Two, "The

Law and the History", Sections V and VII. Standing: reported measurements, set beside the derived field equations, which hold Newton's constant and the cosmological constant and no constant of acceleration.

The dark matter is required: each of the three contexts carries a distortion that is not zero. *The Weight of Possibility*, Chapter 2, Section I, and Appendix A, Section IX. Standing, in two parts, as *The Weight of Possibility* gives them. That each column of context carries a distortion that is not zero is derived from the Incommensuration Theorem and the three axioms of the modalities, as stated in *The Gravitational Passage*, Chapter 3, Section IV, and Chapter 4, Section V. That the distortion of possibility is the measured dark matter rests on the identification of *The Weight of Possibility*, Chapter 1, Section IV (its Chapter 2 opens "Rests on: ... the identification (Chapter 1, Section IV)"). In words: content is discontinuously symmetric, so context is continuously asymmetric; the theorem applies to each of the three columns of context (time, space, possibility); Axiom III (distinct, inseparable, non-interchangeable) then places a distortion of its own in each column. The theorem's own wording covers "any event or comparison" (*The Gravitational Passage*, Chapter 3, Section IV).

The six internal dimensions are a space of possibility. *The Weight of Possibility*, Chapter 1, Section III, quoting *The Gravitational Passage*, Appendix C, Section VIII; *The Weight of the Unseen*, answer 2.3. Standing: the Passage's identification ("I identify the two sixes as one set"), which Chapter 11 of this book makes in the first person. The internal space is $\mathbb{C}P^2 \times S^2$, read "the complex projective plane times the two-sphere": $\mathbb{C}P^2$ is the space of states of a system with three alternatives, and S^2 (which is $\mathbb{C}P^1$) that of a system with two. $\mathbb{C}P^2$ has four real dimensions: two fix the weights of the three alternatives (which sum to one), and two fix their relative phases; on S^2 the latitude fixes the two weights and the longitude the one relative phase. The radii are $\sqrt{6}$ Planck lengths for $\mathbb{C}P^2$ (read "the square root of six", about 2.45) and one Planck length for S^2; the Planck length is about 1.6×10^{-35} meters.

The internal space is held at one size and one shape at every point of the exterior. *The Weight of Possibility*, Chapter 1, Section IV; *The Weight of the Unseen*, answers 2.3, 2.5 and 3.1. Standing: the Passage's result (*The Gravitational Passage*, Chapter 11, Section II): each direction of the internal space stands at the modal boundary, which is the same throughout the exterior. The Planck scale bounds how sharply anything can be located from a place, and it is not a least length of space. The floor is one mechanism that holds it there (*The Gravitational Passage*, Appendix D).

The dark matter is made of gyrations, conserved excitations of the six held internal dimensions. *The Weight of Possibility*, Chapter 1, Section IV ("The dark matter is a conserved excitation of the six dimensions of possibility, made at the turn, with no exit afterward"); *The Weight of the Unseen*, answers 3.1 and 3.2. Standing: an identification, argued; the book names it as one. Its ground: the internal space is held, so its excitations have definite energies, as the phonons of a crystal do. *The Branches of the Kinds*, Chapter 4, Section III, and *The Story of the Particles*, Level 9, Section IV (with its note 29), state the same identification with the further specification that the excitation belongs to the context's own instance of $\mathbb{C}P^2 \times S^2$.

A black hole is a region in which matter is packed so densely that nothing that falls in, not even light, comes back out; an epoch is one cycle of the universe, from one turn to the next. *What Comes After the Dark*, Chapter 1, "Clumping and Departing" ("A black hole is a region in which matter is packed so densely that nothing can climb back out of it, not even light"); *The Weight of the Unseen*, "Words Used" (epoch). Standing: definitions.

The gyrations are made only at the turn, the beginning of our epoch. *The Weight of Possibility*, Chapter 1, Sections II and IV; *The Weight of the Unseen*, answers 3.9 and 6.4. Standing: part of the identification ("I take the turn to be the only place where the dark component is made", Chapter 1, Section II); no gyration passes from one epoch into the next. Its ground: a component that gives energy to nothing after it is made, and takes energy

from nothing, can have exchanged energy with the rest of the world only where conditions were extreme enough. At the turn, and only there, the six internal dimensions and the three open dimensions re-form together. After the turn, the one remaining way in which gyrations could be made is their production in pairs by a hot plasma through gravity alone. The account requires that the temperature of the new epoch keep that way closed (*The Weight of Possibility*, Chapter 1, Section II, and Chapter 4, Section VI).

The mass of a gyration is of the order of the Planck mass. *The Weight of the Unseen*, answer 3.2 and "Words Used"; *The Weight of Possibility*, Chapter 4, Section V. Standing: computed; about $\sqrt{2}$ Planck masses (about 1.7×10^{19} GeV) in the simplest calculation and about 0.6 Planck masses with the first correction. The Planck mass (unreduced) is about 1.22×10^{19} GeV, about 10^{19} proton masses ("ten billion billion" in the chapter). Three states share the lowest mass at every order computed: one of spin two and two of spin one.

Near the Sun there is about one gyration in every few tens of thousands of cubic kilometers. *The Weight of the Unseen*, answer 5.10. Standing: computed from the gyration mass and the measured local density; about one gyration for every 1.5 to 3.4×10^{18} protons and neutrons.

The dark matter is dark because instruments register content and the dark matter is a vibration of a context; instruments register it only through its pull on content. *The Weight of the Unseen*, answer 3.3 ("It shows itself only by its weight"); *The Weight of Possibility*, Chapter 2, Section VI. Standing: follows from the identification.

Gyrations scatter off one another, by their weight alone, at least forty-five powers of ten below the Bullet Cluster bound. *The Weight of the Unseen*, answer 3.5. Standing: computed. The bound is an upper limit on the self-scattering cross section per unit mass, about 1 cm^2/g (read "one square centimeter per gram"; Markevitch and others 2004).

All three exits are closed, so the dark matter does not decay. *The Weight of the Unseen*, answers 4.1 to 4.7; *The Weight of Possibility*, Chapter 1, Section IV, and Chapter 4. Standing: derived from the identification. Into content: closed, since the geometry of possibility re-forms only at the turn. Into waves of the open geometry: closed by the antipodal parity, the map of S^2 to its opposite points, which leaves the action of the metric unchanged; the lasting state is the lightest level odd under that map. The even excitations of the breathing kind decay within about a Planck time, through the term of Gauss and Bonnet in the ten-dimensional action, for a coefficient of natural size (*The Weight of Possibility*, Chapter 4, Section III). Into evaporation: closed, since an excitation at the Planck scale has no lower level of its kind. The parity is exact because two arrangements of the whole geometry differing only by the map are one arrangement (*The Weight of the Unseen*, answer 4.4).

No detector will catch the dark matter except by its weight, and no collider makes a gyration. *The Weight of the Unseen*, answers A.10 and 3.10; *The Weight of Possibility*, Chapter 5, Section VII. Standing: a prediction of the identification, shared with other accounts of dark matter that acts only through gravity. The Large Hadron Collider's proton collisions run at 13 TeV in Run 2 (2015 to 2018) and 13.6 TeV in Run 3 (from 2022), about 1.45×10^4 proton masses (the proton's mass is about 0.938 GeV). Its lead nuclei collide in Run 3 at 5.36 TeV per pair of nucleons, about 1.1×10^3 TeV for the whole collision, about 1.2×10^6 proton masses. About 1.2×10^6 proton masses is the figure that *The Weight of the Unseen*, answer 3.10, gives as "about a million times the energy of a proton's mass" for two heavy nuclei collided head on. One gyration holds about 10^{19} proton masses, about 10^{13} times more.

No process within our epoch turns ordinary matter into dark matter. *The Weight of the Unseen*, answer 3.10. Standing: follows from the identification together with the energy argument. The one way in which gyrations could be made within an epoch, their making in pairs through gravity alone, needs a gas hotter than about one thirtieth of a gyration's mass, and

nothing in our epoch has been that hot. The measured amount of dark matter caps the temperature of our epoch at about 2 to 5×10^{17} GeV (*The Coming of the Kinds*, Chapter 2, Section IV).

No dark-matter species exists among the kinds. *The Story of the Particles*, Level 9, Section IV; *The Particular Evidence*, Case 15, Section IV; *The Branches of the Kinds*, Chapter 4, Section III. Standing: derived from the closed list of kinds, on ground separate from *The Weight of Possibility*; four routes converge (completeness of the spectrum; no axion; the occupied slot; the Dirac neutrino). The algebra is $\mathbb{C} \oplus \mathbb{H} \oplus M_3(\mathbb{C})$ (read "the complex numbers, plus the quaternions, plus the three-by-three complex matrices"), carrying sixteen states per generation, all occupied. The slot a dark-matter particle would need (a spinor with no label but the phase) is held, once in each generation, by the right-handed component of the neutrino. By the identity principle, a second spinor of that kind in the same generation would be told from it by nothing.

The neutrinos are not the dark matter. *The Weight of Possibility*, Chapter 3, Questions. Standing: follows from the identification (the neutrinos are content), and, on separate ground, from measurement. By the exclusion principle (Tremaine and Gunn 1979), dwarf spheroidal galaxies need a fermion of at least 130 eV (Alvey and others 2021). The sum of the neutrino masses lies below 0.064 eV in the standard model of cosmology (DESI Collaboration 2025), and the electron neutrino's mass below 0.45 eV (Aker and others 2025, KATRIN). The shortfall is a factor of at least about three hundred in mass.

No dark chemistry. *The Weight of Possibility*, Chapter 4, Section V, and Chapter 6, Section II; *The Weight of the Unseen*, answer 3.5. Standing: a requirement of the account, that the fields of the rotations of S^2 not reach the open spacetime as a long-range force on charges that do not cancel (Chapter 6, Section II), met at the coupling the book computes. The coupling of those fields to the lightest odd level is of order 6 (in units in which electromagnetism has 1/137), computed by Weinberg's prescription at the Passage's radii (Chapter 4, Section V). At that coupling the field is

strongly coupled at the Planck scale and confines there, dressing each gyration into a neutral odd state (Chapter 6, Section II). Measured bounds on a dark-only force: Kesden and Kamionkowski 2006 (Sagittarius streams, below about ten percent); Bean, Flanagan, Laszlo and Trodden 2008 (about five percent of gravitation).

Ordinary matter alone would have formed no galaxy. *The Weight of Possibility*, Chapter 1, Section I. Standing: arithmetic on measured inputs. In words: the matter departures at last scattering are about three times the temperature departures of about 10^{-5}. They grow in proportion to the scale factor once matter rules, by about 1,090 since last scattering, reaching about 3×10^{-2}, and less than that, since the growth slows once the cosmological constant rules. Collapse requires an excess of order one. In symbols: $\delta_b \approx 3 \times 10^{-5} \times 1090 \approx 3 \times 10^{-2}$, where δ_b, read "delta sub b", is the fractional excess of density of the ordinary matter. The dark departures grow logarithmically in the scale factor during radiation domination (Mészáros 1974) and linearly afterward (Peebles 1982). Cham and Whiteson write that without dark matter the first galaxies would have taken "many more billions of years" to form (*We Have No Idea*, ch. 15, "Gravity Versus Pressure"); the arithmetic above gives no galaxy.

The dark matter built the scaffolding of the galaxies; galaxies form inside halos that gather hierarchically. *The Weight of the Unseen*, answer 1.6; *The Weight of Possibility*, Chapter 1, Section I, and Chapter 2, Section VII. Standing: reported standard physics (White and Rees 1978; Rees and Ostriker 1977), carried by the gyrations because they are a cold component acting only through gravity.

The gyrations are perfectly cold and cluster exactly as standard cold dark matter does. *The Weight of Possibility*, Chapter 5, Section VI; *The Weight of the Unseen*, answers 3.6 and A.14. Standing: computed. A gyration with the speed it would have in a plasma at one thirtieth of its mass travels about two centimeters in the whole history of the universe. A gyration that left the turn with a hundred times its mass in momentum travels

less than a meter. The present bound on a small-scale cut-off: half-mode mass below about 10^7 solar masses at 95 percent confidence (Nadler and others 2021).

Measured values told in the chapter

Rubin and Ford: velocities of 67 H II regions in M31, mostly from Hα, measured with the image-tube spectrograph of the Department of Terrestrial Magnetism (DTM) at the Lowell Observatory 72-inch and Kitt Peak 84-inch telescopes, at 3 to 24 kiloparsecs from the nucleus. The mass rises roughly linearly to about 14 kiloparsecs and more slowly beyond; maximum rotation velocity about 270 km/s. V. C. Rubin and W. K. Ford, Jr., "Rotation of the Andromeda Nebula from a Spectroscopic Survey of Emission Regions", *The Astrophysical Journal* 159 (1970) 379 to 403.

Zwicky: the galaxies of the Coma cluster move too fast for the visible galaxies to hold them. F. Zwicky, "Die Rotverschiebung von extragalaktischen Nebeln", *Helvetica Physica Acta* 6 (1933) 110 to 127.

The Bullet Cluster, 1E 0657-56: the lensing mass lies with the galaxies, apart from the X-ray gas. D. Clowe, M. Bradač, A. H. Gonzalez, M. Markevitch, S. W. Randall, C. Jones and D. Zaritsky, "A direct empirical proof of the existence of dark matter", *The Astrophysical Journal* 648 (2006) L109 to L113. Self-scattering below about 1 cm^2/g (an upper limit): M. Markevitch and others, "Direct constraints on the dark matter self-interaction cross section from the merging galaxy cluster 1E 0657-56", *The Astrophysical Journal* 606 (2004) 819 to 824.

A changed law: clusters still short of mass (R. H. Sanders, *Monthly Notices of the Royal Astronomical Society* 342 (2003) 901 to 908); third acoustic peak too low without dark matter (S. S. McGaugh, *The Astrophysical Journal* 611 (2004) 26 to 39). Wide binaries from Gaia DR3: Newtonian dynamics preferred over the modified dynamics at 19 standard deviations (I. Banik, C. Pittordis, W. Sutherland, B. Famaey, R. Ibata, S. Mieske and H. Zhao, "Strong constraints on the gravitational law from Gaia DR3 wide binaries", *Monthly Notices of the Royal Astronomical Society* 527 (2024) 4573 to 4615).

No decay of the dark matter since recombination for any lifetime shorter than about 160 billion years (a lower limit on the lifetime): V. Poulin, P. D. Serpico and J. Lesgourgues, "A fresh look at linear cosmological constraints on a decaying dark matter component", *Journal of Cosmology and Astroparticle Physics* 08 (2016) 036.

LZ: no signal; spin-independent scattering excluded down to about 2×10^{-48} cm² at 40 GeV (as *The Alphabet of Particles*, entry N3, reports it). LZ Collaboration, "Dark Matter Search Results from 4.2 Tonne-Years of Exposure of the LUX-ZEPLIN (LZ) Experiment", *Physical Review Letters* 135 (2025) 011802.

Chapter 3. What Is Dark Energy?

Each paragraph below gives one claim of Chapter 3 in one plain sentence, the corpus book that carries it, its standing as that book states it, and its exact values. Symbols are read aloud where they first appear.

The accelerating expansion and the constant term

Claim: the expansion of the universe slowed for its first seven or eight billion years and has sped up since, because matter thins as space grows and the energy of empty space does not. Carried by: *The View from Inside*, Chapter 1, "A Strange Discovery" and "Energy Curves Space" (Figure 1 and its caption); *What Comes After the Dark*, Chapter 1, "Faster, Not Slower". Standing: reported measurement, with the standard account of why a uniform energy that does not thin drives acceleration. Value: the 1998 discovery paper put the distant supernovae, on average, ten to fifteen percent farther away than a slowing universe would (*What Comes After the Dark*, Chapter 1).

Claim: Einstein added a constant term to his field equations in 1917 to hold a static universe, the term was set aside after the expansion was found, and it returned in 1998 as the simplest account of the acceleration. Carried by: *The View from Inside*, Chapter 1, "The Cosmological Constant"; *What Comes After the Dark*, Chapter 1, "Faster, Not Slower". Standing: re-

ported history. Symbols: the geometric constant is written Λ ("lambda"), with units of inverse length squared; the energy density it corresponds to is written ρ_Λ ("rho lambda"), and the two are related by $\Lambda = 8\pi G\rho_\Lambda$, read "lambda equals eight pi times Newton's constant G times rho lambda", in units where the speed of light is one.

Claim: the cosmological constant bends time, in the sense that in a flat epoch the whole large-scale bending lies in the course of the universe over time, and it increases the distance between every pair of distant places. Carried by: *The Weight of Possibility*, Chapter 2, Section II, "Three Things That Bend the Arena", and Chapter 1, Section V, "One of Three Distortions"; *The Weight of the Unseen*, "About This Book". Standing: stated by those books as the second of the three distortions of context, one for each context of the grid of measures (gravitation distorts space, the cosmological constant distorts time, the dark matter distorts possibility).

The vacuum and its total

Claim: the vacuum, every field at its lowest energy with no particles present, holds a zero-point energy, and one effect of that energy, the Casimir force, has been measured. Carried by: *The View from Inside*, Chapter 1, "What Is 'Empty' Space?". Standing: established physics, reported, with its measurement. Value: Lamoreaux (1997) measured the force within about five percent of the computed value.

Claim: summing the zero-point energies of all fields up to the Planck energy gives a vacuum density about ten to the one hundred twenty-three times the observed one. In Chapter 3 of this book I name the cutoff in words as the smallest length that the present theories reach, which is the Planck length, about 1.6×10^{-35} meters. The Planck length is the scale at which *The View from Inside* (Chapter 9, "The Modal Boundary") sets the six internal dimensions. Carried by: *The View from Inside*, Chapter 1, "The Number That Shouldn't Exist", and Chapter 10, "Back to the Numbers"; on separate ground, *Non-Commutative Geometry and the Immanent Metaphysics*, Chapter 16, Section I, "The Term". Standing: reported computation of standard quantum field theory; the second book states the same ra-

tio for the leading term of the spectral action of Chamseddine and Connes, and states that "The spectral action does not by itself explain this ratio". Values: the Planck density $M_{Pl}{}^4$ ("the Planck mass to the fourth power") $= 2.222 \times 10^{76}$ GeV^4, with $M_{Pl} = 1.221 \times 10^{19}$ GeV (*The View from Inside*, Appendix C, "The Inputs"); the observed $\rho_\Lambda = 2.52 \times 10^{-47}$ GeV^4. The ratio of observed to computed is about 10^{-123} against the full Planck mass, about 10^{-120} against the reduced Planck mass, and roughly 10^{-111} against a cutoff near 10^{16} GeV (*Non-Commutative Geometry and the Immanent Metaphysics*, Chapter 16, Section I). The authors' range, ten to the sixty to ten to the hundred (*We Have No Idea*, ch. 3, "What Could Dark Energy Be?"), is given in the chapter as theirs.

Claim: energy is the rate at which findings can be made, and space bends where findings can be made, in proportion to how many can be made there, with the strain spreading through the continuous arena from where it is placed. Carried by: *The View from Inside*, Chapter 8, "Energy Is the Rate of Finding", "In Proportion to What Can Be Found" and "From Here and Now to Everywhere at Once". Standing: the first part is an identification, stated in the first person ("I identify energy with the rate at which that change can occur: the most findings a system can yield in a given time"); the book sets beside it the theorem of Margolus and Levitin, that a system passes through at most $2E/(\pi\hbar)$ distinguishable states per second, read "twice the energy, divided by pi times the reduced Planck constant", where E is the mean energy above the ground state. The form of the field (Einstein's tensor with one constant term) is fixed by Lovelock's theorem, as the book reports it.

Claim: the vacuum's total energy is real, of the size quantum theory gives, and curves nothing, because no comparison finds it whole. Carried by: *The View from Inside*, Chapter 10, "What Curves Space", "A Cup from the Sea", "The Shape That No Comparison Finds" and "The Share and the Total". Standing: derived, on two grounds that point the same way. The first ground rests on an identification the book states in the first person: what a measurement receives of the vacuum's energy is what is held by the degrees of freedom it engages, and no measurement engages them all.

The second ground is the Incommensuration Theorem: the total, taken whole, would be perfectly symmetric (the same at every place and for every comparer in steady motion) and perfectly continuous (without a break), and no comparison finds anything perfect in both ways at once. In The View from Inside I state that the argument that the vacuum's total energy curves nothing holds whatever the size of the total and whichever way of doing the sum is preferred.

Claim, on separate ground: the cosmological term of the spectral action counts the whole Hilbert space without distinguishing anything, and so carries no content within any class of comparison. Carried by: *Non-Commutative Geometry and the Immanent Metaphysics*, Chapter 16, Section II, "The Reading", by Theorem 5.4 of that book (the algebraic form of the Incommensuration Theorem for a finite spectral triple). Standing: the book fixes the form of the term and computes no value.

The share

Claim: an observer is inside the vacuum it measures and entangled with it, so part of the information about the vacuum is held in the correlation and is not accessible to the observer; a system cannot fully measure itself. Carried by: *The View from Inside*, Chapter 11, "Inside, and Joined"; *The Gravitational Passage*, Chapter 13, Section I, "The Problem of Being Inside". Standing: the deficit is identified, in the first person, as an instance of the Incommensuration Theorem at the cosmological scale ("the knower inside the known cannot hold the whole of what it knows", *The View from Inside*, Chapter 11). *The View from Inside* states the position of being inside at three scopes: every finding in science is made from inside the world it finds ("On the Purpose of This Book"); for most measurements being inside costs almost nothing (Chapter 1, "The Emptiest Space Is Not Empty", section "A Different Kind of Question"); and the picture of the cupful, with its share and never the whole, is drawn for a measurement of the vacuum's energy (Chapter 10, "A Cup from the Sea", and Figure 15).

Claim: I identify the cosmological constant with the share of the vacuum's energy that is open to a measurement made from inside the vacuum, and not with the total. Carried by: *The View from Inside*, Chapter 11, "The Share We Find"; *The Gravitational Passage*, Chapter 13, Section II, "The Information Deficit Formula". Standing: an identification, stated in the first person in both books.

Claim: the degrees of freedom are counted on the particle horizon by the Bekenstein–Hawking rule. In words: the count is the area of the horizon divided by four squares of the Planck length. In symbols: $S = \pi R^2 / l_{Pl}^2$, read "S equals pi times R squared, divided by the Planck length squared", where S is the count, R the radius of the particle horizon and l_{Pl} the Planck length (about 1.6×10^{-35} meters). Carried by: *The View from Inside*, Chapter 12, "Information Written on a Surface" and "The Edge of What Has Reached Us"; *The Gravitational Passage*, Chapter 13, Section II, equation (13.2). Standing: the count is the standard Bekenstein–Hawking entropy; its assignment to the particle horizon is an identification ("the bound of what has been compared is the bound of the information available to the comparison", *The Gravitational Passage*, Chapter 13, Section II). A second, separate reason selects the same edge: the formula gives exactly the constant only on an edge $\sqrt{(8f)} = 2.654$ times the de Sitter radius, read "the square root of eight f", and the particle horizon is the only one of the four edges that grows that large; it stands today at 2.632 times the de Sitter radius (*The View from Inside*, Chapter 12, "A Second Reason, Quite Separate", and Appendix C, "Results"). Values (Planck 2018 parameters): R = 46.14 billion light-years; $S = 2.292 \times 10^{123}$; de Sitter radius $r_\Lambda = 17.53$ billion light-years (*The View from Inside*, Appendix C, "The Horizon").

Claim: a measurement takes in the vacuum through three ways, one for each content it registers (pattern in space, force in time, probability in possibility); the contexts supply none of their own. In Chapter 3 of this book I call the three ways the three kinds of content that a measurement registers. In *The View from Inside* I call each of the three ways a channel. Carried by: *The View from Inside*, Chapter 12, "Why Three", and Chapter 9, "The Number Three"; *The Gravitational Passage*, Chapter 13, Section II.

Standing: an identification of the ways with the contents a measurement registers, with a second route to the same number: the count of independent classes of the complex projective plane, $\chi(\mathbb{C}P^2) = 3$, read "the Euler characteristic of C P two equals three", written $c_1 = 3$ ("c one").

Claim: each of the three takes in one whole tile, a different tile for each, and the tiles are counted once for the one stance from which the measurement is made, however many instruments that stance carries. Carried by: *The View from Inside*, Chapter 11, "Tiles on the Horizon". Standing: the one tile for each is stated in the first person ("I take each channel to take in one tile: a channel registers one content, and content, as Chapter 8 found, comes whole, in steps"); the different tile for each rests on the third axiom (the three distinct, inseparable, and none able to stand in for another); the counting once is argued from the comparer as one stance ("Does a telescope and a thermometer, used together, take six tiles?").

Claim: the total that the degrees of freedom share is the Planck density less the energy left in four dimensions by the curvature of the six compact dimensions at their derived size, which has the sign that draws space together. In words: one, less three parts in eight pi, which is 0.881 of the Planck density. In symbols: $f = 1 - 3/(8\pi) = 0.8806$, read "f equals one minus three over eight pi". Carried by: *The View from Inside*, Chapter 9, "A Small Trim" (the picture of a sheet of spring steel rolled into a coil is that book's); *The Gravitational Passage*, Chapter 13, Section II, equation (13.1). Standing: derived from the curvature of the internal space at the size the modal boundary fixes; the book states that this 3 is a different number from the count of the three ways of the paragraph above. Value: without the trim the energy of empty space comes out about fifteen percent above the measured value (*The View from Inside*, Chapter 9).

Claim: the measured vacuum density is three degrees of freedom's worth of the trimmed total. In words: divide the trimmed Planck density into S equal parts and take three. In symbols: $\rho_\Lambda = c_1 \, f \, M_{Pl}{}^4/S$, read "rho lambda equals c one times f times the Planck mass to the fourth, divided by S". Carried by: *The View from Inside*, Chapter 11, "The Equation, Piece

by Piece"; *The Gravitational Passage*, Chapter 13, Section II, equation (13.3). Standing: follows from the identification of the share, the count at the particle horizon and the three ways. Value: 2.56×10^{-47} GeV^4, against the measured 2.52×10^{-47} GeV^4; the ratio of predicted to observed is 1.0168 with one set of parameters (*The View from Inside*, Chapter 13, "The Same Number, Seen from Other Sides", and Appendix C, "Results"; *The Gravitational Passage*, Chapter 13, opening, "about 1.7 percent above the observed one").

Claim: the share and the Friedmann equation must agree, and setting them equal leaves one equation in pure numbers, the identity, which fixes the matter fraction. The Friedmann equation, in words: in a flat universe the critical density is three times the square of the expansion rate, divided by eight pi times Newton's constant; in symbols $\rho_c = 3H^2/(8\pi G)$, read "rho c equals three H squared over eight pi G", where H is the expansion rate today. The chapter's unit of distance set by the expansion is the Hubble radius, c/H, read "the speed of light divided by H"; the chapter's "slice of the pie" is a fraction of the critical density. The identity, in words: the square of the horizon's distance measured in Hubble radii, times the vacuum's fraction of the critical density, equals eight less three over pi. In symbols: $I^2\Omega_\Lambda = 8f = 8 - 3/\pi = 7.045$, read "I squared times omega lambda equals eight minus three over pi", where I is the particle horizon in Hubble radii and Ω_Λ ("omega lambda") is the vacuum's fraction. I is the integral from redshift zero to infinity of dz over the square root of $(\Omega_\Lambda + \Omega_m(1+z)^3 + \Omega_r(1+z)^4)$, read "the sum over every redshift z of one over the expansion rate at z relative to today", where Ω_m is the matter fraction and Ω_r the radiation fraction. Carried by: *The View from Inside*, Chapter 13, "Two Surveyors", "The Second Way: The Astronomers' Way", "Setting the Two Equal" and "One Equation, One Unknown", and Appendix C, "The Identity"; *The Gravitational Passage*, Chapter 13, Section III. Standing: derived; Newton's constant and the Hubble constant cancel. Scope: the identity is a statement about the epoch of the present measurement, the one act that fixes the constant (*The Gravitational Passage*, Chapter 13, Section VI; *The View from Inside*, Chapter 15, "An Astronomer Long

Ago"). Values: $\Omega_m = 0.3108$ (0.311 ± 0.001 over the measured range of the radiation fraction), $\Omega_\Lambda = 0.6891$; $I = 3.181$ with the Planck 2018 parameters. Without the trim ($f = 1$) the identity gives $\Omega_m = 0.2798$.

Constancy, and why now

Claim: within one geometry the cosmological constant is one number. In words: the field equations conserve energy and momentum identically, so a constant term that varied in place or time would break that conservation exactly where it varied. In symbols: the divergence of the Einstein tensor vanishes and the matter stress tensor is conserved, so the gradient of Λ is zero. Carried by: *The View from Inside*, Chapter 15, "One Map, One Scale"; *What Comes After the Dark*, Chapter 2, "The Second Way: One Number for Our Whole Epoch". Standing: a theorem about Einstein's equations, using no measurement.

Claim: the constant is fixed once, by the present measurement at the present horizon, and the reconstructed history carries that one value at every era of the epoch; the equation of state is $w = -1$ exactly (w, "double-u", is the ratio of pressure to density). Carried by: *The View from Inside*, Chapter 14, "What This Means for the Cosmological Constant", and Chapter 15, "Which Measurement Fixes It" and "Exactly Constant"; *What Comes After the Dark*, Chapter 3, "One Number Through Our Whole Epoch"; *The Gravitational Passage*, Chapter 13, Sections V and VI. Standing: derived from the share entering as the one constant term of one geometry, together with the book's argument that the present act is the one measure of the constant. Value: applied on paper to the horizon of the era at redshift 1, the formula gives about 7.05 times the constant; today it gives 1.017 times (*The View from Inside*, Chapter 15, "Why Now?"); the book states that no record carries those other-era figures as findings.

Claim: no new field drives the acceleration: the closed list of kinds holds one field that fills space with a settled value, the Higgs field, which settled long before the acceleration began; and an energy that followed the growing particle horizon would have w of about -0.12 today and would not accelerate the expansion. Carried by: *What Comes After the Dark*,

Chapter 3, "One Number Through Our Whole Epoch"; *The View from Inside*, Chapter 15, "Exactly Constant" (the horizon-following case, after Li 2004). Standing: derived from the closed list of kinds, with the time at which the Higgs field settled taken from physicists' calculations of the early universe, as the book reports them.

Claim: because the constant is one positive number through the epoch with $w = -1$, it never changes sign and does not meet the condition for a rip (w below -1). Carried by: *What Comes After the Dark*, Chapter 2, "The Second Way: One Number for Our Whole Epoch", and Chapter 3, "What a Rip Needs" and "One Number Through Our Whole Epoch". Standing: derived; the rip condition is that of Caldwell, Kamionkowski and Weinberg, as the book reports it.

Claim: the question "why now?" has three parts: the present age measured in de Sitter times, which the identity fixes; the date at which the measurement is made, a fact of content taken from the world as found; and why the real act stands at the era where the identity holds, which the book answers from the first axiom (only the present act is given, and the history is reconstructed from it afterward). The nearness of the matter and vacuum densities today is the identity holding in the era of the act that fixes the constant. The de Sitter time is the de Sitter radius divided by the speed of light: the time in which a universe of empty space alone grows by a factor of e, about 2.718; the chapter calls it the growth time. Carried by: *The View from Inside*, Chapter 15, "Why Now?", and Appendix C, "Results"; *What the Beginning Left Behind*, Chapter 14. Standing: the age ratio is derived; the date is taken from the world as found; the third part is argued from the first axiom. Values: $t_0 H_\Lambda = 0.792$ predicted, read "the age times the de Sitter rate", against 0.787 ± 0.009 from the measured age (about 13.8 billion years) and the measured de Sitter time (about 17.5 billion years). The date is about 10^{61} Planck times after the beginning (*The View from Inside*, Chapter 15, "Why Now?").

Measured values told in Chapter 3, with their primary papers

The accelerating expansion: Riess, A. G. and others (1998), "Observational Evidence from Supernovae for an Accelerating Universe and a Cosmological Constant", *Astronomical Journal* 116, 1009–1038; Perlmutter, S. and others (1999), "Measurements of Ω and Λ from 42 High-Redshift Supernovae", *Astrophysical Journal* 517, 565–586.

The Casimir force: Casimir, H. B. G. (1948), "On the Attraction Between Two Perfectly Conducting Plates", *Proceedings of the Koninklijke Nederlandse Akademie van Wetenschappen* 51, 793–795; Lamoreaux, S. K. (1997), "Demonstration of the Casimir Force in the 0.6 to 6 μm Range", *Physical Review Letters* 78, 5–8.

The rate of distinguishable change: Margolus, N. and Levitin, L. B. (1998), "The Maximum Speed of Dynamical Evolution", *Physica D* 120, 188–195.

The expansion equation: Friedmann, A. (1922), "Über die Krümmung des Raumes", *Zeitschrift für Physik* 10, 377–386.

The matter fraction, the vacuum density and the equation of state: Aghanim, N. and others (Planck Collaboration) (2020), "Planck 2018 Results. VI. Cosmological Parameters", *Astronomy and Astrophysics* 641, A6: $\Omega_m = 0.315 \pm 0.007$; $w = -1.03 \pm 0.03$ (microwave background with baryon acoustic oscillations and type Ia supernovae). The measured vacuum density 2.52×10^{-47} GeV^4 and the de Sitter age ratio 0.787 ± 0.009 are computed from those parameters, as *The View from Inside*, Appendix C, and *What the Beginning Left Behind*, Chapter 14, report. Later combinations of survey data, and what the account says they will find, are given in the appendix "What the Coming Measurements Will Find".

The horizon count: Bekenstein, J. D. (1973), "Black Holes and Entropy", *Physical Review D* 7, 2333–2346; Hawking, S. W. (1975), "Particle Creation by Black Holes", *Communications in Mathematical Physics* 43, 199–220; Fischler, W. and Susskind, L. (1998), "Holography and Cosmology", arXiv:hep-th/9806039.

The opening scene: Einstein, A. (1917), "Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie", *Sitzungsberichte der Königlich Preussischen Akademie der Wissenschaften* (1917), 142–152, read to the Academy on 8 February 1917; Einstein to Paul Ehrenfest, 4 February 1917, *The Collected Papers of Albert Einstein*, Volume 8, Document 294; the English rendering quoted in the chapter is that of O'Raifeartaigh, C., O'Keeffe, M., Nahm, W. and Mitton, S. (2017), "Einstein's 1917 Static Model of the Universe: A Centennial Review", *European Physical Journal H* 42, 431–474.

Chapter 4. What Is the Most Basic Element of Matter?

Every claim of Chapter 4 that comes from the corpus is listed below in the order of the chapter, with the book, chapter and section that carry it and its standing as that book states it. The measured values the chapter tells follow, with their primary papers.

Claims from the corpus

Particles of one kind are found exactly alike. *The Matter We Know*, Volume One, Chapter 1, Section II: "Two electrons are always found exactly alike, even when one was made in a laboratory this morning and the other in the first second of our history". Standing: a measured fact, stated as such. *Incommensuration*, Chapter 6, Section XI, places the same fact in the theorem's terms: "That every electron is indistinguishable from every other electron is symmetry in the strict sense: sameness of content across difference of context".

No two particles of matter of one kind share a state. *The Matter We Know*, Volume One, Chapter 1, Section IV, from the principle of identity as *The Quantum Passage*, Chapter 8, Section VI, states it: what no comparison can distinguish, in any way at all, even in principle, is one thing and not two. Standing: derived from that principle alone; the argument is that of *The Quantum Passage*, Chapter 8, Section VI, which *The Matter We Know* sets out; *The Quantum Passage* states, and *The Matter We Know* quotes, that "the theorem of Pauli is not used". The same two steps give the opposite

rule for the force particles (any number share one state); *The Story of the Particles*, Level 0, Section III, gives both from one principle applied to the two poles of the content and context partition.

Every comparison has three positions, and the three carriers fill them. *The Story of the Particles*, Level 0, Sections I and VI. The positions are the act of comparing (the immanent), the thing compared (the omniscient) and the thing compared against (the transcendent); they are distinct, inseparable and non-interchangeable, which is the content of the third axiom of comparison. The photon is the act of comparing, the electron is the thing compared, and the proton is the thing compared against. Standing: an argument from the three axioms; the three statements are identities in the frame of measurement, the frame in which the comparing act is light. The naming of the photon by its position is a definition (Level 0, "Why the Naming Cannot Fail"), and the identity holds in the frame in which the measurements are made. At finer resolution the photon of that frame is a combination of two carriers of a finer frame, and that combination is exactly the carrier of the act (Level 0, Section II; Level 7). The three carriers are "the three positions of comparison expressed as particles" (Level 0, Section I). The book's summary sentence: "The three carriers are the minimum cost of admission for a world in which anything can be known".

Each carrier's character follows from its position. *The Story of the Particles*, Level 0, Sections II, III and IV. The photon: no rest mass, no charge, spin one, Bose statistics. The electron: rest mass, the unit charge, spin one half, Fermi statistics, stable. The proton: the opposite charge, much greater mass, an interior, stable. Standing: derived from position for each property, except that stability joins a structural fact (a conserved count) to a measured one (which member of each kind is lightest), as Level 0, Section VII, states. The ratio of the proton's mass to the electron's is measured and is not fixed by the list of kinds (Level 0, Section IV).

The electron shows no inside because it is the unit. *The Story of the Particles*, Level 0, Section IV: the electron is pointlike at this level, "and one does not measure the unit itself by opening it up". *The Alphabet of Particles*, the electron's entry: "no internal structure found at any resolution reached", with the standing "Measured; pointlike as the unit of its frame".

The three generations are the three rotations of the content. *The Story of the Particles*, Level 5, Sections I and II; *The Kinds of Particle*, Chapter 7, Section I. In words, every occupant of a position has three pairs of aspects, one pair for each position, and in Chapter 4 of this book I call the pairs "respects". Sameness and difference are the omniscient pair, of the thing compared; the objective and the subjective are the immanent pair, of the act; content and context are the transcendent pair, of the thing compared against. One act of comparing reads the occupant through one pair, the pair foremost. A rotation of the content moves which pair is foremost while the position stays fixed. Each pair must be foremost in some instance, and two instances read through different pairs are two particles. A fourth rotation brings the first pair foremost again and is the first instance. The first generation has the immanent pair foremost, the second the omniscient pair, and the third the transcendent pair (*The Story of the Particles*, Level 5, Sections I and II). The order of the pairs foremost in the three generations is the order in which any comparison, as the comparison is lived, takes the pairs up. Any comparison takes up first a perspective and something compared from the perspective, then sameness and difference, then content within its context. The order of the pairs foremost is the direction of the cycle of the second axiom. *The Kinds of Particle*, Chapter 7, Section I, bounds the count from both sides. From above: of the six ways the three pairs can stand at the three positions, three keep the direction of the cycle of the second axiom; each of the other three exchanges two pairs and gives no instance. From below: the third axiom holds of instances, so no pair is left never foremost. Result, as the book states it: "The generations number exactly three, one for each pair foremost". Standing: an argument with stated premises. Within the Standard Model the number three is an input (*The Kinds of Particle*, Chapter 7, Section VII). In the spec-

tral-triple classification of Chamseddine and Connes the number of generations is a free multiplicity (*The Connes Correspondence*, "Three Generations: An Input and Its Grounds", Section I).

Only matter comes in three. *The Story of the Particles*, Level 5, Section I: a rotation of the content multiplies instances of content, and context has no separated instances, so the photon, the other force particles and the Higgs field do not come in three. A context field presents all three pairs at once, as one continuous field; the act of comparing has no fixed characteristic of its own, and so has no pair to turn foremost. Standing: derived.

The later generations are heavier, and decay. *The Story of the Particles*, Level 5, Section III; *The Kinds of Particle*, Chapter 7, Section VI. In words, the first generation is read by its fixed characteristic alone (its charge and rest mass), the least a reading of content can hold. The second generation is read by sameness and difference. The second generation agrees with the first generation in charge, spin and every interaction, so by the principle of identity the second generation differs from the first generation in mass. The third generation, read by the transcendent pair, takes in every instance that the content of the third generation could be. What a reading holds beyond the fixed characteristic is held as energy, and energy held at rest is mass (Level 5, Section III, citing Level 0). Each step up costs energy, and each step back releases it, which is a decay. The electron's stability rests on structure and measurement together: that nothing of its own kind lies lower is structural, and that no particle of another kind carrying charge lies lower is measured (Level 5, Section III). The order of the masses in each charged sector is structural; the mass values are measured: electron 0.511 MeV, muon 105.7 MeV, tau 1,777 MeV; the muon about 207 times and the tau about 3,477 times the electron's mass. (MeV, read "mega electron volt", is a million electron volts, used as a unit of mass by Einstein's relation, energy equals mass times the square of the speed of light.) The neutrinos are the exception to the structural order: the order of their three masses is a value (Level 5, Section IV).

No particle of the list is optional. *The Story of the Particles*, Coda, Section II: "No particle in the zoo is optional" and "Not the muon (required by the three rotations of the content)".

Three generations allow exactly one phase in the weak force's mixing. *The Story of the Particles*, Level 7, Section III: "and the one phase that three generations allow is how the two come to differ". In words, the weak force reaches each quark's partner (the other member of its doublet) as a mixture of the generations (Level 9, Section V). The table of that mixture can carry phases, a phase being a position on a circle, like the position of the hand of a clock. With two generations every such phase can be removed by resetting the phase of each quark's state, which changes nothing that can be measured. With three generations exactly one phase remains that no such resetting removes. The process and its image compared in the chapter are a process and its mirror-and-charge-conjugate: every particle exchanged for its antiparticle (charge conjugation, written C) and space reflected (parity, written P). The exact mirror between a particle and its antiparticle (the same mass, the same lifetime and the same size of every label) is the one under C, P and time reversal taken together (Level 4, Section II). The weak force breaks the joint mirror of C and P, through the one phase (Level 7, Section III). *Why These Numbers*, Chapter 13: with two generations there is no such phase, and the weak force would treat every process and its mirror-and-charge-conjugate (the joint reflection of charge and parity, written CP) alike. *Geeze, Wublets, and the Higgs*, Level 7, Section V, reaches the same need for three turnings, on the proviso that the breaking lives in the quark table.

A second route to three, from the running of the strong force. *Geeze, Wublets, and the Higgs*, Level 5, Section VI; *The Connes Correspondence*, "Three Generations: An Input and Its Grounds", Section V. In words, the inverse strength of the strong force changes with the logarithm of the energy, at a rate fixed by the particles that carry color. The force particles of color contribute minus eleven to the rate, and each color triplet of one handedness contributes plus one third. One generation has four such triplets, so the measured rate, minus seven, counts twelve triplets, which

is three generations. In symbols: $1/\alpha_3(\mu) = 1/\alpha_3(M_Z) - (b_3/2\pi)\ \ln(\mu/M_Z)$. It is read "one over alpha-three at the energy mu equals one over alpha-three at the mass of the Z, less b-three over two pi times the natural logarithm of mu over the mass of the Z". Here α_3 (alpha-three) is the strength of the strong force, and b_3 (b-three) is its one-loop rate. The rate is $b_3 = -11 + (1/3)n$, read "b-three equals minus eleven plus one third of n", with n the number of color triplets of one handedness, so that $b_3 = -7$ gives $n = 12 = 3 \times 4$. The weak force's rate, $b_2 = -19/6$ (b-two equals minus nineteen sixths), with one Higgs doublet, counts twelve left-handed doublets, again three generations. Standing: an argument from quantum field theory's composition of a one-loop rate (Gross and Wilczek 1973; Politzer 1973, as *The Connes Correspondence* cites them), with no use of the cycle of comparison. *The Grand Synthesis*, Chapter 10, Section III, as *The Connes Correspondence* quotes it, states that the measured running across the energies where all six quarks are active agrees with that rate.

A fourth generation is absent at every mass. *The Story of the Particles*, Level 5, Section II: "It is not that the fourth generation is too heavy to produce". Standing: structural.

The list of kinds is closed. *The Story of the Particles*, Level 9, Section IV, and Coda, Sections I and II; *The Kinds of Particle*, Chapter 6, Section IV. A kind is told from every other by three things: its labels (the phase, the doublet and the colors, in one of four kinds of combination), its generation, and its field kind. The field kinds are a spinor field of the content, a vector field built from a symmetry of the internal space or of the line bundle, and a scalar field on a crossed edge. By the identity principle, a proposed kind agreeing with a known one in all three is that kind. A new kind would need a fourth label, a known label toward the wrong term, a fourth generation or a fourth field kind, and the structure has none. The chapter's "force that light carries" is the force on the phase as it meets us at low energy (Level 7, Section IV), and its "field of the kind the Higgs field is" is the scalar field on the one crossed edge (Level 8). Standing: a structural claim, and a claim about kinds, not values (Level 9, Section V; Coda, Section I: "The argument is not empirical"). *The Kinds of Particle*,

Chapter 6, Section IV: "No further kinds exist: no fourth generation, no supersymmetric partner, no X or Y boson, no graviton, no dark-matter particle of any type".

The list fixes the kinds and the order of the masses in each charged sector; it does not fix the values of the masses. *The Story of the Particles*, Level 9, Section V: "The zoo is the classification; the values are measurement and arithmetic"; heavier composites wait at higher energies, and a new kind does not. *The Story of the Particles*, Coda, Section III: the masses, the couplings and the mixings are measured, and working them out from the structure is arithmetic, which that book does not do. Chapter 5 of this book gives what other books of the collection find of the charges and of the masses.

The descent ends in the structure of comparison. *The Story of the Particles*, Coda, Section IV: "It was a journey into deeper and deeper aspects of what comparison is" and "It is a portrait of the act of knowing the world". The kinds derived are "the kinds of any domain in which comparison is measured" (The Scientists, Section I).

Thomson's measurement and the identity of kinds. *The Particular Evidence*, Case 1, Sections III and IV, tells the 1897 measurement and states: "Thomson's universality is the identity principle made visible".

Measured values told in the chapter

The ratio of mass to charge of the cathode-ray particles, as Thomson gave it at the Royal Institution on 30 April 1897, was about 1.6×10^{-7}, against 10^{-4} for an atom of hydrogen, in the units of his discourse. The path of the rays in a magnetic field was the same in hydrogen, air, carbonic acid and methyl iodide: J. J. Thomson, "Cathode Rays", *Proceedings of the Royal Institution of Great Britain* 15 (1897) 419–432.

The same ratio for every cathode metal and every gas, and more than a thousand times smaller than for the hydrogen ion in electrolysis: J. J. Thomson, "Cathode Rays", *Philosophical Magazine*, Series 5, 44 (1897) 293–316 (as *The Particular Evidence*, Case 1, and *The Alphabet of Particles*, the electron's entry, report it).

The exclusion principle as the rule ordering atomic electrons: W. Pauli, "Über den Zusammenhang des Abschlusses der Elektronengruppen im Atom mit der Komplexstruktur der Spektren", *Zeitschrift für Physik* 31 (1925) 765–783.

The number of light neutrino species from the invisible width of the Z boson, $N_\nu = 2.9963 \pm 0.0074$ (read "N-nu equals two point nine nine six three, plus or minus zero point zero zero seven four"), a difference of 0.12 percent from three: P. Janot and S. Jadach, "Improved Bhabha cross section at LEP and the number of light neutrino species", *Physics Letters B* 803 (2020) 135319 (reported in *The Kinds of Particle*, Chapter 7, Section VII).

The exclusion of a fourth generation of the Standard Model kind by the rate of Higgs production through gluons: A. Djouadi and A. Lenz, "Sealing the fate of a fourth generation of fermions", *Physics Letters B* 715 (2012) 310–314 (reported in *The Kinds of Particle*, Chapter 7, Section VII).

Searches at the Large Hadron Collider for new kinds, as *Side by Side*, Volume One, prints them under its Prediction 30, have found none. The excluded ranges are: gluinos below about 2,300 GeV; a W' with the couplings of the W below about 6,000 GeV; a Z' with those of the Z below about 5,150 GeV; and leptoquarks below about 1,500 to 1,800 GeV. GeV, read "giga electron volt", is a billion electron volts.

The first measured difference between a process and its mirror-and-charge-conjugate, in the decay of the long-lived neutral kaon into two pions: J. H. Christenson, J. W. Cronin, V. L. Fitch and R. Turlay, "Evidence for the 2π Decay of the ${K_2}^0$ Meson", *Physical Review Letters* 13 (1964) 138–140 (in the title, "2π" is read "two pi" and means two pions, and ${K_2}^0$, read "K-two-zero", is the long-lived neutral kaon).

The muon's anomalous magnetic moment: the measured value less the Standard Model value of 2025 is $(38 \pm 63) \times 10^{-11}$: Muon g−2 Collaboration, "Measurement of the positive muon anomalous magnetic moment to 127 ppb", *Physical Review Letters* 135 (2025) 101802; R. Aliberti and others

(Muon g−2 Theory Initiative), "The anomalous magnetic moment of the muon in the Standard Model: an update", *Physics Reports* 1143 (2025) 1–158 (reported in *The Kinds of Particle*, Chapter 6, Section IV).

Chapter 5. Are the Particles' Numbers Just Arbitrary?

Every claim of Chapter 5 that comes from the corpus is listed below in the order the chapter makes it, each with the book, chapter and section that carry it, its standing as that book states it, and its exact values. The measured values the chapter tells follow, with their primary papers.

The charges of one generation

Claim: the up quark carries plus two thirds and the down quark minus one third of the electron's unit, as the unique solution of four premises, so that the proton's charge is exactly plus one. Where: *The Story of the Particles*, Level 6, Section IV, "Fractional Charges" (with Level 0 for the unit and Level 3 for the neutral neutrino); retold in *Why These Numbers*, Ch. 2, "Charges in Thirds". Standing: derived from the structure of comparison; *Why These Numbers* states the charges as set by the structure, "with no measured number in them except that the electron's charge is the unit". The premises, in words: the two members of a weak pair differ by one unit; the neutrino carries no charge; the electron carries the unit, minus one; and the charges of one complete generation, each quark counted once for each of its three colors, add to zero. In symbols: $Q_u - Q_d = 1$ and $Q_\nu - Q_e = 1$; $Q_\nu = 0$; $Q_e = -1$; $3(Q_u + Q_d) + Q_e + Q_\nu = 0$. Read aloud: Q-sub-u and Q-sub-d are the charges of the up and the down quark, Q-sub-nu and Q-sub-e those of the neutrino and the electron, each in units of the magnitude of the electron's charge; the factor three counts the three colors. Result: $Q_u = 2/3$, $Q_d = -1/3$; proton $2/3 + 2/3 - 1/3 = +1$; neutron $2/3 - 1/3 - 1/3 = 0$.

The reason for each premise, as that book gives it. The doublet unit: a doublet is one thing with two sides that differ in one respect, charge (Level 2, Section II, "The Doublet"). The quark doublet and the lepton

doublet are the same two zero-modes of the internal space (Level 6, Section II). So the up-type and down-type quarks differ by the same unit as the neutrino and the electron. The neutral neutrino: the neutrino is the shadow of the known, sharing the electron's kind and carrying none of the characteristics that make the electron visible to light (Level 3, Section II, "The Shadow of the Known"). The unit: the electron's -1 is the unit of the frame (Level 0). The sum rule: charge is the label by which light, the comparing act of this frame, reads content; the act carries no charge; a complete generation is everything of one instance of the content that the act can address; across that whole there is nothing left to set the total against except the act itself; a nonzero total would be a charge read against nothing (Level 6, Section IV). The same section states that this is the principle that made charge conserved at Level 4, applied to the whole of what the act addresses. The ledger with its clerk is the main text's picture of this step.

Color, as the main text glosses it: the charge the strong force acts on, in three kinds. *The Story of the Particles*, Level 6, Section III, "Confinement and Color", reads the three colors as labels for the three positions of comparison inside the content, and adds "The word is only a name; nothing is colored".

Claim: the four anomaly conditions on one generation that are not satisfied by group theory alone reduce to the zero-sum rule, given the doublet unit; quarks alone and leptons alone are anomalous; hydrogen is neutral for every charge of the neutrino. Where: *The Kinds of Particle*, Ch. 5, "The Charges", Section I, "The Algebraic Route to the Charges" (the box "Hydrogen is neutral for every charge of the neutrino"), and Section VIII. Standing: derived (a computation with stated premises). In words, then symbols: with S the total charge of one generation, each quark counted once per color, the mixed weak-hypercharge sum is $S/2$ and the cubic hypercharge sum is minus three quarters of S, so the four nontrivial conditions hold exactly when $S = 0$. With the doublet unit and $S = 0$ at three colors, and the neutrino's charge Q_ν left open, the proton carries $1 - Q_\nu$

and the electron $Q_\nu - 1$, whose sum is zero for every Q_ν; the neutron carries $-Q_\nu$. The quark parts of the two nontrivial sums are $+1/2$ and $-3/4$, the lepton parts $-1/2$ and $+3/4$.

Claim: the unimodularity condition on the unitaries of the algebra $\mathbb{C} \oplus \mathbb{H} \oplus M_3(\mathbb{C})$ reduces the group to $U(1) \times SU(2) \times SU(3)$ up to a finite group, and with the representation of the algebra on the fermion states it gives exactly the Standard Model hypercharges, which are not put in. Where: *Non-Commutative Geometry and the Immanent Metaphysics*, Ch. 14, "The Gauge Group and the Fermion Representations", Sections III, "Unimodularity", and IV, "Hypercharges": "They are not put in: they follow from the representation of Chapter 8 and the unimodularity condition". Standing: a computation in the finite spectral geometry, whose steps that book lists in its Appendix C; the unimodularity condition is that of Chamseddine, Connes and Marcolli. Values: hypercharges $Y = 1/6$ (left-handed quark doublet), $2/3$ (right-handed up), $-1/3$ (right-handed down), $-1/2$ (lepton doublet), -1 (right-handed electron), 0 (right-handed neutrino), in the convention $Q = T_3 + Y$, where Q is the electric charge, T-sub-3 the weak isospin component and Y the hypercharge. The main text gives the two inputs in words: "the particles of one generation, each set in its place in that mathematics" is the representation, and "over all the states together the turns cancel" is the condition that the determinant of each unitary's action on the fermion states is one.

A further route to the same charges, given here: from the kinds of particle (the book's motes), the Higgs field's hypercharge of one half and the consistency of the forces, the cubic hypercharge sum is $-(3t - 1/2)^3$, which vanishes at one value only, $t = 1/6$, and that value fixes every charge. Where: *Geeze, Wublets, and the Higgs*, Level 5, "The Measure of Charge", Sections I and III to V. Standing, as that book states it: the charges are reached in the cases it calls tines A and B0 (the two readings of whether the second side of the lepton doublet, the book's plain, has a right-handed partner: in tine A it has none, in tine B0 its partner carries no mark of any kind); in the third case, tine $B\pm$ (the second reading, with a

charged partner), every sum vanishes for every t and the charges are not fixed, and that case is excluded by the rule that I call the Place Rule in that book (the principle that the immanent holds no place of its own inside content), a premise of that book, which I state in its after-note, in every standpoint, as unimodularity. Symbol read aloud: t is the hypercharge of the left-handed quark doublet, left unknown until the sum fixes it.

Claim: every whole complete in color carries a whole-unit charge, and every free particle yet observed carries a whole multiple of the electron's charge. Where: *The Story of the Particles*, Level 6, Sections III and IV; *Geeze, Wublets, and the Higgs*, Level 5, Section V, "Thirds, Never Alone"; *The Unquantized Arena*, Ch. 5, Section V, "Marker 4: No Discrete Charge"; *The Particular Evidence*, Case 1, "The Glow in the Tube", Sections III and IV. Standing: the first is derived; the second is a measured fact cited.

A value that lands

Claim: a value that agrees with measurement before the reason for the value is found is a question, and the value is evidence of a reason not yet known. The word "coincidence" says that the agreement has no reason, which no one has shown. As a grade, "coincidence" closes the inquiry where the question opens the inquiry. Where: *Physics Is Not Math*, Ch. 13, "A Value That Lands", Sections III to V; Balmer's rule and Bohr's reason are told in Section III. Standing: the book's own argument about method, with two historical cases. Balmer's rule, in words then symbols: the wavelength of a line is a fixed length times the square of a whole number divided by that square less four; $\lambda = \mathrm{h}\,\mathrm{m}^2/(\mathrm{m}^2 - 4)$, with $\mathrm{h} = 364.56$ nanometers and $\mathrm{m} = 3, 4, 5, 6$, giving 656.2, 486.1, 434.0 and 410.1 nanometers, and 397.0 nanometers for $\mathrm{m} = 7$. Read aloud: lambda is the wavelength, m the whole number, h Balmer's fixed length. Ångström's four measured wavelengths are about 656, 486, 434 and 410 nanometers (a nanometer is a millionth of a millimeter).

The ladder of masses

The strip of paper, with its values: the top at 172.60 GeV; seven folds give 172.60/128 = 1.35 GeV; the charm at 1.27 GeV sits 7.08 halvings below the top; the electron at 0.511 MeV is about 338,000 times lighter than the top, between 2^{18} (about 262,000) and 2^{19} (about 524,000). Where: *Why These Numbers*, Ch. 9, "Folding the Top in Half".

Claim: one comparison is one halving, so the ladder of masses counts in base two. Where: *Why These Numbers*, Ch. 9, "Why the Ladder Counts in Twos": one comparison divides the open possibilities in two, "and the book reads that division, counted in mass, as a division of the mass by two"; the same chapter recalls Ch. 7, where one comparison is one bit and one bit, read in mass, is one halving. Standing: set by the structure (the form of the ladder).

Claim: every charged particle of matter sits a counted number of halvings below the top quark, by one formula with three numbers per family and one shared step factor. Where: *Why These Numbers*, Ch. 9, "Families, Rungs and One Formula" and "Why the Formula Has This Shape"; the values are carried by *The Measures of the Kinds*, Ch. 7 and later. In words: the count of halvings by which a member of a family sits below the top is the family's offset, plus the generation number times the family's step cost, plus the generation number squared times the family's curvature, all multiplied by the step factor; the generation number is zero for the heaviest generation, one for the middle and two for the lightest. In symbols: $n(s, g) = (o_s + g\,k_s + g^2\,c_s)\,f$. Read aloud: n of s and g is the count of halvings below the top for family s at generation number g; o-sub-s is the offset, k-sub-s the step cost and c-sub-s the curvature of family s; f is the step factor. Values: f = 1.0128448; up quarks o = 0, k = 6, c = 1; down quarks o = 53/10, k = 6, c = −7/12; charged leptons o = 391/60, k = 9/4, c = 16/9. The main text calls the offset the starting place, the step cost the step, and the curvature the widening. The gap from generation 0 to gener-

ation 1 is (k + c) f, and from generation 1 to generation 2 it is (k + 3c) f; for the up quarks, k + c = 7 and k + 3c = 9 (Ch. 9, "Ladders That Speed Up and Slow Down").

The step factor, from *Why These Numbers*, Ch. 10, "The Step Factor and Its Leftover" and "What the Z Mass Requires". In words: the step factor is one, plus the small leftover, less twenty-eight fifths of the small leftover squared. In symbols: $f = 1 + \varepsilon - (28/5)\,\varepsilon^2$, with $\varepsilon = 11/(80\pi^2) = 0.013932$. Read aloud: epsilon is the small leftover, eleven divided by the product of eighty and pi squared. In percent: the small leftover is 1.3932 percent, the second-order part $(28/5)\varepsilon^2$ is 0.1087 percent, and the whole excess $f - 1$ is 1.2845 percent; the main text gives these as about one and four tenths, about a tenth, and about one and a quarter percent. Standing of the first-order part: the small leftover is the mismatch between a counted measure and its smooth reading, the mark that the Incommensuration Theorem leaves on the particle side, with eleven as three squared plus two and eighty as four squared times five. Standing of the second-order coefficient: "The Z mass sets the coefficient"; for the settled Z mass to equal the measured 91.19 GeV the step factor must be 1.0128436, and "the landing of twenty-eight fifths is measured, with its reason still a question"; the muon requires the same coefficient from a measurement that does not enter the Z mass. *Why These Numbers*, Ch. 1, "Which Numbers Measurement Supplies", states the general case: measured information also enters through constants that are fixed by agreeing with measurement, and that each number such a constant touches lands on measurement is measured, with its reason still a question.

Standing of the form and of each number, as the book states it. The form is set by the structure: three generations give three points, and three points fix exactly a zero, a unit and an extent. The quark step cost of six is set by the structure, from six independent verdicts of two outcomes each, one for each of the six aspects of comparison (Ch. 9, "Six Verdicts, Six Halvings"); it rests on one premise, that no aspect is fixed by the other five. The six aspects are sameness and difference, content and context, the subjective and the objective, three positions times two poles; the main text

gives them as the two sides of each of the three respects in which Chapter 4 reads a particle of matter. The lepton step cost of nine quarters is set by the structure at first order, as six times three eighths, three eighths being the charged leptons' share of one generation's squared charges (Ch. 9, "The Leptons' Share"): squared charges with three colors and two hands sum to 16/3, and the charged lepton's part is 2, so the share is 2 divided by 16/3, which is 3/8. The main text counts one hand only (8/3 and 1), which gives the same share. The ground for paying a share is the book's share rule (Ch. 9, "Four Families and the Rule of Color" and "The Leptons' Share"): at the third scale of comparison, the scale of the three colors, the quarks are the content and the leptons its two contexts, so the quark ladder is the one content ladder, the whole, and pays its step cost undivided, while each context ladder pays its share of the whole that the comparing act reads; the book reads the rule from *An Immanent Metaphysics*, aphorisms 1.47-5 and 1.47-6. *The Kinds of Particle* writes the same share as the kernel ratio $3/(3+5)$. The three curvatures are set by the structure (Ch. 9, "How Each Ladder Bends"), and they close: $3 \times (16/9) + 4 \times (-7/12) = 3 \times 1$. Read aloud: three times the lepton curvature plus four times the down curvature equals three times the up curvature; the closure holds for any pair of legs of the triangle, and the down value, three quarters less four thirds, fixes the lepton curvature as a square. The up curvature is one because the up sector is comparison measuring itself, whose extent is the identity. The two ladder offsets, 53/10 and 391/60, are found by a condition from the measured bottom quark and the measured tau, and enter as measured, each with the question why its writing in the triangle's numbers lands (Ch. 9, "Why the Formula Has This Shape"; Ch. 10; Ch. 18, "Two Accounts of What Measurement Supplies"). The electron's mass is the measured unit (Ch. 9, "What the Ladder Counts Against").

The triangle, from *Why These Numbers*, Ch. 2, "Three and Two", "A Triangle on a Napkin" and "Why It Is the One Triangle". Comparison gives two whole numbers: three, the count of its positions, and two, the count of the pair content and context. On the side of content every measure is a

count, so the sides are whole numbers, and the radius of the inner circle is the unit, one. With whole-number sides and a radius of one, the three touching distances (from each corner to the points where the inner circle touches the two sides meeting there) must add up to what they multiply to, and only one, two and three do: one, two and three are the sizes of comparison's three basic sets (the one who compares, the two members of a pair, the three pairs of aspects). Each side is the sum of the touching distances at its two ends: $1 + 2 = 3$, $1 + 3 = 4$, $2 + 3 = 5$; the corner with touching distance one is a right angle, and $9 + 16 = 25$ follows. The triangle with sides three, four and five is the only whole-number right triangle whose inner circle has radius one.

The ladder's baseline, exactly as *Why These Numbers*, Ch. 9, "What the Formula Is Tested By", states it: "For the three charged sectors the formula holds nine numbers, which stand as a table of three rows, one row each for the up quarks, the down quarks and the charged leptons, and each row holds an offset, a step cost and a curvature. The up offset is zero, by the reference. The rest are two step costs (six and nine quarters), three curvatures (one, minus seven twelfths and sixteen ninths), two ladder offsets (five and three tenths, and six and thirty-one sixtieths), and the step factor: eight numbers, as many as the eight charged particles of matter heavier than the electron. For any values of eight masses there are eight numbers that reproduce them. So the formula is tested by its numbers: the test lies in their fractions and in the identities among them, and not in the agreement of the undressed formula with the masses alone. The numbers that reproduce the masses lie close to simple fractions of three, four and five, and they satisfy three identities among themselves". The same chapter's Summary: "The formula holds eight numbers for the eight charged masses above the electron, and eight numbers can always be found to fit eight masses. The ladder's test lies in its fractions and the identities among them". Ch. 10, "The Test Lies in the Fractions", names what that test holds: the constants are simple fractions of three, four and five, each an exact measure of the triangle in the slot of its own kind; they close among themselves (the quark doublet at five halves, the three

curvatures at three, the charge-weighted curvatures at thirty-five quarters); the two ladder offsets are written in one unit form over sixty; the step factor's leftover, $11/(80\pi^2) = 0.013932$, is met at four places by four measurements that share nothing; and the lepton ladder gives the span's second-order constant from the charged leptons alone.

Measured agreements the chapter gives in words (all from *Why These Numbers*, Ch. 9, with the Particle Data Group's masses of 2024 and 2026 as that chapter states them). The joint quark step cost from the measured masses is 5.9989 ± 0.0044 with the light quarks read at 2 GeV, undressed; 5.9921 at the floor of twice the proton's mass; dressed, 6.0044 and 5.9976. The ratio of the lepton step cost (2.24974, from the tau and the muon) to the joint quark step cost is 0.37502 ± 0.00028, against $3/8 = 0.375$. The charm stands 7.0832 halvings below the top, and the ladder places it at 7.0825. On the up ladder, in steps of the step factor, the top, the charm and the up stand at 0, 7 and 16. From the electron alone the bare lepton ladder gives the muon at 205.18 and the tau at 3468.88 electron masses, against the measured 206.7682827 and 3477.37 (0.77 and 0.24 percent low); in ratios to the electron the offset drops out, and nothing is set against measurement except what goes into the step factor (*Why These Numbers*, Ch. 11, "The Muon from the Electron").

The muon at full precision: with the turnover (the lepton ladder's dressing, with coupling one sixth of the small leftover and second-order constant seven ninths) the muon is 206.7682862 electron masses, against the measured 206.7682827, about two parts in a hundred million apart (*Why These Numbers*, Ch. 11, "The Turnover"). The muon's window for the second-order constant, two margins each side, runs from 0.77623 to 0.78119, and among all fractions with bottom numbers up to forty seven ninths alone lies in it; the book states that the muon "pins the dressing to about two parts in a hundred million". Standing of the muon, as Ch. 18, "The Twenty-Six Numbers", states it: set by the structure on the ladder to first order, and at its full precision measured, with its reason still a question (the turnover's coupling and its second-order constant seven ninths are premises, and the landing of each is a question the book states).

The ceiling and the top quark's coupling

Claim: every coupling to the condensate lies between zero and one, so no particle of matter is heavier than $v/\sqrt{2} = 174.1036$ GeV. Where: *Why These Numbers*, Ch. 17, "The Ceiling"; Ch. 18, "What Is Set, What Lands, What Decides". Standing: set by the structure (the ceiling); the mass rule $m = y\,v/\sqrt{2}$ is standard physics. Read aloud: m is the mass of a particle of matter, y its coupling to the condensate, v the vacuum value of the Higgs field, 246.21967 GeV (measured).

Claim: the top quark's coupling to the condensate is exactly one. Where: *The Story of the Particles*, Level 8, Section IV, "What About the Fermions?", and Level 9, Section V; *Why These Numbers*, Ch. 2, "What the Structure Sets, and What Measurement Fills In", and Ch. 17, "The Top's Coupling of One". The reason, as Ch. 17 gives the argument of *The Story of the Particles*: the up-type family sits at the immanent position, the comparing act turned upon its own content; the extent of that position is the identity, and the comparison of a thing with itself yields exactly one; only the third-generation member, the top, has a reading that takes in all that its content could be, so it alone meets the whole. Standing: a structural value, with the scheme in which the one is read fixed by convention and not by measurement; every value of the top's mass is measured, with its reason still a question (*Why These Numbers*, Ch. 18, "The Twenty-Six Numbers"). Values: the measured coupling $\sqrt{2}\,m_t/v$ is 0.99136; the measured top sits 0.01251 halvings below the content whole of 174.10 GeV, which stands 0.87 percent above the measured top; the book reads that shortfall as one small leftover at first order, which lowers the whole to 172.43 GeV. The route of *Geeze, Wublets, and the Higgs* reaches the ceiling (173.9 GeV from 246 GeV over $\sqrt{2}$) from "A part is never more than the whole" and holds its occupant undecidable from its own basis (*Geeze, Wublets, and the Higgs*, Level 7, Sections I to III).

Koide's relation

Claim: the masses of the electron, the muon and the tau satisfy Koide's relation; with it the tau follows from the electron and the muon; the quarks are not predicted to obey it. Where: *Why These Numbers*, Ch. 11, "The Electron, the Muon and the Tau", from "Three of One Kind" to "The Tau from the Electron and the Muon"; the argument is given by *The Measures of the Kinds* and retold in *Why These Numbers*; which kinds obey, from their kind alone, is stated in *Geeze, Wublets, and the Higgs*. Standing: set by the structure once a stated step is taken, the step being that each part of the masses' arrow (the common part and the differing part) is measured by its share of the squared size (*Why These Numbers*, Ch. 1, "Four Ways a Number Can Stand"; Ch. 11, Summary). In words, then symbols: the sum of the three masses divided by the square of the sum of their square roots is two thirds; $K = (m_e + m_\mu + m_\tau)/(\sqrt{m_e} + \sqrt{m_\mu} + \sqrt{m_\tau})^2 = 2/3$. Read aloud: K is Koide's quantity; m-sub-e, m-sub-mu and m-sub-tau are the masses of the electron, the muon and the tau. Equivalently, the arrow of the three square roots stands at forty-five degrees to the direction in which all three are equal, so the sameness share is one half. The reason the quarks are not predicted to obey: the equal-weight argument holds for a kind whose three instances are read against one context only, the condensate; for the quarks, color is a second context (Ch. 11, "Where the Relation Holds, and Why the Quarks Do Not Obey"). Values: from the measured masses $K = 0.66666446 \pm 0.00000508$, against $2/3 = 0.66666667$; the tau from the measured electron and muon with one sign for the three square roots is 1776.969 MeV (read back from the vacuum value in Ch. 18: 1776.9691 MeV), against the measured 1776.93 ± 0.09 MeV. The quark triples give $K = 0.849$ (up, charm, top) and 0.731 (down, strange, bottom), from the Particle Data Group's quark masses of 2024. The two routes to the charged leptons' masses, the ladder and Koide's relation, share only the electron (Ch. 11).

The count and the standing of the numbers

Claim: the Standard Model as first written has nineteen adjustable numbers, and Dirac neutrinos add seven, for twenty-six. Each of the twenty-six numbers has one standing: set by the structure; set by the structure once a stated step is taken; measured; or measured, with the reason for the number still a question. The seven numbers of the neutrinos stand at forks, each carried by two arguments side by side until a measurement decides between the two arguments. Where: *Why These Numbers*, Ch. 1, "Counting the Numbers" and "Four Ways a Number Can Stand"; Ch. 18, "The Twenty-Six Numbers"; *The Story of the Particles*, Coda, Section III, "The Boundary". Standing: the count is a count; the standings are those the book states, number by number, in its Ch. 18 table. The nineteen: nine masses of charged particles of matter, three quark mixing angles and one quark phase, three strengths of force, the Higgs mass and the vacuum value, and the strong force's angle; the seven: three neutrino masses, three lepton mixing angles and one lepton phase. The authors' twenty-one (*We Have No Idea*, ch. 16, "How Will We Know If We Are Done?"): twelve masses of quarks and leptons (the nine charged masses and the three neutrino masses), four quark mixing parameters, three strengths of force and two parameters of the Higgs theory; adding the three lepton mixing angles, the lepton phase and the strong force's angle gives the twenty-six.

Claim: in the working account measurement supplies the electron's mass (the unit), the strength of light, the strength of color, the vacuum value and the two ladder offsets; in the closure account, with the step written as a product, "the legend shrinks to one line, the electron's mass, for the chain that reaches the vacuum value, the top and the Higgs mass"; both accounts are true, and the vacuum value stands measured, with the electron's value beside it. Where: *Why These Numbers*, Ch. 18, "The Legend of the Map" and "Two Accounts of What Measurement Supplies". Standing: as stated; the closure account rests on a stated identification of the factor each domain supplies to the product step. Values from the closure account: the vacuum value 246.21966 GeV against the measured 246.21967 GeV; the top 172.5622 GeV against the measured 172.60 GeV.

Claim: the structure draws the proportions, and measurement supplies what the proportions leave open. Where: *Why These Numbers*, Ch. 1, "Four Ways a Number Can Stand" (the tailor's pattern, the main text's picture, for a measured number) and Ch. 18, "The Legend of the Map" ("The structure draws the proportions ... Measurement writes the legend"), after *Two Theories, One World*, Ch. 15, "Its Role and Its Size" (there said of Newton's constant and the scale of the world: the axioms draw the proportions, and the measured value of Newton's constant writes the legend). Standing: the book's argument.

Claim: every number is to reach one of two ends, derivation through the law of that number or a proof that no law fixes that number. A value shown not derivable is closed under reason as fully as a derived value. No comparison's verdict depends on a unit, so no unit is derived. Where: *Why These Numbers*, Ch. 1, "Two Ends for Every Number", "Two Questions in One" and "Units and Pure Numbers". Standing: the book's argument.

Measured values told in the chapter, with their primary papers

The four visible lines of hydrogen, about 656, 486, 434 and 410 nanometers (Ångström's measurements), and Balmer's rule: J. J. Balmer, "Notiz über die Spectrallinien des Wasserstoffs", *Annalen der Physik und Chemie* 25 (1885) 80–87. Bohr's reason: N. Bohr, "On the Constitution of Atoms and Molecules", *Philosophical Magazine* 26 (1913) 1–25. The unit of charge from oil drops, 1909 to 1913: R. A. Millikan, "On the Elementary Electrical Charge and the Avogadro Constant", *Physical Review* 2 (1913) 109–143. Hard scattering of electrons inside the proton: E. D. Bloom and others, "High-Energy Inelastic e–p Scattering at 6° and 10°", *Physical Review Letters* 23 (1969) 930–934; M. Breidenbach and others, "Observed Behavior of Highly Inelastic Electron-Proton Scattering", *Physical Review Letters* 23 (1969) 935–939. The discovery of the top quark: CDF Collaboration, F. Abe and others, "Observation of Top Quark Production in $\bar{p}p$ Collisions", *Physical Review Letters* 74 (1995) 2626–2631; D0 Collaboration, S. Abachi and others, "Observation of the Top Quark", *Physical Review Letters* 74 (1995) 2632–2637. The top's direct mass, 172.60 $\pm$ 0.27 GeV, as *Why These*

Numbers takes it from the Particle Data Group's edition of 2026 (F. Takahashi and others, *International Journal of Modern Physics A* 41 (2026) 2630011). The tau, 1776.93 $\pm$ 0.09 MeV: Particle Data Group, S. Navas and others, "Review of Particle Physics", *Physical Review D* 110 (2024) 030001. Koide's relation: Y. Koide, "A Fermion-Boson Composite Model of Quarks and Leptons", *Physics Letters B* 120 (1983) 161. Koide's quantity from the measured masses, 0.66666446 $\pm$ 0.00000508, as computed in *Why These Numbers*, Ch. 11, "What the Measurement Says", with the electron and muon from the recommended values of 2022 and the tau from the Particle Data Group's average of 2024.

Chapter 6. What Is Mass?

Each paragraph below gives one claim of the chapter, where the corpus carries it, its standing as that book states it, and its exact values. Symbols are read aloud where they first appear.

The field

Claim: a field is something spread through all of space whose smallest ripples are the particles, and the Higgs boson is a quantum of the Higgs field. Where: *The Story of the Particles*, Level 0, Section II ("The Comparing Act"), and Glossary, "Field"; Level 8, Section V ("The Higgs Particle"). Standing: a definition (the field), and a stated fact of physics (the Higgs particle as the quantum of its field, found at 125 GeV).

The share of the proton's mass

Claim: about ninety-nine percent of the proton's mass comes from the color field, the motion and binding of quarks and gluons, and the three quarks supply about one percent. Where: *Why These Numbers*, Chapter 8, "What You Weigh When You Weigh Yourself"; *The Matter We Know*, Volume One, Chapter 2, Section VII ("Where the Proton's Mass Comes From"). Standing: standard physics, reported (*Why These Numbers*, Chapter 8: "Standard physics gives the share"). Values: the proton's mass is 938.272 MeV (a MeV, a million electron volts, is used as a unit of mass

by dividing by the speed of light squared); an up quark is about 2 MeV and a down quark about 5 MeV, so the three quarks of a proton come to about 9 MeV, about one percent.

Claim: the mass of a whole at rest is its total energy in its rest frame divided by the speed of light squared, and that energy is the sum of the parts' rest energies, the energies of their motion inside the whole, and the energy of the binding field. Where: *Why These Numbers*, Chapter 8, "How a Whole Weighs More, or Less, Than Its Parts"; *The Matter We Know*, Volume One, Chapter 2, Section VII. Standing: standard physics (special relativity). In words first: mass at rest equals energy at rest over the speed of light squared, and that energy has three parts. In symbols: $M = E_{rest} / c^2$, with $E_{rest} = \Sigma\, m_i c^2 + K + U$. Read aloud: M, the mass of the whole; E_{rest}, its total energy seen by an observer at rest with it; c, the speed of light; $\Sigma\, m_i c^2$, the sum over the parts of each part's mass times c squared; K, the energy of the parts' motion inside the whole; U, the energy of the field that binds them, negative for a whole lighter than its parts.

Claim: a hydrogen atom is lighter than a free electron and a free proton by its binding energy. Where: *Why These Numbers*, Chapter 8, "How a Whole Weighs More, or Less, Than Its Parts"; *The Matter We Know*, Volume One, Chapter 2, Section VII. Standing: standard physics. Values: the binding energy is 13.6 eV; the hydrogen atom's mass is about 938.78 MeV; the ratio is 13.6 eV / $(938.78 \times 10^6$ eV$) \approx 1.45 \times 10^{-8}$, about one and a half parts in a hundred million.

Claim: the proton's mass has been computed from the theory of the strong force on a grid of points in space and time. Where: *The Matter We Know*, Volume One, Chapter 2, Section VII; *Why These Numbers*, Chapter 8, "The Stretched Tube". Standing: reported measurement and computation. Values: Dürr and colleagues (2008), with the masses of the pion, the kaon and one other hadron as their only inputs, computed the nucleon at 936 MeV, with an uncertainty of 25 MeV from the random scatter of the computation and 22 MeV from its method, against the measured 939 MeV; 936/939 differs from one by 0.32 percent.

Why the binding is inertia

Claim: a state of motion is a relation of a content to its context, and inertia is the resistance of a content to a change in its relation to its context. Where: *The Gravitational Companion*, "One Mass, Three Elevators", Section II ("Inertia Is a Comparison"), resting on *The Gravitational Passage*, Chapter 18, Section IV. Standing: derived from comparison ("a difference that no comparison can register is no difference"); the book states that general relativity alone does not give it, since its equations allow empty solutions that still have inertial frames.

Claim: the binding of the quarks is part of the proton's inertia, because it stays inside the proton, cannot pass out of it, and is found again with the proton every time the proton is met. Where: *Why These Numbers*, Chapter 8, "How a Whole Weighs More, or Less, Than Its Parts". Standing: argued from the structure of comparison alone, with no measured number; the size of the share, about ninety-nine percent, rests on standard physics. That the binding is inertia rests on comparison, and how much of the inertia it is rests on standard physics; the two statements have two separate grounds, and both hold. In Why These Numbers I state the two bases in one sentence: "Comparison gives the first statement, standard physics the second, and both hold".

Pattern, and one relation found three times

Claim: the pattern of a content is how much of it there is to be found, how many comparisons it can enter; since to compare, to interact and to relate are one act, every finding is an interaction, and physics measures the capacity of a content to be found by its energy, and, for a body at rest, by its mass. Where: *The Gravitational Companion*, "One Mass, Three Elevators", Section IV ("The Third Finding: Pattern"), resting on the Root Tautology (the identity of comparison, interaction and relation: one act under three names) of *The Gravitational Passage*, Chapter 1, Section IV. Standing: argued from comparison; the measure of the count by energy and momentum is stated through the Root Tautology.

Claim: weight (the hold of the context on a content) and inertia (the content's resistance to a change of its place in the context) are one quantity, and pattern (how much of the content there is to be found) is what that quantity measures; mass is the measure of that one relation. Where: *The Gravitational Passage*, Appendix A, Section II; *The Gravitational Companion*, "One Mass, Three Elevators", Sections III and IV. Standing: an identification, made in the first person in the Passage ("I take the coupling as the degree of participation in the context, and the inertial response as the degree of resistance to change of context, and I identify the two as one quantity"); the chapter states it once, in the first person. The ground the Companion gives: "that is the only relation of a content to the context that the context offers", so "the coupling and the inertia have nothing to differ by", while a charge, a separate label of the content, leaves a charge and an inertia two things to differ by. Value: gravitational and inertial mass are measured equal to about one part in 10^{15} (Touboul and colleagues 2022, as both books report it); Chapter 7 tells that measurement.

Claim: the mass of a body follows the pattern, the arrangement and motion of its parts: a hot body weighs more than the same body cold, a wound spring more than the same spring unwound, a box of light more than the empty box. Where: *The Gravitational Companion*, "One Mass, Three Elevators", Section V ("The Proton and Light"); *Measurement*, Chapter 7, Section I ("The mass follows the pattern of the relations among the parts"). Standing: stated as standard physics, with Ji (1995) and Dürr and colleagues (2008) cited for the proton.

Claim: a body that gives off light loses inertia in proportion to the energy given off. Where: *The Gravitational Companion*, "One Mass, Three Elevators", Section IV; Einstein (1905). Standing: established physics.

The cup

The chapter's figure for the cup is computed from standard values, with stated assumptions: the coffee is taken as three hundred grams of water, with specific heat 4186 joules per kilogram per kelvin, cooling by sixty kelvin, in a lidded cup that loses no water. In words first: the heat

given off is the mass of water times its specific heat times the fall in temperature, and the loss of mass is that heat divided by the speed of light squared. In symbols: $Q = m_w\, c_p\, \Delta T$ and $\Delta m = Q / c^2$. Read aloud: Q, the heat given off; m_w, the mass of the water; c_p, its specific heat; ΔT, the fall in temperature; Δm, the loss of mass; c, the speed of light. Values: $Q = 0.300\ \text{kg} \times 4186\ \text{J kg}^{-1}\ \text{K}^{-1} \times 60\ \text{K} \approx 7.53 \times 10^4\ \text{J}$; $\Delta m \approx 7.53 \times 10^4\ \text{J} / (2.998 \times 10^8\ \text{m s}^{-1})^2 \approx 8.4 \times 10^{-13}\ \text{kg}$, which is 8.4×10^{-7} mg, a little less than a millionth of a milligram.

Three meanings of mass

Claim: mass means rest mass for the electron, exchange mass for the photon and confinement mass for the proton, one meaning for each position of comparison; mass and charge each come in three versions, one for each position. Where: *The Story of the Particles*, Level 0, Section V ("What Are the Three Meanings of Mass?"); *Why These Numbers*, Chapter 8, "Three Meanings of Mass". Standing: an argument of *The Story of the Particles* from the three positions of comparison (Axiom III for the inseparable parts of the proton), with the proton's measured values as its illustration.

Claim: the quarks can never be taken out of the proton, because the gluons carry color themselves and attract one another, so the field between two quarks pulled apart gathers into a tube whose energy grows with its length, and the tube breaks by making a new pair of quarks. Where: *Why These Numbers*, Chapter 8, "The Stretched Tube" (the rubber band is that section's picture). Standing: standard physics (confinement of color).

Claim: the proton-to-electron mass ratio is a ratio across meanings (confinement over rest), its two masses set by two different laws, and the muon-to-electron ratio is a ratio within one meaning. Where: *Why These Numbers*, Chapter 8, "What You Weigh When You Weigh Yourself" ("The two masses are set by two different laws") and "Three Meanings of Mass". Standing: stated by the book; it names the law that joins the two masses of a ratio its joining law, and says of the proton and the electron:

"the joining law is the binding of the strong force, and that law turns the ratio into a statement about the strength of the strong force at one resolution". Values: the proton-to-electron mass ratio is 1836.15 (Particle Data Group 2024); the muon-to-electron ratio is about 206.77.

Claim: read through its reduced Compton wavelength, mass is how tightly the quantum of action is packed into space. Where: *The Measures of the Kinds*, Chapter 7 ("The Mass Ladder"), Section I. Standing: a definition used as a second picture of the same mass ("The relation between mass and wavelength is a definition and changes no number"). In words first: the heavier the particle, the shorter the length tied to it. In symbols: $\lambda\!\!\!^{-} = \hbar / (mc)$. Read aloud: $\lambda\!\!\!^{-}$, the reduced Compton wavelength; $\hbar$, the reduced Planck constant (the quantum of action divided by two pi); m, the mass; c, the speed of light. Value given there: the top quark's mass of 172.60 GeV corresponds to $\lambda\!\!\!^{-} = 1.143 \times 10^{-18}$ m.

What the Higgs field does

Claim: a mass joins a particle's two handednesses, because a particle with mass moves slower than light, so an observer can overtake it, and seen by the overtaking observer its motion is reversed and its handedness with it. Where: *The Matter We Know*, Volume One, Chapter 2, Section VIII ("The Light Pions, and Why Every Meson Decays"); *Geeze, Wublets, and the Higgs*, Level 8 ("The Ghosts"), Section III ("A mass joins the two hands into one line, so the line carries both hands at once, and the handedness of its motion is not the same for every observer"). Standing: standard physics (special relativity); the football is the chapter's picture of it.

Claim: a fermion acquires mass by coupling to the condensate with a strength of its own, the stronger the coupling the larger the mass; the condensate joins each particle's left-handed component (which carries the weak doublet) to its right-handed component (which does not), and that joining is its mass. Where: *The Story of the Particles*, Level 8, Section IV ("What About the Fermions?"). Standing: an argument of the book from the edge between the two sides of the doublet. In words first: a fermion's mass is its coupling times the condensate's value divided by the square

root of two. In symbols: $m_f = y_f \, v \, / \, \sqrt{2}$. Read aloud: m_f, the fermion's mass; y_f, its coupling to the condensate; v, the condensate's value, 246.22 GeV. Values: the top quark's coupling is exactly one by structure, "a role fixed by structure, and one is its measure"; the value obtained from the top's mass, $\sqrt{2} \times 173$ GeV / 246 GeV, is about 0.99 (*The Story of the Particles*, Level 8, Section IV); the electron's coupling is $\sqrt{2} \times 0.511$ MeV / 246,220 MeV $\approx 2.9 \times 10^{-6}$ (*Why These Numbers*, Chapter 8, "What You Weigh When You Weigh Yourself").

Claim: with the condensate switched off, the elementary fermions would be massless, protons and neutrons would keep most of their mass, the pions would lose all of theirs, and the W and Z would be nearly massless, so that the weak force would reach almost as far as light. Where: *The Story of the Particles*, Level 8, Section V; *Why These Numbers*, Chapter 8, "Switching Off the Higgs". Standing: derived; *Why These Numbers* gives the four steps ('t Hooft anomaly matching and Goldstone's theorem): the trines (wholes of three quarks, one of each color, such as the proton and the neutron), of spin one half, keep their binding mass, so the chiral transformations (the separate turnings of the left-handed and right-handed light quarks among themselves) are hidden in the ground state, and the pions, of spin zero, are the massless wholes. Value: the W and Z would keep a small mass, about 30 MeV, from the quarks' own pairing, the hidden chiral symmetry of the strong force, taking three of the massless pions as their extra motions (*The Story of the Particles*, Level 8, Section V).

Claim: the size of an atom and the gaps between its energy levels depend mainly on the electron's inertia, and on the proton's only through a small recoil, a correction of about one part in 1836. Where: *Why These Numbers*, Chapter 8, "Three Meanings of Mass". Standing: standard physics.

Energy as a relation

Claim: energy is no seventh measure but a relation expressible in the six measures (pattern, space, force, time, probability, possibility); rest mass and energy are one currency, and the sources of mass are distinct.

Where: *Measurement*, Chapter 7 (“Units, Constants and the Limits of a Domain”), Section I (“The Grid as the Frame of Units”). Standing: stated by the book, from its grid of the six measures taken as the frame of units; the currency ($E = mc^2$ for a body at rest, $E = pc$ for a body with no mass at rest) is standard physics. In words first: the energy of a body at rest is its mass times the speed of light squared; the energy of a body with no mass at rest is its momentum times the speed of light. In symbols: $E = mc^2$ (at rest) and $E = pc$ (no rest mass). Read aloud: E, energy; m, mass at rest; p, momentum; c, the speed of light.

Measured values told in the chapter, with their primary papers

The new boson, 4 July 2012: ATLAS reported a new particle near 126 GeV and CMS near 125 GeV, each at five standard deviations, as the CERN press release of that day states; the papers are ATLAS Collaboration, “Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC”, *Physics Letters B* 716 (2012) 1–29, and CMS Collaboration, “Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC”, *Physics Letters B* 716 (2012) 30–61.

The nucleon from the theory of the strong force: S. Dürr and others, “Ab initio determination of light hadron masses”, *Science* 322 (2008) 1224–1227; nucleon $936 \pm 25 \pm 22$ MeV against the measured 939 MeV.

The inertia of energy: A. Einstein, “Ist die Trägheit eines Körpers von seinem Energieinhalt abhängig?”, *Annalen der Physik* 18 (1905) 639–641.

The division of the proton’s mass within the theory of the strong force: X. Ji, “QCD analysis of the mass structure of the nucleon”, *Physical Review Letters* 74 (1995) 1071–1074.

The masses of the proton, the electron, the muon and the quarks: Particle Data Group, S. Navas and others, “Review of Particle Physics”, *Physical Review D* 110 (2024) 030001; the binding energy of hydrogen as the Committee on Data for Science and Technology recommended in 2022.

Chapter 7. Why Is Gravity So Different from the Other Forces?

The chapter's claims from the corpus, each with the book that carries it, its standing as that book states it, and its exact values.

The three forces

Claim: a force is a change, a change is a comparison of before with after, and structured content carries exactly three things a comparison can act on (color, the doublet, the phase), one per position of comparison, so there are exactly three forces. Source: *The Story of the Particles*, Level 7, Section I ("A force, in the deepest sense, is a change"; "Therefore there are exactly three ways that comparison can transform structured content"); *Why These Numbers*, Chapter 2, "Three Ways to Change, and Twelve Carriers" ("A force, at root, is a change, and a change is itself a comparison, of before with after"). Standing: an argument of that book, from the three positions of comparison; the book adds that there is no fourth way "because comparison has no fourth position".

Claim: each of the three belongs to one position: color to the known (the thing compared), the doublet to the beyond (the thing compared against), the phase to the act of comparing. Source: *Why These Numbers*, Chapter 2, "Three Ways to Change, and Twelve Carriers" ("the strong force to the known, whose pattern is color; the weak force to the beyond, whose two sides are the doublet; the force on the phase to the act, which reads every state through its phase"); *The Story of the Particles*, Level 7, Section VII (the strong force "the omniscient force", the weak force "the transcendent force", the force on the phase "the immanent force"). Standing: an assignment of that book, from the roles of the three positions.

Claim: each of the three things a particle carries belongs to a position, and which matter carries each of them is a further fact: a quark carries the three positions (color) and a lepton none; a transformation moves a state within a structure the state carries, and cannot give three positions to a state that has none. Source: *The Story of the Particles*, Level 7, Section I ("a quark carries the three positions, a lepton none"; "A transformation moves

a state within a structure the state carries; it cannot give three positions to a state that has none, or take them away"). Standing: an argument of that book. The electron is a lepton, so it carries no color, though Chapter 4 places it as the thing compared among the three carriers of the measured world.

Claim: the carriers number eight, three and one. Source: *The Story of the Particles*, Level 7, Sections II and VII. Standing: stated facts of mathematics applied to the structures named; in words, the transformations among n things that keep the total and change no phase of all of them together number n squared less one. In symbols: $3^2 - 1 = 8$ (gluons, among the three colors) and $2^2 - 1 = 3$ (weak bosons, between the two sides of a doublet), read "three squared minus one is eight" and "two squared minus one is three"; the force on the phase has one carrier, the hypercharge boson.

Claim: when the Higgs field settles into its value in empty space, the hypercharge boson mixes with the neutral weak boson to give the photon (massless) and the Z (heavy), so electromagnetism is the force on the phase as it meets us at low energy; the photon, the carrier of the act in Chapter 4, is the carrier of the force on the phase after the mixing. Source: *The Story of the Particles*, Level 7, Section VII ("On the phase: one hypercharge boson, which mixes with the neutral weak boson to give the photon and the Z. The force on the phase is the immanent force, and at low energy it meets the scientists as the electromagnetic force"); *Why These Numbers*, Chapter 2, "Three Ways to Change, and Twelve Carriers" ("Light's force, electromagnetism, is not one of the three at root", followed by the mixing when the Higgs field settles). Standing: the standard electroweak mixing, as the book states it; the book places the force on the phase in the immanent position, the position of the act. The measured masses: the W about eighty GeV and the Z about ninety-one GeV (*Why These Numbers*, Chapter 2, by measurement).

Gravity as the arena

Claim: gravity is the arena, the space and time of every measurement, which is context and not content; the three forces are fields within the arena; the pull of gravity is the arena's shape. Source: *The Story of the Particles*, Level 7, Section VI ("Gravity is not a fourth force with a carrier in this sequence". "It is the arena"; "The arena has a shape, and the scientists know its pull as gravity"; "it is the arena itself, the space and time that are two of the context measures of every measurement"). Standing: an argument of that book from the partition of content and context; the identification of gravity as the context-modal phenomenon is stated in *The Unquantized Arena*, Chapter 5, Section VII, as P18 ("I identify gravity as the context-modal phenomenon of physics, by the match of all four markers"), and in plain words in *Two Theories, One World*, Chapter 9, "The Identification" ("I identify gravity as the arena of physics, the context of every physical measurement, by that match"). Standing of P18: an identification, the one in the chain of *The Unquantized Arena* that experiment tests directly.

Claim: the carriers of the three forces are context in a first, narrow sense (fields on the continuous side of the partition, living within the arena); gravity is context in a wider sense (the arena itself). Source: *The Story of the Particles*, Level 7, Section VI ("The carriers of the three forces are context in the first sense of Level 6, Section VI: fields on the continuous pole of the partition, living within the arena. Gravity is context in a wider sense: it is the arena itself"). Standing: an argument of that book.

Claim: the zoo has no graviton; the word names at most a quantum of a description of small waves of a classical geometry. Source: *The Story of the Particles*, Level 7, Section VI. Standing: an argument of that book (a field within the arena has quanta; the shape of the arena is no field within the arena).

Claim: the arena carries two of the three bends of Chapter 1 (gravitation, the bend of space; the cosmological constant, the bend of time); the third, the dark matter, is the bend of possibility. Source: *The Weight of Pos-*

sibility, Chapter 2, Section I ("Each column therefore carries a distortion that is not zero: in space, gravitation; in time, the cosmological constant; in possibility, the dark matter"), with the arena as space and time together (*The Unquantized Arena*, Chapter 5, Section I). Standing: the two statements of those books, set together.

The four markers

Claim: any context-modal phenomenon (any phenomenon that is the context of the content of a domain) couples to every content, admits no shield, has one mass for coupling and inertia, and has no discrete charge. Source: *The Unquantized Arena*, Chapter 5, Propositions 5.1 to 5.4 (Sections II to V), with Table 5.2 in Section VI; in plain words, *Two Theories, One World*, Chapter 9; Proposition 10.1 of *Measurement*, Chapter 10, Section II, states the first marker in the same words. Standing: derived for any context-modal phenomenon before any phenomenon is named, from the inseparability principle (P5), the characterization of content and context (P7), the law of continuity (P6) and Propositions 4.1 and 4.2 of that book; Proposition 5.3 rests also on an identification stated in its argument ("I identify the two, for the context, as one relation of the content to the context, found twice"), which is the identification of weight with inertia that the main text recalls from Chapter 6.

Claim: no shield of gravity can be made, by a structural argument (a region without context is not a region) and by a physical mechanism (covering needs an opposite to the source and parts the field moves apart); so no arrangement of matter covers a source of gravity. Source: *The Unquantized Arena*, Chapter 5, Section III, and Section IX (second question); *Two Theories, One World*, Chapter 9, "The Second Mark: Nothing Shields It" ("So no arrangement of matter covers a source of gravity"). Standing: the structural argument uses only the character of context; the physical mechanism uses the positivity of energy and the universality of free fall, and the book gives it as a picture that agrees with the structural argument. The measured bound on absorption (Majorana's coefficient, be-

low) is a separate, measured statement: the Earth absorbs none of the Sun's pull, to the precision of lunar laser ranging (*The Unquantized Arena*, Chapter 5, Section III and Table 5.2).

Claim: gravity couples to energy, and the energy of every body yet weighed is positive, so every gravitational pull yet measured between bodies is an attraction. Source: *The Unquantized Arena*, Chapter 5, Section III ("It couples to energy, and the energy of every body yet weighed is positive"); *Two Theories, One World*, Chapter 9, "The Second Mark: Nothing Shields It". Standing: a measured fact, stated as measured; the sign of the pull is given as measured.

Claim: Einstein's form of the equivalence principle follows from the identification of gravity as context, since a uniform acceleration of a frame is a change of context. Source: *The Unquantized Arena*, Chapter 5, Section IV; *Two Theories, One World*, Chapter 9, "The Third Mark: One Mass". Standing: derived given the identification P18 and the identification of Proposition 5.3.

Claim: the equality of the two masses was recorded and not interpreted in Newton's mechanics, and in general relativity it follows from what gravity is. Source: *Physics Is Not Math*, Chapter 13, Sections I and II. Standing: a reported fact of the history of physics, with Einstein's sentence from *Relativity: The Special and the General Theory* (English translation, 1920) quoted there.

The Eötvös parameter, in words: twice the difference of the accelerations of two bodies of different composition in one field, divided by the sum of the two accelerations. In symbols: $\eta(A, B) = 2\,(a_A - a_B)\,/\,(a_A + a_B)$, read "eta of A and B equals two times a sub A minus a sub B, over a sub A plus a sub B", where a_A and a_B are the accelerations of bodies A and B (*The Unquantized Arena*, Chapter 5, equation 5.1).

The energy of gravity itself, in words: the gravitational self-energy of a body, the energy bound up in the pull of its own parts on one another, written as a share of the body's whole energy. For the Earth that share is

about -4.6×10^{-10} and for the Moon about -1.9×10^{-11}, read "minus four point six times ten to the minus ten" and "minus one point nine times ten to the minus eleven" (Williams, Turyshev and Boggs 2009).

The weakness

Claim: between two hydrogen atoms gravity is weaker than the electric pull between one atom's electron and the other's proton by some thirty-six powers of ten, the atoms' mass being nearly two thousand times the electron's; between an electron and a proton by some thirty-nine. Source: *The Matter We Know*, Volume One, Chapter 11, Section I. Standing: computed from measured values.

Claim: gravity is weak on the electron because the electron is very light against the Planck mass; the feebleness and the lightness are one distance read from its two ends. Source: *Why These Numbers*, Chapter 7, "One Distance, Seen from Both Ends". Standing: a statement of that book from the definition of gravity's strength on a body.

Definitions used. Gravity's strength on a body of mass m, in words: Newton's constant times the mass multiplied by itself, divided by the reduced quantum of action times the speed of light. In symbols: $\alpha_G = G\ m^2 / (\hbar\ c)$, read "alpha sub G equals G m squared over h-bar c", where G is Newton's constant, $\hbar$ the reduced Planck constant and c the speed of light. The number α_G is the gravitational pull $G\ m^2 / r^2$ between two bodies of mass m at a distance r, divided by the force $\hbar\ c / r^2$ at the same distance (the yardstick of the main text); both fall as one over r squared, so the ratio is the same at every distance. The strength of light is defined the same way: $\alpha = e^2 / (4\pi\varepsilon_0\ \hbar\ c)$, about 1 / 137.036, read "alpha equals e squared over four pi epsilon nought h-bar c", where e is the electron's charge and ε_0 the electric constant. The (unreduced) Planck mass M_{Pl} is the mass at which $\alpha_G = 1$, so $M_{Pl} = (\hbar\ c / G)^{1/2}$, about 2.18×10^{-8} kg (about twenty-two millionths of a gram). The reduced Planck mass $M_{Pl,red}$ is the mass at which $8\pi G\ M^2 / (\hbar\ c) = 1$, so $M_{Pl,red} = M_{Pl} / (8\pi)^{1/2}$, a factor of about

five lighter (*The Strengths of the Kinds*, Chapter 5, Overview; *Why These Numbers*, Chapter 7, "The Ruler of Halvings"). A halving is a factor of two in mass.

Values, from *Why These Numbers*, Chapter 7, computed from the values of G and of the electron mass m_e recommended in 2022 by CODATA (the Committee on Data for Science and Technology): the unreduced Planck mass sits 74.339 halvings above the electron (the main text's "about seventy-four and a third"); gravity's strength on the electron, $(m_e / M_{Pl})^2$, is about 1.75×10^{-45}, one halved about 149 times (twice 74.339 is 148.68), which is about 44.76 powers of ten; the ratio of the electric to the gravitational force between two electrons, $\alpha / \alpha_G(m_e)$, is a number forty-three digits long beginning 416, about 4.166×10^{42}.

The walk from thirty-six to forty-five powers of ten, in the main text's two steps. Between two hydrogen atoms, gravity over the electric pull is about 8.1×10^{-37} (36.09 powers of ten). Replacing the hydrogen atom's mass, about 1837 electron masses, by the electron's divides the gravitational pull by about 1837^2, about 3.4×10^6 (6.53 powers of ten), giving about 2.4×10^{-43} between two electrons (42.62 powers of ten), the inverse of the forty-three-digit number. Setting the electric push itself beside the yardstick multiplies by α, about 1 / 137 (2.14 powers of ten), giving $\alpha_G(m_e)$, about 1.75×10^{-45} (44.76 powers of ten). Standing: arithmetic on measured values (CODATA 2022), as *Why These Numbers*, Chapter 7, "The Ruler of Halvings", gives the last two steps ("The strength of light divided by gravity's strength on the electron is a number forty-three digits long, beginning 416").

The reduced Planck mass and the count of seventy-two. The reduced Planck mass sits 72.0132112 ± 0.0000162 halvings above the electron (the span $E = \log_2(M_{Pl,red} / m_e)$, read "E equals the logarithm to base two of the reduced Planck mass over the electron mass"), the whole uncertainty coming from G; the difference from the unreduced Planck mass, 2.326 halvings, is the square root of 8π read in halvings. Standing of the span: measured. *Why These Numbers*, Chapter 7, identifies the integer part of the span with the count $72 = 8 \times 9$ (eight first-order states, two outcomes at

each of three positions, times nine joins, three positions set against three across the pair of content and context), one halving to each comparison, on the premise of the endpoints (the span runs from the unit of the things counted, the electron's mass, to the limit of comparison at the reduced Planck mass). Standing, in that book's words: "That identification is the assumed part, and the measured span is its test" (*The Strengths of the Kinds*, Chapter 5, Overview: "The identification of the span with that count is assumed, and the measurement is its test"). Seventy-two halvings above the electron land 0.9 percent below the reduced Planck mass. The remainder $r = E - 72 = 0.0132$ halvings exists by the Incommensuration Theorem (a count read by a continuous whole leaves a residue at every such reading); its first-order size is the small leftover $\varepsilon = 11 / (80\pi^2) = 0.013932$, read "epsilon equals eleven over eighty pi squared"; the measured remainder is 0.948 of ε. Writing $r = \varepsilon(1 - k\varepsilon)$ defines the second-order constant k, measured at 3.7120 ± 0.08 once ε is affirmed (*Why These Numbers*, Chapter 7, "The Second Order"). A second road, through the measured strengths of the forces with their running computed to two loops and with no input from G, returns 72.0120 ± 0.02 halvings; that this road lands on seventy-two is measured, and its reason is carried as the question "why does it land?", with the factor three pi as its clue.

Measured values told in the chapter, with their primary papers

The hammer and the feather: Apollo 15, 2 August 1971, mission elapsed time 167:22:06 to 167:22:58, Hadley; a 1.32-kg aluminum geological hammer and a 0.03-kg falcon feather released together from about 1.6 m struck the surface together (Apollo Lunar Surface Journal, Apollo 15, "The Hammer and the Feather", transcript and the Apollo 15 Preliminary Science Report excerpt reproduced there).

Newton's pendulums: equal boxes filled with wood, gold, silver, lead, glass, sand, salt, water and wheat swung together; a difference of a thousandth part would have been seen (Newton, *Philosophiae Naturalis Principia Mathematica*, 1687, Book III, as reported in *Physics Is Not Math*, Chapter 13, Section I).

Eötvös's torsion balance, 1889 to 1909: equality to a few parts in a billion (Eötvös, R. v., Pekár, D., and Fekete, E., "Beiträge zum Gesetze der Proportionalität von Trägheit und Gravität", *Annalen der Physik* 68 (1922) 11–66).

Rotating torsion balance: $\eta(\text{Be, Ti}) = (0.3 \pm 1.8) \times 10^{-13}$ (Schlamminger, S., Choi, K.-Y., Wagner, T. A., Gundlach, J. H., and Adelberger, E. G., "Test of the equivalence principle using a rotating torsion balance", *Physical Review Letters* 100 (2008) 041101).

MICROSCOPE, titanium and platinum in orbit, 2016 to 2018: $\eta(\text{Ti, Pt}) = [-1.5 \pm 2.3\ (\text{stat}) \pm 1.5\ (\text{syst})] \times 10^{-15}$ (Touboul, P., and others, MICROSCOPE Collaboration, "MICROSCOPE mission: final results of the test of the equivalence principle", *Physical Review Letters* 129 (2022) 121102).

Lunar laser ranging: the Earth's and the Moon's ratios of gravitational to inertial mass agree to $(-1.0 \pm 1.4) \times 10^{-13}$ (the main text's "about one part in ten trillion"); the part due to gravitational self-energy is $(-2.0 \pm 2.0) \times 10^{-13}$; Majorana's absorption coefficient $h = (3 \pm 5) \times 10^{-23}$ cm^2 g^{-1} (Williams, J. G., Turyshev, S. G., and Boggs, D. H., "Lunar laser ranging tests of the equivalence principle with the Earth and Moon", *International Journal of Modern Physics D* 18 (2009) 1129–1175).

Antihydrogen falls: $a_g = (0.75 \pm 0.13 \pm 0.16)$ g, which excludes a repulsion of the size of g (Anderson, E. K., and others, ALPHA-g Collaboration, "Observation of the effect of gravity on the motion of antimatter", *Nature* 621 (2023) 716–722).

Light couples to gravity with the strength general relativity requires: $\gamma - 1 = (2.1 \pm 2.3) \times 10^{-5}$ (Bertotti, B., Iess, L., and Tortora, P., "A test of general relativity using radio links with the Cassini spacecraft", *Nature* 425 (2003) 374–376).

Newton's constant $G = 6.67430(15) \times 10^{-11}$ m^3 kg^{-1} s^{-2}, the electron mass, the proton mass (about 1836.15 electron masses) and the fine-structure constant α (about 1 / 137.036), CODATA 2022 (as used in *The Strengths of the Kinds* and *Why These Numbers*).

The chapter also draws on: *The Matter We Know, Volume One*, Chapter 11, Section I.

Chapter 8. How Does Gravity Meet the Quantum?

The chapter's claims come from *Two Theories, One World* (plain form), *The Unquantized Arena* (technical form, as numbered propositions), *The Gravitational Passage* (a separate route to the field equations) and *What Cannot Be*. Each claim is given below in one plain sentence, with the place that carries it and its standing as that book states it.

The claims

Content and context. Quantum theory describes the content of physics, whose findings are discontinuously symmetric, and general relativity describes its context, the arena, which is continuously asymmetric. Source: *Two Theories, One World*, "The Answer in a Page" and Ch. 3, "What Is Found and Where It Is Found"; *The Gravitational Passage*, Ch. 6, Sec. III. Standing: an identification, made in the first person ("I identify quantum theory as the description of the content of physics", *Two Theories, One World*, "The Answer in a Page").

The Incommensuration Theorem. Of the ten pairings of continuity, discontinuity, symmetry and asymmetry, two cannot be perfected together at the foundation of any event or comparison: continuity with symmetry, and asymmetry with discontinuity. The two that survive are continuity with asymmetry, and symmetry with discontinuity. The theorem, in its exact wording: "Symmetry and continuity cannot both be applied, simultaneously and fundamentally, to any event or comparison; and neither can asymmetry and discontinuity" (*Incommensuration*, Ch. 2, Sec. VI); *The Gravitational Passage*, Ch. 3, Sec. IV, states and proves the same theorem. Source: *Two Theories, One World*, Ch. 5; *The Gravitational Passage*, Ch. 3, Sec. IV; *What Cannot Be*, Ch. 17, "Two Tools and Three Scales" ("a structural fact about the nature of knowing"). Standing: a theorem, a structural fact about the nature of knowing, with no physical premise.

Quantizing as a change of character. To quantize a theory exchanges the characters of both its levels together: its findings change from smooth to stepped, and its mathematics changes from holding its symmetries exact to holding its continuity exact. Source: *Two Theories, One World*, Ch. 11, "Quantizing, Shown on Light". Standing: derived from the theorem and the cross-modal principle; the same chapter's table sets five theories beside it, and each agrees.

The category error. A quantized arena would carry at least one of the two forbidden pairings, and both where all four characters are asked of the same directions of space and time. A change of character of the arena would also remove the context in which every description is made. So to quantize the arena is to apply a concept where it does not belong. Source: *Two Theories, One World*, Ch. 11, "Why the Arena Admits No Mode Exchange" and "The Category Error, Stated in Full"; *The Unquantized Arena*, Ch. 6, Propositions 6.1 and 6.2; *What Cannot Be*, Ch. 17, "What One Theory Would Have to Be". Standing: derived, given the identification of gravity as the context (*The Unquantized Arena*, P18).

What "not quantized" means. The arena has no least length, area or duration, and nothing is a quantum of the arena itself at any scale; a quantum field of content on the arena, as in quantum electrodynamics, is untouched. Source: *The Unquantized Arena*, Ch. 6, Proposition 6.3; *Two Theories, One World*, Ch. 11, "Exactly What Is Excluded". Standing: derived.

One geometry for each alternative. Each alternative of the quantum matter carries its own smooth geometry, shaped through Einstein's equations by the energy and momentum of that alternative alone, and the relative phases of the alternatives are kept. In words first: the state of the matter is a sum over its alternatives, each alternative with its own weight. For each alternative, the Einstein tensor of that alternative's geometry equals eight pi times Newton's constant over the fourth power of the speed of light, times the stress-energy tensor of that alternative. In symbols: $|\Psi\rangle = \Sigma_i \, c_i \, |\psi_i\rangle$, and $G_{\mu\nu}[g^{(i)}] = (8\pi G/c^4) \, T^{(i)}{}_{\mu\nu}$ for each i. Here Ψ (psi) is the state of the matter, ψ_i (psi sub i) is alternative i, and c_i (c sub

i) is the weight of alternative i. $G_{\mu\nu}$ (G mu nu) is the Einstein tensor, the measure of curvature that Einstein's equations set equal to the matter's energy, and $g^{(i)}$ (g superscript i) is the geometry of alternative i. G is Newton's constant, c is the speed of light, and $T^{(i)}{}_{\mu\nu}$ (T superscript i, mu nu) is the stress-energy tensor of alternative i, which carries that alternative's energy and momentum. Source: *The Unquantized Arena*, Ch. 7, Proposition 7.1 (equation 7.3); *Two Theories, One World*, Ch. 12; *The Gravitational Passage*, Ch. 12, Sec. VI. Standing: an identification, made on the ground of the inseparability of content and context ("I identify the geometry with the context of each alternative of the matter", *The Gravitational Passage*, Ch. 12, Sec. VI). Scope as stated there: the relative phase of the alternatives is constructed where their geometries differ by small departures, share a far region and stay far below the Planck curvature, and there the construction is that of linearized quantum gravity.

The averaged geometry fails both ways. One geometry shaped by the average of the alternatives' energies, each weighted by its probability (in symbols, sourced by the expectation value of the stress-energy), fails in two ways. If its weights never change, it fails the experiment of Page and Geilker, as the chapter tells. If its weights change when a finding is made, it sends signals faster than light. Source: *The Unquantized Arena*, Ch. 7, Proposition 7.3; *Two Theories, One World*, Ch. 12, "The Experiment of Page and Geilker" and "No Signal Faster Than Light". Standing: derived from a measured result (Page and Geilker 1981) and from established physics (Gisin 1990; Bahrami, Großardt, Donadi and Bassi 2014).

Why changing weights would signal faster than light. *Two Theories, One World*, Ch. 12, "No Signal Faster Than Light", walks the second failure with a laboratory on the Moon, which light from the Earth takes a little more than a second to reach. A body on the Earth is put into a superposition of two places, and that superposition is entangled with a partner particle in the laboratory on the Moon. The experimenter on the Moon can put one of two measurements to the partner. On the averaged account with changing weights, the first measurement leaves the body on the Earth sharply in one place or the other, and the second leaves it in an even

combination of both places. The averaged geometry on the Earth would then point toward one place after the first measurement, and toward the midpoint of the two places after the second. A sensitive balance on the Earth could read from that gravity which of the two measurements was made on the Moon, before any light from the Moon could bring the news, and that is a signal faster than light. Mohammad Bahrami and colleagues set out this consequence in 2014. A geometry for each alternative changes at no finding, here or on the Moon, so it sends no such signal. Each alternative already carries its geometry before any finding is made, and a finding selects which alternative is the case.

The graviton. Small waves of geometry about a smooth background can be described by quanta, and the graviton names at most a quantum of that description, never a quantum of the arena; a detector that registers single clicks from a gravitational wave would not show gravitation quantized. Source: *Two Theories, One World*, Ch. 14 (all sections) and Ch. 26, "Gravitational Waves Must Come in Gravitons"; *The Unquantized Arena*, Ch. 6, Proposition 6.3; *What Cannot Be*, Ch. 17, "What the Theorem Leaves in Place". Standing: derived; the description by quanta is established physics (Donoghue 1994), admitted as a description.

Gravitational waves as ripples of the context. Gravitational waves are small oscillations of the context, traveling at the speed of light, with the two polarizations of a massless field of spin two. Source: *The Gravitational Passage*, Ch. 16, Sec. V, where the field equations themselves are reached by a separate route (the reduction of Ch. 11 and Lovelock's theorem, Ch. 12, Sec. VII), with Newton's constant the one constant taken from measurement. Standing: derived on that route; the waveforms and polarizations are those of general relativity, which the book recovers.

The Planck scale. Every mass has a gravitational size, Newton's constant times the mass over the square of the speed of light, and a quantum size, the reduced Planck constant over the mass times the speed of light. The two sizes are equal at the Planck mass, where both equal the Planck length. The gravitational size is half the radius of the horizon of a black hole of the same mass that does not spin (that radius, the Schwarzschild

radius, is $2GM/c^2$). So a body squeezed inside twice its gravitational size would be a black hole, as I say in Chapter 8 of this book. In symbols: $r_g = GM/c^2$ and $\lambda = \hbar/(Mc)$; setting $r_g = \lambda$ gives $M = m_P = \sqrt{(\hbar c/G)}$, and then $r_g = \lambda = l_P = \sqrt{(\hbar G/c^3)}$. Here r_g (r sub g) is the gravitational size, λ (lambda) the quantum size, M the mass, G Newton's constant and c the speed of light. $\hbar$ (h-bar) is the reduced Planck constant, m_P (m sub P) the Planck mass and l_P (l sub P) the Planck length. At the Planck scale neither description dominates, and the theorem forbids one description that perfects both characters there, so two descriptions meet and stay two. The Planck length bounds how sharply a comparison made from inside the world can place a body, and it is no least length of the arena. Its role is fixed by the ground and its size by the measured value of Newton's constant. Source: *Two Theories, One World*, Ch. 15 (all sections); *The Gravitational Passage*, Ch. 17; *The Unquantized Arena*, Ch. 6, Sec. IV. Standing: the two sizes and their crossing are standard physics. That the crossing is the meeting of two descriptions, and that the Planck length is a bound on findings, is derived from the theorem.

The infinities and the singularities. Gravity quantized by the method that worked for the other forces is not renormalizable: its infinities cannot be removed by the method that removes them for the other forces. The effective theory still computes finite corrections at ordinary energies. The failure marks the edge of the domain of the description of small waves, at the Planck curvature. The Planck curvature is the curvature at which the quantum corrections become as large as the effects they correct. There a ripple would be as large as the geometry it rides on, in the sense that the ripple's bending of space would equal the background's. The structural argument of the chapter (the category error) rests on the Incommensuration Theorem and the identification of gravity as the context, and not on the infinities. Singularities mark the edge of the smooth description's domain, where the curvature it computes reaches the Planck curvature. Source: *Two Theories, One World*, Ch. 2, "Two Roads", Ch. 14, "Where the Description of Small Waves Ends", and Ch. 26, "The Singularities Demand a Quantum Gravity"; *The Unquantized Arena*, Ch. 9, Sec. IV. Standing: the

non-renormalizability is established physics ('t Hooft and Veltman 1974; Goroff and Sagnotti 1986); that it marks the edge of the description's domain is derived.

Hawking radiation. Hawking radiation is quantum fields on a classical geometry, and in Unruh's fluid model of 1995 the thermal glow does not depend on how waves behave at the shortest wavelengths. Source: *Two Theories, One World*, Ch. 26, "Hawking Radiation Is Quantum Gravity at Work". Standing: established physics (Hawking 1974; Unruh 1976, 1995); the book states it as quantum content on a classical context. Hawking announced the glow in S. W. Hawking, "Black hole explosions?", *Nature* 248, 30 (1974), and gave the full calculation in S. W. Hawking, "Particle creation by black holes", *Communications in Mathematical Physics* 43, 199 (1975).

Already unified. The two theories are already unified, in the only way they can be: as the two conjugate sides of one domain of comparison, met in the act of measurement, and set side by side, never merged. Two things are conjugate when neither comes before the other and each can be perfected only at the cost of the other (*What Cannot Be*, Ch. 3). The domain of comparison is the range within which comparisons can be made (*What Cannot Be*, Ch. 5, "The Two Edges"). *What Cannot Be* calls the joining "a product, the two set side by side and joined through the act". Source: *What Cannot Be*, Ch. 17, "Joined Through the Act of Measurement"; *Two Theories, One World*, Ch. 24; *The Unquantized Arena*, Ch. 6, Proposition 6.4. Standing: derived from the first axiom and the theorem.

Exact values used in the chapter

Planck mass: 2.17643×10^{-8} kilograms, about twenty-two millionths of a gram; a quartz sphere of that mass, at 2650 kilograms per cubic meter, is 0.250 millimeters across (*Two Theories, One World*, "The Numbers", Part IV and "The Calculations in Words"). Planck length: 1.61626×10^{-35} meters; a proton's width of about 1.7×10^{-15} meters is 1.05×10^{20} Planck lengths (same place). Gravitational sizes: the Earth 4.44 millimeters, the Sun 1.48 kilometers; quantum size of a proton 2.10×10^{-16} meters, about

an eighth of its width (same place). Quantum correction to Newton's law at one meter: the ratio $G\hbar/(r^2c^3)$, which is $(l_P/r)^2$, is 2.6×10^{-70}, and the correction is $41/(10\pi)$, about 1.3, times that ratio (Donoghue 1994; *The Unquantized Arena*, Ch. 18, Sec. VII, and Ch. 9). The stretch of a LIGO arm in GW150914: a strain of about 1.0×10^{-21} on four kilometers, about 4×10^{-18} meters, against a proton width of about 1.7×10^{-15} meters (*Two Theories, One World*, "The Numbers", Part IV).

Measured values told in the chapter, with their primary papers

GW150914, 14 September 2015, 09:50:45 UTC: signal seen first at Livingston and about 7 milliseconds later at Hanford; frequency rising from about 35 to 250 hertz; peak strain about 1.0×10^{-21}. Source masses about 36 and 29 solar masses, final mass about 62; about 3 solar masses radiated; distance about 410 megaparsecs (about 1.3 billion light-years); waveform matching general relativity. B. P. Abbott and others (LIGO Scientific Collaboration and Virgo Collaboration), "Observation of Gravitational Waves from a Binary Black Hole Merger", *Physical Review Letters* 116, 061102 (2016).

The first sighting in Hannover (the scene): D. Castelvecchi, "Gravitational waves: How LIGO forged the path to victory", *Nature* 530, 261–262 (2016), doi:10.1038/530261a.

Page and Geilker: a torsion balance whose large masses were placed by a Geiger counter's reading; the bar turned each time as the actual placement required. D. N. Page and C. D. Geilker, "Indirect Evidence for Quantum Gravity", *Physical Review Letters* 47, 979 (1981). The averaged geometry they tested: C. Møller (1962); L. Rosenfeld (1963). Signaling by an averaged geometry with changing weights: M. Bahrami, A. Großardt, S. Donadi and A. Bassi, "The Schrödinger–Newton Equation and Its Foundations", *New Journal of Physics* 16, 115007 (2014).

GW170817 and GRB 170817A, 17 August 2017: a merger of two neutron stars about 40 megaparsecs away (about 130 million light-years, *The Matter We Know*, Volume One, Ch. 6, Sec. VI), with the burst of gamma rays arriving about 1.7 seconds after the merger. The speed of gravitation-

al waves differs from the speed of light by between -3×10^{-15} and $+7 \times 10^{-16}$ of the speed of light (*The Gravitational Passage*, Ch. 16, Sec. V). B. P. Abbott and others, "Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A", *Astrophysical Journal Letters* 848, L13 (2017).

Single clicks from a classical wave: D. Carney, V. Domcke and N. L. Rodd, *Physical Review D* 109, 044009 (2024). The effective theory of gravity and its corrections: J. F. Donoghue, *Physical Review D* 50, 3874 (1994). Non-renormalizability: G. 't Hooft and M. Veltman, *Annales de l'Institut Henri Poincaré A* 20, 69 (1974); M. H. Goroff and A. Sagnotti, *Nuclear Physics B* 266, 709 (1986).

No single graviton has been detected. The authors report one calculation by which a detector the size of Jupiter would see one graviton every ten years "even if it was near an intense graviton source" (*We Have No Idea*, ch. 6, "Black Hole Colliders"). Their estimate is close in kind to the figure of T. Rothman and S. Boughn, "Can Gravitons Be Detected?", *Foundations of Physics* 36, 1801 (2006). Rothman and Boughn give at most about one graviton in a century for a detector of Jupiter's mass in close orbit around a neutron star.

Chapter 9. Is There a Theory of Everything?

Every claim of Chapter 9 that comes from the physics collection is listed below, in the order of the chapter, with the book, chapter and section that carries it and its standing as that book states it.

Claim, in one plain sentence	Where the corpus carries it	Standing as the book states it
The phrase "theory of everything" has two meanings: an account that leaves nothing out, and one description of one character throughout from which everything follows; the Incommensuration Theorem allows the first and forbids the second.	*Two Theories, One World*, Ch. 24, "One World, One Account, Two Descriptions"	Derived from the Incommensuration Theorem.
The Incommensuration Theorem, in its exact wording: "Symmetry and continuity cannot both be applied, simultaneously and fundamentally, to any event or comparison; and neither can asymmetry and discontinuity".	*Incommensuration*, Ch. 2, Sec. VI; proved also in *The Gravitational Passage*, Ch. 3, Sec. IV	A structural fact about the nature of knowing.
A common source is two descriptions arising from the same act of comparison and applying to the same world, each perfected in one of the two characters; a merger is one description in which the directions of space and time themselves carry both characters at the foundation.	*Two Theories, One World*, Ch. 24, "Two Kinds of Unity"; *The Last Turtle*, Ch. 22, Sec. VI; *The Unquantized Arena*, Ch. 6, Sec. V, Proposition 6.4	Definitions (terminology of the account).

Claim, in one plain sentence	Where the corpus carries it	Standing as the book states it
A quantized arena is a merger, and it is excluded in principle, and therefore in all practice, because the obstacle lies in what a comparison can perfect.	*Two Theories, One World*, Ch. 24, "What the Theorem Forbids"	Derived from the Incommensuration Theorem.
Quantum fields on a classical curved geometry are the permitted unity already in use, and the framework in which black holes were found to radiate; the two descriptions meet at bridges (the probability rule, the formula of Ryu and Takayanagi, the Planck scale).	*Two Theories, One World*, Ch. 24, "What the Theorem Permits"	Stated fact of established physics, read by the account.
The theorem is silent on joining one content to another; the absence of a single larger force rests on separate ground.	*Two Theories, One World*, Ch. 24, "What the Theorem Permits" (last paragraph); *The Last Turtle*, Ch. 22, Sec. VI	Scope statement of the theorem.
A force is a change, a change is a comparison, and structured content carries exactly three things a comparison acts on (color, the doublet, the phase), so there are three forces.	*The Story of the Particles*, Level 7, Sec. I; *Why These Numbers*, Ch. 2, "Three Ways to Change, and Twelve Carriers"	Argument from the structure of comparison.
Gravity is the arena and not a fourth force with a carrier.	*The Story of the Particles*, Level 7, Sec. VI; Level 9, Sec. IV	Argument from the structure of comparison (gravity as context).

Claim, in one plain sentence	Where the corpus carries it	Standing as the book states it
No transformation turns a quark into a lepton; transformations of different labels commute, so the algebra of the gauge transformations is the sum of three commuting parts; the algebra of a simple Lie group is no such sum; so no simple group is the gauge group at any scale and no gauge boson joins a quark to a lepton.	*The Kinds of Particle*, Ch. 4, Sec. I	Derived.
The structure has no unifying group; at every energy the symmetry of the forces is the three symmetries side by side; a unifying theory adds carriers that turn a quark into a lepton, which do not exist.	*Why These Numbers*, Ch. 5, "One Force, or Three?" and "Where the Crossings Are"; Ch. 2, "What Has No Place Among the Kinds"	Derived (from the list of kinds of *The Story of the Particles*).
The three forces are distinct, inseparable (anomaly cancellation ties quarks and leptons of one generation) and non-interchangeable: three views of one structure, as a triangle has three sides, angles and vertices.	*The Kinds of Particle*, Ch. 5, Sec. II	Argument (the forces realize Axiom III).
Electromagnetism is the combination of the neutral weak carrier and the phase carrier that the Higgs condensate leaves massless; at root the three forces are color, the weak force and the force on the phase.	*Why These Numbers*, Ch. 2, "Three Ways to Change, and Twelve Carriers"; *The Kinds of Particle*, Ch. 4, Sec. I	Standard physics, read by the account.

Claim, in one plain sentence	Where the corpus carries it	Standing as the book states it
The proton does not decay: no carrier joins color to the weak charge, so no change alters baryon number, and the proton is the lightest particle of baryon number one.	*Why These Numbers*, Ch. 2, "What Has No Place Among the Kinds"; *What Comes After the Dark*, Ch. 5, "Does the Proton Last?"; the record of 1 November 2026, Prediction 33, as reproduced in *Side by Side*, Vol. One, Appendix B	Derived; the record states that the stability "rests on its being the lightest whole of baryon number one, which is measured", and that sphaleron changes cause no decay of a single proton.
The three strengths cross in pairs at three different places and never meet at one place.	*Why These Numbers*, Ch. 5, "One Force, or Three?", "Where the Crossings Are"	The spacing ratio is set by the list of particles (structure); the places are read from the measured strengths run upward (measured input).
Every program of quantum gravity found something real, and each met the difficulty its founding step predicts: multiplicity for deriving the arena from quanta, dynamics for quantizing the geometry, recovery for giving up the continuum; the programs that leave the arena unquantized (emergent gravity, twistor theory, non-commutative geometry) meet none of the three.	*Two Theories, One World*, Ch. 22, "The Search Was Not Wasted", "The Gradient", "One Error, Four Expressions"	Argument (the four questions of Ch. 21 applied to ten programs).

Claim, in one plain sentence	Where the corpus carries it	Standing as the book states it
String theory's landscape, about ten to the five hundred valleys and beyond, comes from fields threaded through the loops of its six curled dimensions; this physics threads no field through the six and has one valley.	*What Comes After the Dark*, Ch. 4, "No Threads, No Landscape"	Derived, from the action of the metric alone, whose choice the book states with its reason.
Depth is the order of presupposition: metaphysics, physics, computation, mathematics.	*Physics Is Not Math*, Ch. 5, "What Depth Means", Secs. I, II, V	Definition, with the order argued.
The journey through the particle levels was a journey into deeper aspects of comparison, not into smaller things: each level peeled back one more layer of comparison's structure.	*The Story of the Particles*, "What the Scientists Learned", Sec. IV	Argument (the closing of the book).
Mathematics meets the question of its ground by ascending (the consistency of each formal system is studied in a stronger one); the metaphysics meets it by closing: the axioms describe their own content and their own derivation, the third order of self-description collapses into the second, and the descent of grounds ends at a structure that holds its own ground.	*The Last Turtle*, "Three Orders of Knowledge", Sec. VII	Argument (self-descriptive closure).
To doubt one of the axioms is already to use it.	*The Last Turtle*, "Three Orders of Knowledge", Sec. III	Argument.

Claim, in one plain sentence	Where the corpus carries it	Standing as the book states it
A description reaches what it describes as closely as one wishes and never contains it; in practice exact derivation of chemistry from quantum mechanics is never possible except for the simplest systems, and in principle no description contains everything it describes.	*Physics Is Not Math*, Ch. 11, Sec. V	Argument (cross-modal principle), with the chemistry case as stated fact.
The account adds nothing to the mathematics and changes no prediction of quantum theory; below the Planck curvature it and the effective field theory of gravity give the same result for every experiment now proposed.	*Two Theories, One World*, Ch. 19; *The Unquantized Arena*, Ch. 6, Sec. IV	Stated scope of the account.
The framework stands to the Standard Model as hardware to software; it is no rival theory and names the constraints every correct theory meets.	*What Cannot Be*, Ch. 20, "The Standard Model as Inherited Code"	Argument, with a picture.

The unifying group, in symbols. In Chapter 9 of this book I speak of families of changes under which the laws stay the same. Physicists call each such family a gauge symmetry, and physicists call the algebra of each such family a Lie algebra. The gauge group of the Standard Model is $\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1)$, read aloud as "S U three times S U two times U one", the groups of color, of the doublet and of the phase. A unifying group, such as $\mathrm{SU}(5)$ in the scheme of Georgi and Glashow, is a simple Lie group containing all three; a simple Lie algebra is not the sum of two or more parts that commute with one another, and the algebra of the three factors is such a sum (*The Kinds of Particle*, Ch. 4, Sec. I).

The strengths at the Z mass, in words first. The inverse strength of a force is one divided by its strength. At the mass of the Z, the inverse strength of the force on the phase is about fifty-nine (counted with the factor five thirds that puts it on the same footing as the other two), that of the weak force about thirty, and that of color about eight and a half (*Why These Numbers*, Ch. 5). In symbols, with alpha-one-inverse, alpha-two-inverse and alpha-three-inverse read aloud as "the inverse strength of the phase force, of the weak force and of color": ${\alpha_1}^{-1} \approx 59$, ${\alpha_2}^{-1} \approx 30$, ${\alpha_3}^{-1} \approx 8.5$ at the Z mass.

The crossings, in words first. A crossing is an energy at which two inverse strengths are equal, and its place is counted in halvings above the electron's mass (a halving is a factor of two). Run at three loops from the strengths of the Particle Data Group's 2024 compilation, the crossings of the phase and weak forces, of the phase force and color, and of the weak force and color lie at 54.259, 58.200 and 65.521 halvings; at one loop at 54.16, 58.72 and 67.36 (*Why These Numbers*, Ch. 5, "The Law of Place" and "Where the Crossings Are"). In energy, at one loop, they lie near ten thousand billion, two hundred fifty thousand billion and a hundred million billion GeV, so that the last lies nearly ten thousand times higher in energy than the first; this is the factor the chapter gives, at one loop. At three loops the first and last crossings are 11.262 halvings apart, a factor of two raised to the power 11.262, about 2,460, in energy. The spacing ratio, the distance from the middle crossing to the last divided by the distance from the first to the middle, is 218/115 (1.8957) at one loop, set by the carriers' self-action and the one Higgs doublet alone, with the three generations canceling; at three loops it is 1.8581 ± 0.0006. Near the end of the span, at 5.3 billion billion GeV, the three inverse strengths are about thirty-four, forty-nine and fifty-one, and unequal.

The proton. The record of 1 November 2026, Prediction 33, states: "No unifying group exists at any scale, and the measured couplings meet at no scale". Measured: the lifetime divided by the branching fraction for decay into a positron and a neutral pion exceeds 2.4×10^{34} years, and into a muon and a neutral pion 1.6×10^{34} years, at ninety percent confidence

(Takenaka and others, Super-Kamiokande Collaboration, "Search for proton decay via $p \to e^+\pi^0$ and $p \to \mu^+\pi^0$ with an enlarged fiducial volume in Super-Kamiokande I–IV", *Physical Review D* 102 (2020) 112011). The detector: Fukuda and others, "The Super-Kamiokande detector", *Nuclear Instruments and Methods in Physics Research A* 501 (2003) 418–462 (data taking from April 1996; 50,000 tons of water; 11,146 photomultiplier tubes of 50 cm diameter in the inner detector).

Particles of a unifying group. As the record reports under Prediction 30: none has been found; the Large Hadron Collider excludes a W′ with the couplings of the W below about 6000 GeV, a Z′ with those of the Z below about 5150 GeV, and leptoquarks below about 1500 to 1800 GeV.

The programs' results told in the chapter. Strominger and Vafa, "Microscopic Origin of the Bekenstein-Hawking Entropy", *Physics Letters B* 379 (1996) 99–104. Shaposhnikov and Wetterich, "Asymptotic Safety of Gravity and the Higgs Boson Mass", *Physics Letters B* 683 (2010) 196, giving 126 GeV "with only a few GeV uncertainty"; the particle was found in 2012 near 125 GeV (ATLAS Collaboration, *Physics Letters B* 716 (2012) 1; CMS Collaboration, *Physics Letters B* 716 (2012) 30), as *Two Theories, One World*, Ch. 22 and its notes, report. Jacobson, "Thermodynamics of Spacetime: The Einstein Equation of State", *Physical Review Letters* 75 (1995) 1260 to 1263: Einstein's equation derived from the proportionality of entropy to horizon area and the relation of heat, entropy and temperature. Chamseddine, Connes and Marcolli, "Gravity and the Standard Model with Neutrino Mixing", *Advances in Theoretical and Mathematical Physics* 11 (2007) 991: the Standard Model with gravity as one spectral action, the geometry of space and time held classical.

The opening scene's paper: H. Georgi and S. L. Glashow, "Unity of All Elementary-Particle Forces", *Physical Review Letters* 32 (1974) 438–441. Georgi's recollection of the evening is quoted in J. Riordon, "Unity of All Elementary-Particle Forces", *APS News* 11, no. 10 (November 2002).

Chapter 10. What Is Space?

Each paragraph below gives one claim of the chapter, the corpus book, chapter and section that carries it, its standing as that book states it, and any exact value.

Space as a pattern. Claim: space is the pattern of which events can affect which, and no container that exists before the events it holds. Source: *What Cannot Be*, Chapter 12, "What Space Is", in the words "Space is the pattern of which events are causally connected with which, and it is no container that exists before the events it holds". Standing: a definition, stated there as what the word "space" names. The same section calls the pattern, in mathematical terms, the connectivity topology of causal relations, a topology being "the pattern of what hangs together with what, taken apart from any measure of distance". In What Cannot Be I place the definition of space inside general relativity. In general relativity, spacetime has no properties apart from the relations of spacetime. The causal structure alone fixes the topology of spacetime (Malament 1977; Hawking and Ellis 1973, named in What Cannot Be for the proofs). *The Basis of Physics*, the essay "Causation, Connectivity, and the Domain Boundary of Comparison", abstract, states the same in the words "space is constituted by causal relations", and its Section III, "What Space Is", sets the argument out.

The edges of space are the edges of comparison. Claim: every causal connection is an interaction, every interaction is a comparison, so the edges of space are the edges of what can be compared. Source: *What Cannot Be*, Chapter 12, sections "Every Cause Is a Comparison" and "What Space Is". Standing: argued there from the identity of interaction, comparison and relation (the Root Tautology of that book's Chapter 1). The same chapter gives space the omniscient context and time the immanent context, and holds time prior to space by the first axiom.

Why the arena bends, smoothly, following its content. Claim: every comparison demands that its comparing connect without a break (continuity) and that its content be the same for every comparer (symmetry).

By the Incommensuration Theorem, wherever continuity is perfected in a comparison, asymmetry travels with it somewhere in the comparison. The content cannot carry the asymmetry, since it keeps its sameness; the comparing cannot carry it, since the comparing is the act of joining and not something laid out from place to place; and by the third axiom neither can hand its work to the other. So the context carries it, and the context is continuously asymmetric: smooth, and different from place to place wherever there is content. The difference from place to place lies in the arena, the part of the context laid out from place to place, as the source says next: "Where there is content, the arena differs from one place to the next. The arena bends". Source: *Two Theories, One World*, Chapter 8, "Why the Arena Bends", sections "The Comparing Connects", "The Content Holds Together", "Neither Can Carry Both" and "The Context Carries the Rest" (the pan balance is that chapter's picture; the handshake is this chapter's picture of an act of joining that is not laid out from place to place). Standing: reasoned from the structure of comparison ("I reason that the asymmetry ... is carried by the context"), in the focus in which all three axioms hold. *Two Theories, One World* derives three facts: that there is a bending, that it is smooth, and that it goes with the content. The form of the relation is taken from general relativity as established physics, and Newton's constant is a measured input (section "What the Established Theory Adds"). Measured value of Newton's constant, as *The Unquantized Arena*, Chapter 9, Section VI, gives it from the 2022 adjustment of the Committee on Data of the International Science Council (CODATA 2022): $G = 6.67430(15) \times 10^{-11}\ \mathrm{m^3\ kg^{-1}\ s^{-2}}$, read "six point six seven four three zero, with an uncertainty of fifteen in the last two digits, times ten to the minus eleven cubic meters per kilogram per second squared".

The smooth clock rate and the uneven arena. Claim: the arena is smooth (the clock rate changes by no step as the height changes) and asymmetric (no two heights above the Earth are exactly alike), and the asymmetry is there because the Earth is there; the clocks raised in 2010 agree with this. Source: *Two Theories, One World*, Chapter 8, "You Live in a Bent Arena": "In each case the arena behaves as the reason says it must. It

is smooth: the clock rate changes by no step as the height changes. It is asymmetric: no two heights above the Earth are exactly alike". Standing: the smoothness and the asymmetry are what the reason from comparison requires; the measurement of Chou and colleagues compared two clocks at one difference of height and found the rate difference general relativity gives.

The expansion as a growth of the arena. Claim: the moving away of distant galaxies, at effective rates above the speed of light, is a growth of the arena between them and no signal across it. The effective rate is taken in the natural way that the source states: the distance to a very distant galaxy as it stands today, and how fast that distance grows; for the most distant galaxies it grows by more than a light-year each year. Source: *What Cannot Be*, Chapter 12, "What Stays Exactly as It Was", citing Davis and Lineweaver (2004). Standing: stated there as left untouched by the chapter's exclusion, which concerns only what crosses the edge of the causal domain.

Gravitational waves at the speed of light. Claim: a change in the shape of the arena spreads through it as a wave at the speed of light. Source: *Two Theories, One World*, Chapter 8, "What the Established Theory Adds". Standing: reported as established physics; GW170817 with GRB 170817A bounds $(v_{gw} - c)/c$ between -3×10^{-15} and $+7 \times 10^{-16}$ (Abbott and others 2017; *The Unquantized Arena*, Chapter 19, Table 19.2); v_{gw} (v-sub-g-w) is the speed of the waves and c the speed of light. In Chapter 15 of this book I find the speed of light to be the outer edge of comparison, the same for every comparer.

No least step, and no quantum of the arena. Claim: the arena has no least length, area or duration, and nothing is a quantum of the arena itself, at any scale. Small waves of geometry about a smooth background can be described by quanta, which are quanta of the description; the phonon is the nearest sense of such a quantum, and the arena is no held structure. Source: *The Unquantized Arena*, Chapter 6, Section IV, Proposition 6.3 and the four things it leaves allowed. Standing: a proposition, argued from the

law of continuity and Propositions 4.2 and 6.1; the chain to it contains one identification, gravity as the context-modal phenomenon (P18), which Chapter 7 of this book states.

The Planck length as the place where two descriptions meet. Claim: every object of mass m has a gravitational size and a quantum size; the two are equal only at the Planck mass, where both equal the Planck length; there neither description dominates, and the Planck length is no least length of the arena. Source: *The Unquantized Arena*, Chapter 9, Section V, Proposition 9.3; *What Cannot Be*, Chapter 18, "The Horizon of the Very Small"; *The Gravitational Passage*, Chapter 17, Sections II and IV ("The boundary is not a wall that matter cannot cross"). Standing: a proposition, from the two sizes of a mass and the Incommensuration Theorem. In words first: the gravitational size, as Proposition 9.3 defines it, is Newton's constant times the mass divided by the square of the speed of light; the quantum size is the reduced Planck constant divided by the mass times the speed of light; they are equal when the mass is the square root of the reduced Planck constant times the speed of light divided by Newton's constant. In symbols: $r_g = Gm/c^2$ (r-sub-g, the gravitational size, equals G times m over c squared); $\lambda = \hbar/(mc)$ (lambda, the quantum size, equals h-bar over m times c); $r_g = \lambda$ when $m = M_P = (\hbar c/G)^{1/2}$ (M-sub-P, the Planck mass, the square root of h-bar c over G). The size of a black hole of mass m (its Schwarzschild radius) is $2Gm/c^2$, twice r_g, so the gravitational size is half the size of a black hole of that mass, as Chapter 8 of this book defines it. So in Chapter 10 of this book I say that the gravitational size and the quantum size are equal at the Planck mass, where both sizes equal the Planck length. Values: $M_P = 2.176 \times 10^{-8}$ kg (about twenty-two millionths of a gram); $l_P = (\hbar G/c^3)^{1/2} = 1.616 \times 10^{-35}$ m (l-sub-P, the Planck length); $t_P = 5.391 \times 10^{-44}$ s (t-sub-P, the Planck time). The bound on placing a body: *The Unquantized Arena*, Chapter 9, Section V, cites Belenchia and colleagues (2018) for a limit on localization of about a Planck length, "a bound on placing" that gives the geometry no least value. The microscope picture is from *Two Theories, One World*, Chapter 15.

The grain of space tested with the most energetic light. Claim: light of very different energies from distant gamma-ray bursts arrives together, which places any grain that slows light in proportion to its energy below the Planck length. Source: *What Cannot Be*, Chapter 18, "The Horizon of the Very Small"; *Two Theories, One World*, Chapter 15; *The Unquantized Arena*, Chapter 19, Section V, Prediction 19.4 and Table 19.2. Standing: measured; the account's own claim of no least step rests on Proposition 6.3, and the measurements agree with it. In words: in the usual description, a photon of energy E travels at a speed that differs from the speed of light by a term of order $(E/E_{QG,n})^n$, with n equal to one or two, where $E_{QG,n}$ (E-sub-QG-n) is the energy at which that term would reach one; bounds are stated against the Planck energy $E_{Pl} = 1.22 \times 10^{19}$ GeV (a GeV being a billion electron volts). Values (Table 19.2): the Fermi Gamma-ray Space Telescope, GRB 090510, a photon of 31 GeV arriving 0.829 seconds after the trigger (as *Two Theories, One World*, Chapter 15, reports it), $E_{QG,1} > 1.2\ E_{Pl}$ (Abdo and others 2009). Fermi, bursts including GRB 090510, subluminal case: $E_{QG,1} > 7.6\ E_{Pl}$ (Vasileiou and others 2013). The Large High Altitude Air Shower Observatory (LHAASO), GRB 221009A: $E_{QG,1} > 10\ E_{Pl}$ and $E_{QG,2} > 6 \times 10^{-8}\ E_{Pl}$ (Cao and others 2024). The corpus states the bound in energy; the chapter's length, "below about a tenth of the Planck length", is the first-order LHAASO bound converted by the relation $l = \hbar c/E_{QG,1}$ (l equals h-bar c over E-sub-QG-1), against $l_P = \hbar c/E_{Pl}$. Scope, as *The Unquantized Arena*, Chapter 19, Section V, states it: these timing bounds test the discrete pictures that predict a dispersion; a discreteness that keeps Lorentz invariance, as in causal sets (Bombelli, Henson and Sorkin 2009), predicts no such dispersion and is tested by its own signatures; the account predicts that no observation will show a least length, area or duration, whatever its relation to Lorentz invariance.

The cup and the Moon. The mean distance from the Earth to the Moon, about 384,400 kilometers, divided by the speed of light, 299,792.458 kilometers per second, gives about 1.28 seconds, "a little more than a second" in the chapter.

Measured values the chapter tells, with their primary papers. The eclipse of 29 May 1919: starlight passing the Sun bent by the amount general relativity requires (Dyson, Eddington and Davidson 1920), as *Two Theories*, *One World*, *Measurement* and *The Gravitational Companion* report it. For a ray grazing the Sun's edge the amount general relativity requires is $4GM_S/(c^2R_S)$ (four G times the Sun's mass, over c squared times the Sun's radius; M-sub-S and R-sub-S are the Sun's mass and radius), about 1.75 seconds of arc. The clock raised by about a third of a meter ran faster than the lower one by the amount general relativity gives (Chou, Hume, Rosenband and Wineland 2010). The fractional rate difference general relativity gives for a height h is gh/c^2 (g times h over c squared, g being the acceleration of a falling body at the Earth's surface), about 4×10^{-17} for a third of a meter. The first detection of gravitational waves, from two black holes spiraling together, reported in 2016 (Abbott and others 2016). GRB 090510 (Abdo and others 2009) and GRB 221009A (Cao and others 2024), as above.

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by the Sun's Gravitational Field, from Observations Made at the Total Eclipse of May 29, 1919". *Philosophical Transactions of the Royal Society of London A* 220, 291–333. Malament, D. B. (1977). "The Class of Continuous Timelike Curves Determines the Topology of Spacetime". *Journal of Mathematical Physics* 18, 1399–1404. Clarke, S. (ed.) (1717). *A Collection of Papers, which passed between the late learned Mr. Leibnitz and Dr. Clarke, in the years 1715 and 1716*. London. Leibniz's third paper, paragraphs 4 and 5.

Chapter 11. How Many Dimensions Are There?

In Chapter 11 of this book I count the dimensions of the three settings of every finding, I say why six of those dimensions are never traversed, and I set the count beside the measurements. Each claim below is given with the corpus book that carries it and its standing as that book states it.

Words of the chapter and words of the corpus

The chapter's "six aspects" of comparison (the word of Chapter 5) are the corpus's six intrinsics: sameness and difference; content and context; the subjective and the objective. The chapter's "the side the comparison is made from" and "the side it is made about" are the subjective and the objective, which *At the Edge of Reality*, Chapter 4, "Six Ideas in Every Comparison", also calls the comparing and the compared. The chapter's "point of view" is the corpus's stance: "Together they are the stance from which every comparison is made" (*At the Edge of Reality*, Chapter 5, "The Stance, and What Can Be Followed"). The chapter's "three positions" of every comparison (the word of Chapter 4) are the three roles of *At the Edge of Reality*, Chapter 4, "Three Roles and Their Order", which the three pairs of intrinsics fill. *The Story of the Particles*, Overture, Sec. III, "What Comparison Requires", names them: "the immanent (the act of comparing), the omniscient (the thing compared) and the transcendent (the thing compared against)". The chapter's "context" is the corpus's context, the pole

of the pair of content and context; each of the chapter's three "settings" (space, time and possibility) is one column of the context, which the corpus also calls a context.

The definition and the numbers available

Claim: a dimension of a setting is the number of independent ways in which two findings can differ in that setting, and this is the dimension of a smooth space in the ordinary sense. Source: *At the Edge of Reality*, Chapter 5, "The Definition"; *Measurement*, "Ten Dimensions in Plain Words", Section I, and Section IX, third question. Standing: a definition.

Claim: the only numbers the structure of comparison supplies as a count of independent ways are one, two, three, four and six, the sizes of its sets of elements. The five sets are these: the single comparing; the two members of a pair; the three pairs; the four intrinsics that can be followed apart from the stance, namely sameness, difference, content and context; and the six intrinsics. Source: *At the Edge of Reality*, Chapter 5, "The Numbers Comparison Supplies"; *Measurement*, "Ten Dimensions in Plain Words", Section II. Standing: derived from the six intrinsics of comparison (*At the Edge of Reality*, Chapter 4, "Six Ideas in Every Comparison"). Combinations of elements are excluded because a composed way is not independent: the eight combinations of the three pairs, each taken in one member, are three choices of two. The list is complete, as *Measurement*, Section II, states. The other sets of the ground (the three roles, the two rows of the grid, the six measures, the two levels of a theory) have sizes already on the list. The four compounds, the eight combinations and the ten pairings of compounds are composed from the intrinsics, and add no size.

Claim: the subjective and the objective cannot be followed apart from the stance, because together they are the stance; the other four intrinsics can be followed, and are called followable. Source: *At the Edge of Reality*, Chapter 5, "The Stance, and What Can Be Followed"; *Measurement*, "Ten Dimensions in Plain Words", Section II. Standing: derived.

Claim: the minimality principle, that of the numbers comparison supplies a context takes the least that meets every requirement comparison places on it. Source: *At the Edge of Reality*, Chapter 5, "The Minimality Principle". Standing: a principle, stated with its reason: a further way of differing that nothing in comparison registers as distinct adds nothing any comparison could find. *Measurement* names the principle beneath it the principle of no unregistered difference.

One of time, three of space

Claim: time has one dimension, because the comparing is one stance and from one stance any two findings are earlier and later. Source: *At the Edge of Reality*, Chapter 6, "Time Has One Dimension"; *Measurement*, "Ten Dimensions in Plain Words", Section III. Standing: derived.

Agreements with the count of time (concordances, on which the count does not rest) are two. First, the cone of precedence at each event falls into a before and an after only with exactly one time direction. In symbols, the metric signature has exactly one negative sign, $(-, +, +, +)$, read "minus, plus, plus, plus" (*The Gravitational Passage*, Chapter 10, Section III). Second, with two or more time directions the wave equation is ultrahyperbolic, and its initial value problem is ill posed for data on a surface containing no time direction (Tegmark 1997; Craig and Weinstein 2009, as cited there).

Claim: space has three dimensions. The number of dimensions of space is not one, because space and time are distinct and a context has no feature but its form of difference. The number of dimensions of space is not two, by the placing rule: the distinction between two ways of a context is placed in that context when, and only when, the context has a way not composed from those two ways. Three, four and six meet the doubling (every difference is placed twice, by a comparing and in a context), and the minimality principle takes three. Source: *At the Edge of Reality*, Chapter 6, "Space Is Not One" to "Three by the Minimality Principle"; *Measurement*, "Ten Dimensions in Plain Words", Section IV. Standing: derived,

given one identification stated in the first person in *At the Edge of Reality*, Chapter 6: the space so counted is the familiar directions of the large world.

Claim: a second road, sharing no step with the first, reaches three of space and one of time from the cycle of Axiom II (three transitions, one direction of return). Source: *The Gravitational Passage*, Chapter 10, Sections I, II and IV; *At the Edge of Reality*, Chapter 7, "A Second Road to Ten"; *Measurement*, "Ten Dimensions in Plain Words", Section VIII. Standing: derived given two identifications, each stated in the first person: each independent transition of the cycle with an independent direction of extension, and the cycle's directedness with the one direction of time. Axiom II in its exact wording: "A class of the transcendent will precede an instance of the immanent. A class of the immanent will precede an instance of the omniscient. A class of the omniscient will precede an instance of the transcendent".

Six of possibility

Claim: possibility has six dimensions. Possibility is the range of what a comparison could find. A finding is specified in all six intrinsics: its verdict, same or different; its respect, content in a context; and its place in the stance of the comparing and the compared. Possibility stays bound to the stance, so it cannot be confined to the four followable intrinsics. Source: *At the Edge of Reality*, Chapter 7, "Possibility Has Six"; *Measurement*, "Ten Dimensions in Plain Words", Section V (the particle counter). Standing: derived. In the particle counter of the main text, the verdict (a click or no click) carries the two intrinsics sameness and difference, so the four ways listed (verdict, content, context, the two sides) span the six intrinsics. The progression one, three, six (one; one and two; one, two and three) and the count of six pairs among four ways are concordances; the count does not rest on them (*At the Edge of Reality*, Chapter 7, "One, Three, Six").

Claim: the four of time and space are traversed by located comparers, and the six of possibility are met only as what could be found. So to a comparer inside the world the six present as compact and closed, with no

depth; their extent shows only through its effects, among them the strength of gravity. Source: *At the Edge of Reality*, Chapter 7, "Why We Never See Them"; *Measurement*, "Ten Dimensions in Plain Words", Section VII. *The Compactification*, Chapter 1, Section II, quotes *Measurement*, Chapter 11, Section XII: "Four are traversed by located comparers, and six are met only as what could be found". Standing: derived.

Scope: the count of dimensions gives the six no shape and no size (*Measurement*, "Ten Dimensions in Plain Words", Section IX; *The Compactification*, Chapter 1, Section II). The shape and the size belong to the internal space read with radii, the context instance, as *The Gravitational Passage* gives it.

The internal space: its shape, its size, and the one set

Claim: the internal space is the complex projective plane times the sphere, of dimension four plus two. In symbols it is $\mathbb{C}P^2 \times S^2$, read "C P two times S two". $\mathbb{C}P^2$ is the space of pure states of a system with three alternatives; S^2 is the space of pure states of a system with two alternatives (for a two-state system, the Bloch sphere). Source: *At the Edge of Reality*, Chapter 7, "The Shape of the Six" and "A Space of Possibilities"; *The Gravitational Passage*, Chapter 9. Standing: derived given three identifications, each stated in the first person, and one condition. The first identification: each measure of the grid of six gets its own direction. The six measures come from the six intrinsics, one measure for each, so each of the six intrinsics has its own direction. The second identification: the internal space is a product of a piece carrying the three roles (the three positions) and a piece carrying the two rows (content and context). The third identification: each piece carries its terms as its independent cells. The condition: each piece is homogeneous, because the arena in which content is compared cannot single out one point. Then the classification of compact homogeneous spaces leaves one answer: the only such surface with Euler characteristic two is S^2, and the only such four-dimensional space with Euler characteristic three is $\mathbb{C}P^2$. In symbols: $\chi(\mathbb{C}P^2) = 3$ and $\chi(S^2) = 2$, where χ ("chi") is the Euler characteristic, which for these shapes, built

only from cells of even dimension, is the number of their cells. The natural distance on such a space of states measures how well one state can be told apart from another (Wootters 1981, as reported in *At the Edge of Reality*, Chapter 7).

Claim: I identify the two sixes as one set: the six dimensions of possibility counted from comparison, and the six dimensions of the internal space. Source: *At the Edge of Reality*, Chapter 7, "A Space of Possibilities". Standing: an identification, stated in the first person, with its ground: both sixes are indexed by the same six intrinsics and by nothing else, so no comparison can register a difference between them.

Claim: the six are a few Planck lengths across: the sphere has radius one Planck length, and the complex projective plane has radius the square root of six, about 2.45, Planck lengths. In symbols, $R_T = l_{Pl}$ and $R_O = \sqrt{6}\ l_{Pl}$, read "R T equals the Planck length" and "R O equals root six Planck lengths", where R_T is the radius of S^2 and R_O the radius of $\mathbb{C}P^2$. The ratio $R_O/R_T = \sqrt{6}$ follows from the Einstein condition on the product, since the Fubini–Study metric on $\mathbb{C}P^2$ has Ricci constant $6/{R_O}^2$ and the round S^2 has Ricci constant $1/{R_T}^2$. Source: *At the Edge of Reality*, Chapter 8, "How Small the Six Are"; *The Gravitational Passage*, Chapter 10, Section V, and Chapter 11, Sections II and IV. Standing: the ratio is derived given the Einstein condition, which is an identification with its ground stated in *The Gravitational Passage*, Chapter 9, Section IX. The overall scale rests on one identification, stated in the first person in *At the Edge of Reality*, Chapter 8: each of the six directions, on its own, reaches the curvature of the Planck scale. The Planck length is about 1.6×10^{-35} meters, about a hundred billion billion times smaller than a proton (*At the Edge of Reality*, Chapter 8, with the exact value in its Appendix C).

Claim: the six are held compact as content of the four large dimensions taken as their context, with a reference for inertia fixed in the large world (the compactification conditions). Their compact form depends on the large world being there, and their size, a few Planck lengths, is set by the Planck scale. Source: *At the Edge of Reality*, Chapter 8, "Held, Not Given"

and “No Content Without a Context” to “The Two Conditions”. *The Compactification*, Chapter 1, Section II: “The six were never directions of space, and the account never has them traversed”. Standing: derived from Axiom III (content and context are inseparable), with the Mach principle in its weakest form supplied by the principle that a difference no comparison can register is no difference. The main text’s “standard of rest and of turning” is the reference for inertia, illustrated, as in *At the Edge of Reality*, Chapter 8, “Inertia Is a Comparison”, by a gyroscope that keeps pointing at the same distant stars.

Claim: the gyrations of Chapter 2 are excitations of the six held internal dimensions. Source: *The Geometric Route*, the entry on the context instance, citing *The Weight of Possibility*, Chapter 1, Section IV. Standing: as Chapter 2 of this book states it.

Kaluza’s step kept, and the strength of gravity

Claim: the product $M^4 \times \mathbb{C}P^2 \times S^2$ (read “M four times C P two times S two”, where M^4 is the four-dimensional arena) is a Kaluza–Klein compactification. The ten-dimensional Einstein–Hilbert action, integrated over the internal space with the moduli held, gives the four-dimensional Einstein equations, and Lovelock’s theorem in four dimensions fixes their form. Source: *The Gravitational Passage*, Chapter 8, Section IV, and Chapter 11, Sections I and V. Standing: given the structural identifications of Chapters 9 and 10 of that book and the floor of its Chapter 11, Section II, every remaining step is a theorem or a standard technique (Chapter 11, Section V). In symbols, the action is $S_{10} = \int d^{10}x \, \sqrt{(-g_{10})} \, R_{10}$, read “the ten-dimensional action is the integral over ten dimensions of the square root of minus the determinant of the metric times the scalar curvature”. The main text’s “summed over every point of the six” is this integration over the internal space.

Claim: the four-dimensional Planck mass is set by the ten-dimensional scale and the volume of the internal space. In words first: the square of the Planck mass equals the eighth power of the ten-dimensional mass scale times the volume of the six. In symbols: $M_{Pl}{}^2 = M_{10}{}^8 \times \mathrm{Vol}(K)$, where

M_{Pl} is the full Planck mass, M_{10} the scale formed in the same way from the ten-dimensional coupling, and Vol(K) the volume of the internal space K. Source: *The Gravitational Passage*, Chapter 11, Section III, equation 11.2; *At the Edge of Reality*, Chapter 7, "Why We Never See Them". Standing: a result of the reduction.

Claim: gravity is weak on the electron because the electron is very light against the Planck mass, the mass at which gravity's strength on a body reaches one. The electron sits about 74.3 halvings below that mass, the unreduced Planck mass, as Chapter 7 of this book counts it. Source: *Why These Numbers*, Chapter 7, "One Distance, Seen from Both Ends" and "The Ruler of Halvings". Standing: as that book states it. The same book counts the span to the reduced Planck mass, smaller than the unreduced one by the square root of eight pi (about 2.3 halvings): seventy-two halvings and a little more, 72.0132 (*Why These Numbers*, Chapter 5, "Three Strengths as One Arrow"). The integer part of that span, seventy-two, is the count that book identifies with the span; the identification is stated there and given with Chapter 7 of this book.

Claim: the moduli (the fields that carry the size and the shape of the six) have masses of 2.25 and 3.09 Planck masses at first order. So the force they carry has a range shorter than the Planck length, some thirty orders of magnitude shorter than the shortest range any test of gravity reaches, and four-dimensional gravity is general relativity. Source: *The Gravitational Passage*, Chapter 11, Section II, "The stiffness of the hold"; *The Compactification*, Chapter 2, Section V. Standing: the hold is argued (from Axiom III and the uncertainty relation) and does not rest on the computation. The masses come from a first-order computation of one mechanism (*The Gravitational Passage*, Appendix D), and the bound needs only their order. Here M_{Pl} is the full Planck mass, 1.221×10^{19} GeV.

The range of a force carried by a field quantum of mass M is about the reduced Compton wavelength of that quantum, $\hbar/(Mc)$, read "h-bar over M c" (standard physics: H. Yukawa, "On the Interaction of Elementary Particles. I", *Proceedings of the Physico-Mathematical Society of Japan* 17

(1935) 48–57). Since the Planck length is $l_{Pl} = \hbar/(M_{Pl}\, c)$, masses of 2.25 and 3.09 M_{Pl} give ranges of about 0.44 and 0.32 Planck lengths. The main text's sentence on the weak force uses the same relation: the weak force's carriers have masses near eighty and ninety-one GeV, and its range is about 2×10^{-18} meters.

String theory's ten beside this ten

Claim: string theory fixes the total of ten by the consistency of the theory and chooses the split into four and six, and the shape of the six, among many possibilities; this account counts each number from comparison and has one shape. Source: *At the Edge of Reality*, Chapter 3, "String Theory's Ten" and "The Answer of This Book". Standing: reported (string theory); derived (this account). On this account's ten, *The Compactification*, Chapter 1, Section II, quotes *Measurement*, Chapter 11, Section XII. The quoted words: "its dimensions are of three kinds; its six are not spatial and are never traversed; the signature of one against three holds within the four of time and space; and nothing in it curls the six or gives them a size".

The scene

Kaluza's paper: T. Kaluza, "Zum Unitätsproblem der Physik", *Sitzungsberichte der Preussischen Akademie der Wissenschaften zu Berlin, Physikalisch-Mathematische Klasse* (1921), 966–972, submitted by Einstein on 8 December 1921. English translation: "On the Unification Problem in Physics", *International Journal of Modern Physics D* 27 (2018) 1870001, arXiv:1803.08616, which carries the "cylinder condition" (the derivatives of the state quantities with respect to the fifth coordinate vanish). Einstein's letter to Kaluza of 21 April 1919: *The Collected Papers of Albert Einstein*, Volume 9 (Princeton University Press), quoted in English in N. Straumann, "Early History of Gauge Theories and Kaluza–Klein Theories", arXiv:hep-ph/9810524. Klein's circle: O. Klein, "Quantentheorie und fünfdimensionale Relativitätstheorie", *Zeitschrift für Physik* 37 (1926) 895–906.

Measured values told in the chapter

The inverse-square law of gravity holds down to about a twentieth of a millimeter: D. J. Kapner, T. S. Cook, E. G. Adelberger, J. H. Gundlach, B. R. Heckel, C. D. Hoyle and H. E. Swanson, "Tests of the Gravitational Inverse-Square Law below the Dark-Energy Length Scale", *Physical Review Letters* 98 (2007) 021101.

The Cassini radio links give $\gamma - 1 = (2.1 \pm 2.3) \times 10^{-5}$, where γ ("gamma") is the post-Newtonian parameter that measures how much space curvature a unit of mass produces, equal to one in general relativity. This excludes a long-range scalar force at the strength a light modulus would carry: B. Bertotti, L. Iess and P. Tortora, "A Test of General Relativity Using Radio Links with the Cassini Spacecraft", *Nature* 425 (2003) 374–376.

The number of spacetime dimensions through which the gravitational waves of GW170817 traveled: 4.02 $(+0.07, -0.10)$ with the distance-ladder Hubble constant and 3.98 $(+0.07, -0.09)$ with the Planck Hubble constant. Source: K. Pardo, M. Fishbach, D. E. Holz and D. N. Spergel, "Limits on the number of spacetime dimensions from GW170817", *Journal of Cosmology and Astroparticle Physics* 2018(07) 048, arXiv:1801.08160 (reported in *Side by Side*, Volume Two, "Wolfram 3").

No heavier copies of known particles (Kaluza–Klein towers) have been found at the Large Hadron Collider, as Cham and Whiteson report (*We Have No Idea*, ch. 9, "Wrapping Up These New Directions").

Chapter 12. What Is Time?

Time comes with comparison: two moments can be told apart only where a change is found, so time is an intrinsic of comparison, of interaction and of perception. Source: *Why Time Travel Is Not a Concept*, Chapter 1, Section II, "Three Times" (the head and the book); the same argument in *What Cannot Be*, Chapter 14, "Three Times", and in *The Last Turtle*, "Two Atoms in an Empty Universe", Section VIII, "Time Comes With the Interaction". Standing: argued in those books from the structure of comparis-

on; *The Unquantized Arena*, Chapter 10, Section II, states the same point as "Findings define the order of event time; they do not occur within a time given before them".

The least interaction that leaves a lasting difference is two hydrogen atoms and the photon that passes between them; one electron with one photon, or one hydrogen atom alone, is not enough. The steps: a free electron cannot absorb a photon, since energy and momentum could not both be conserved; the photon can scatter off it, but a free electron has no internal states in which to keep a record, and nothing else is present against which the change could register; with a proton added, a photon of the right frequency can raise the electron of the one hydrogen atom to a higher orbital, but in an otherwise empty universe that frequency has nothing to be measured against; with a second atom, one emits and the other absorbs. Source: *The Last Turtle*, "Two Atoms in an Empty Universe", Sections I to III. Standing: argued there; the absorption step rests on the conservation of energy and momentum (standard physics, stated there).

An interaction that spans any distance also spans some nonzero duration, and this locality is a special case of continuity. Source: *An Immanent Metaphysics*, the passage on locality in science ("If an interaction spans any distance, then it must also span some nonzero duration"; "The notion of locality, in asserting that there can be no abrupt instantaneous changes, is a special case of the concept of continuity"). Standing: stated there as a consequence of the concept of continuity. Scope: locality in that passage is the assertion that no physical influence, interaction or signal travels faster than the speed of light, that is, that no influence makes a jump between separated points in zero time; it concerns influences across space and time, and the discreteness of what a finding finds (event time, below) is a character of findings, given in *The Unquantized Arena*, Chapter 10, Definition 10.2.

Physics uses the one word "time" for three mathematical objects of different kinds: geometric time, event time and evolution time. Source: *The Unquantized Arena*, Chapter 10, "Three Times", Section II, Definitions 10.1 to 10.3; plain forms in *Two Theories, One World*, Chapter 16, "Three Kinds

of Time", and *What Cannot Be*, Chapter 14. Standing: three definitions; the matching of each with one of the three modalities (geometric time with the omniscient, event time with the immanent, evolution time with the transcendent, in the focus of time) is an identification, P19 of *The Unquantized Arena*; the chapters of this book do not use the identification.

Geometric time, in words: the proper time along each path of a body moving slower than light, together with the causal order of events, both carried by the metric (the rule that gives lengths and durations) of spacetime. In symbols, the proper time along a worldline γ with parameter λ is $\tau[\gamma] = (1/c) \int \sqrt{(-g_{\mu\nu}\, \dot{x}^{\mu}\, \dot{x}^{\nu})}\, d\lambda$; read aloud: tau of gamma, the proper time, equals one over c, the speed of light, times the integral along the path of the square root of minus the metric g, with indices mu and nu, applied twice to the rate of change of position x-dot with respect to lambda. Its character as found: continuous and asymmetric (*The Unquantized Arena*, Chapter 10, Section II).

Event time, in words: the order of findings for a comparer, each finding one outcome of a discrete set, laid down as a record; as a mathematical object, a discrete sequence of outcome labels k of a measurement (a projector P_k or an effect E_k), ordered by precedence. Its character as found: discontinuous and symmetric. Its order is the order of Axiom II, "a precedence and not a clock reading, and it cannot be reversed" (*The Unquantized Arena*, Chapter 10, Definition 10.2). The identification of that one-way order with the direction of time is stated there; Chapter 13 of this book finds that time goes forward because every comparison goes one way, from what could be found, to the finding, to its record.

Evolution time, in words: the parameter t of the strongly continuous one-parameter group of unitary operators U(t) that carries a quantum state. In symbols, $U(s + t) = U(s)\, U(t)$, $U(t) = \exp(-iHt/\hbar)$, and $i\hbar\, d\psi/dt = H\psi$; read aloud: evolving for s and then for t is evolving for s plus t; U of t is the exponential of minus i times H times t over h-bar, where H is the Hamiltonian (the operator of energy) and h-bar is the reduced Planck constant; and i h-bar times the rate of change of the state psi equals H act-

ing on psi (Schrödinger's equation). Stone's theorem (1932) puts such groups in one-to-one correspondence with their self-adjoint generators. Each $U(t)$ has the inverse $U(-t)$, the "exact undoing" of the chapter. Its character: continuous, in the instrumental mode (the formalism) of quantum mechanics; the invariance of H under translations in t is a symmetry of the law, carried to the findings by Noether's theorem as the conservation of energy. Source: *The Unquantized Arena*, Chapter 10, Definition 10.3, equation 10.2.

The three times are distinct, inseparable and non-interchangeable, the three clauses of the third axiom, Axiom III. The third of the distinctness steps, in the words of that book: "the parameter of a group of states is not a direction of spacetime"; the space of states is a complex Hilbert space, generally of infinite dimension, and no signal travels through it from one place to another. Source: *The Unquantized Arena*, Chapter 10, Section III, Proposition 10.1. Standing: argued there, resting on the definitions, the identifications of the focus of time, and the theorems of Stone (1932) and of Pauli as Busch (2008) reports it: no self-adjoint operator is canonically conjugate to a Hamiltonian bounded below, so evolution time is not an observable; the time observables quantum mechanics uses, such as a time of arrival, measure event time.

General relativity holds geometric time and event time natively and has no evolution time; quantum mechanics holds event time and evolution time natively and holds geometric time only as an external parameter. Source: *The Unquantized Arena*, Chapter 10, Section IV, Table 10.2; *Two Theories, One World*, Chapter 16, "Each Theory Holds Two". Standing: argued there from the content of the two established theories. In canonical quantum gravity the Hamiltonian constraint becomes $\hat{H}\Psi[h] = 0$ (read aloud: the constraint operator H-hat annihilates the wave functional Psi of the spatial geometry h), which carries no time parameter (DeWitt 1967; Isham 1993); reported there as the problem of time. *Two Theories, One World*, Chapter 16, end of "Each Theory Holds Two": "The variable of evolution was a time of the arena, and the arena has been turned into the thing that was to evolve". *The Unquantized Arena*, Chapter 10, Section IV:

evolution time disappears from the formalism at the step that puts the arena into the state, and the t of Schrödinger's equation is read from a clock outside the system.

No unified time exists: no one time is geometric time, event time and evolution time together with each perfected, none of them external and none primitive (Definition 10.4). Proposition 10.2, in the words of *The Unquantized Arena*: "A time found both as geometric time and as event time would carry at least one of the two forbidden pairings, and, where all four characters are asked of the same directions, both. A unified time asks all four of one time, and so it would carry both". Of the third time, the same argument: "Evolution time does not alter the verdict, since its continuity lies on the same side as the geometry's". Source: *The Unquantized Arena*, Chapter 10, Section V, Definition 10.4 and Proposition 10.2; the plain form in *Two Theories, One World*, Chapter 16, "Why No Single Time Holds All Three", and *What Cannot Be*, Chapter 14, "Three Times". Standing: argued from the four compounds and the Incommensuration Theorem. Proposition 10.3 adds that any formalism holding two of the three times natively holds the third only as external, as primitive, or not at all.

The Incommensuration Theorem, in its exact wording: "Symmetry and continuity cannot both be applied, simultaneously and fundamentally, to any event or comparison; and neither can asymmetry and discontinuity" (*Incommensuration*, Ch. 2, Sec. VI). It is a structural fact about the nature of knowing (*What Cannot Be*, Chapter 14, "Three Times", restating Chapter 3).

"Time is not another dimension of space. It is a common coordinating aspect (context) of directivity in interaction". Source: *An Immanent Metaphysics*, the passage on time before the Table of Modality Correspondences. Standing: stated there. The one dimension of time counted in Chapter 11 of this book is the direction of geometric time within the four-dimensional arena (*The Gravitational Passage*, Chapter 10, as Chapter 11 reports).

A clock's rate is set by its place in the arena, by its height in a field of gravity and by its motion, and not by how many interactions it takes part in; the felt passage of time goes with the number of changes, and the novelty, in what is perceived. Source: *Why Time Travel Is Not a Concept*, Chapter 1, Section II; *What Cannot Be*, Chapter 14, "Three Times" ("A busy clock and an idle clock"; and "To speak of how fast time flows, one has to say which time is meant"). Standing: stated there; the clock rates are the established physics of general relativity.

The arena is continuously asymmetric where there is content: smooth, and different from place to place; "no two heights above the Earth are exactly alike". Source: *Two Theories, One World*, Chapter 8, "The Context Carries the Rest" and "You Live in a Bent Arena". Standing: argued there from the two demands of every comparison and the Incommensuration Theorem; the form of the bending is taken from general relativity as established physics, with Newton's constant a measured input.

No comparison registers a surface of simultaneity, and the account needs none; a record of a distant finding reaches a comparer only through a signal on or within that comparer's past light cone. Source: *The Unquantized Arena*, Chapter 10, Section VI. Standing: stated there. Comparers in steady relative motion disagree about which distant events are simultaneous, and spacelike separated events stand in no fixed order: *What Cannot Be*, Chapter 12, "A Signal That Would Arrive Before It Was Sent" (the lamp in the train car); established special relativity.

The content laid out by findings is held to symmetry, the same for every comparer who finds it, "so that the findings of many comparers make one history". Source: *Two Theories, One World*, Chapter 8, "The Content Holds Together". Standing: argued there from the second axiom and the law of symmetry (Chapter 7 of that book). The history meant is one in what each finding found; the time order of distant findings differs from one comparer to another, so it is no single time-ordered list of events, which is the history Cham and Whiteson set aside (*We Have No Idea*, ch. 10, "History Is History").

Measured values told in Chapter 12

Measurement	Value	Primary paper
Cesium beam clocks flown around the world, October 1971, compared with the atomic time scale of the United States Naval Observatory	Eastward: lost 59 ± 10 ns (predicted -40 ± 23 ns). Westward: gained 273 ± 7 ns (predicted $+275 \pm 21$ ns).	J. C. Hafele and R. E. Keating, "Around-the-World Atomic Clocks: Predicted Relativistic Time Gains", *Science* 177 (1972) 166–168; "Around-the-World Atomic Clocks: Observed Relativistic Time Gains", *Science* 177 (1972) 168–170.
Net rate of a Global Positioning System satellite clock against a ground clock	4.4647×10^{-10} fast; times 86,400 seconds, about 38 microseconds a day; uncorrected, navigational errors of more than 11 km in one day	N. Ashby, "Relativity in the Global Positioning System", *Living Reviews in Relativity* 6 (2003) 1; N. Ashby, "Relativity and the Global Positioning System", *Physics Today* 55 (5) (2002) 41–47. As reported in *Two Theories, One World*, Chapter 1 and Appendix A.
Aluminum ion optical clock (one $^{27}Al^{+}$ ion) raised by 33 cm	Faster by about 4×10^{-17}, the amount general relativity gives	C. W. Chou, D. B. Hume, T. Rosenband and D. J. Wineland, "Optical Clocks and Relativity", *Science* 329 (2010) 1630–1633. As reported in *Two Theories, One World*, Chapters 1 and 8 and Appendix A.

Chapter 13. Why Does Time Only Go Forward?

Below, each claim of Chapter 13 that comes from the corpus stands with the book, chapter and section that carry the claim, and with the standing that book gives the claim. Where needed, the mathematics follows in words and then in symbols. The measured results the chapter tells follow at the end, with their primary papers.

The laws run both ways

Claim: nearly all of the basic equations of physics (Newton's laws of motion, Maxwell's equations, the Schrödinger equation and Einstein's equations of gravity) are the same run backward as run forward, and the one exception, in the weak interaction, departs from that sameness only slightly. Where: *What Cannot Be*, Chapter 13, "Eggs Break and Do Not Unbreak". Standing: established physics, reported.

Entropy, the second law, and the condition at the beginning

Claim: the entropy of a thing is a count of the arrangements of its small parts that leave the thing looking the same from outside, reckoned relative to a context (for the cup, your glance at it; for the deck of cards, a glance at the deck). The second law says that the entropy of a closed system of many parts does not decrease, and the second law is statistical. Where: *What Cannot Be*, Chapter 13, "The Usual Answer, and Two Worries"; *What the Beginning Left Behind*, Chapter 6, "Counting the Ways", which gives Boltzmann's counting of 1877 and the gloss "a count of its states that a context cannot tell apart". Standing: established physics, reported.

Claim: from any given moment, the same counting predicts higher entropy toward the future and toward the past, so the entropic account needs a condition at one end of the history, the low entropy of the beginning, which David Albert (2000) called the Past Hypothesis and proposed to admit as a law of nature. Where: *What Cannot Be*, Chapter 13, "The Usual Answer, and Two Worries"; *What the Beginning Left Behind*, Chapter 6, "The Gap in the Counting". Standing: established physics, reported, with the name and proposal attributed to Albert.

Lawful reversal and faithful reversal

Definitions: a lawful reversal is a reversed process that obeys the laws; a faithful reversal is a reversed process that passes back through exactly the states the original passed through and arrives at exactly the original

condition. Where: *What Cannot Be*, Chapter 13, "Two Ways to Run Backward"; *The Basis of Physics*, "The Structural Arrow of Time", Section III, "Lawful Reversal and Faithful Reversal". Standing: definitions.

Claim: the laws of physics are time symmetric to an extraordinary degree, and that symmetry guarantees lawful reversal: for nearly every lawful process, the reversed process is lawful too. Where: *What Cannot Be*, Chapter 13, "Summary" and "What Physics Already Shows"; *What the Beginning Left Behind*, Chapter 6, "Lawful and Faithful" and "Summary" ("for nearly every lawful process, the reversed process is lawful too"). Standing: established physics, reported.

Claim: time-reversal symmetry of the laws is symmetry in the sense of the Incommensuration Theorem (sameness of content across difference of context), applied to the one change of context that replaces each time reading by the same reading with its sign flipped. In symbols: let t, read "tee", be the time coordinate, and let T, read "the time reversal", be the map $t \mapsto -t$, read "tee goes to minus tee", with every velocity reversed. The laws are time-reversal symmetric when, for every solution $x(t)$, read "the path x as a function of tee", the reversed path $x(-t)$, read "x of minus tee", with its velocities reversed, is also a solution. Where: *What Cannot Be*, Chapter 13, "Two Ways to Run Backward"; *The Basis of Physics*, "The Structural Arrow of Time", Section III, which states it as "the definition of symmetry applied to one particular contextual difference". Standing: definition.

Perfect time reversal is impossible

Claim: symmetry of the laws guarantees lawful reversal and does not guarantee faithful reversal; faithful reversal needs a specification of the state with no unspecified degree of freedom, which is continuity in the sense of the theorem; so perfect time reversal needs symmetry and continuity perfected together, which the Incommensuration Theorem forbids; therefore no process at any scale is reversed faithfully. Where: *What Cannot Be*, Chapter 13, "Two Ways to Run Backward" and "What We Now Know"; *The Basis of Physics*, "The Structural Arrow of Time", Section III;

What the Beginning Left Behind, Chapter 6, "Lawful and Faithful". Standing: a structural exclusion, derived from the Incommensuration Theorem and the bridge from lawful to faithful reversal (*What Cannot Be*, Chapter 13, "What We Now Know"); *What the Beginning Left Behind* states that "it must be so". The essay in *The Basis of Physics* states the result as quoted in *What the Beginning Left Behind*, Chapter 6: "Perfect time-reversal is therefore precluded, and the preclusion depends on no entropy, no boundary condition, no Past Hypothesis, and no particular formalism".

In words first: write S for the symmetry of the laws under reversal, and C for the continuity of the specification of the state; the theorem says that S and C are not both perfected, absolutely and together, in any comparison; faithful reversal needs both. In symbols: let S, read "ess", stand for perfect time-reversal symmetry of the laws, C, read "see", for a perfectly continuous specification of the state, and F, read "eff", for perfect faithful reversal. Then $F \Rightarrow (S \wedge C)$, read "eff implies ess and see", and the Incommensuration Theorem gives $\neg(S \wedge C)$ taken absolutely, read "not both ess and see, absolutely"; so $\neg F$, read "not eff". The theorem is a structural fact about the nature of knowing, and the words "absolutely and together" are part of it: within any finite domain, symmetry and continuity are both present, each to a finite degree (*What Cannot Be*, Chapter 13, "Two Ways to Run Backward" and "What Physics Already Shows").

Claim: the formalisms of physics hide the gap because their descriptions are complete by construction (a point in phase space; a state vector), so that lawful and faithful reversal coincide inside them; Loschmidt's question of 1876 and Boltzmann's reply are an early sign of the same gap, and Earman (2002) argued that physics writing runs together what time-reversal symmetry is and what it implies. Where: *What Cannot Be*, Chapter 13, "Why the Equations Hide the Gap"; *The Basis of Physics*, "The Structural Arrow of Time", Section III, "Why the Bridge Is Invisible in the Formalism". Standing: argued; the historical items reported.

The order of every comparison, and the identification

Claim: every comparison runs from a stance with its range of what could be found (the transcendent), to the act (the immanent), to the record laid out as structure (the omniscient), and the record shapes the next stance; the order is one of precedence and cannot be reversed. The order is the second axiom of the Immanent Metaphysics (*An Immanent Metaphysics*, aphorism 1.3-1), quoted in *What Cannot Be*, Chapter 13, "The Order of Every Comparison", and in *What the Beginning Left Behind*, Chapter 6, "Position, Click, Print": "A class of the transcendent will precede an instance of the immanent. A class of the immanent will precede an instance of the omniscient. A class of the omniscient will precede an instance of the transcendent". The statement that each axiom holds of every comparison whatever ("An axiom, as Chapter 1 said, is a statement that holds of every comparison whatever") and the photographer's position, click and print are from *What the Beginning Left Behind*, Chapter 6, "Position, Click, Print". The three facts about the settings that Chapter 1 of this book uses (inseparable, not interchangeable, distinct) are the three clauses of the third axiom, "The (classes/instances) of the immanent, omniscient, and transcendent are distinct, inseparable, and non-interchangeable" (*The Weight of Possibility*, Section V, "The Three Axioms": "The first three heads below are the three clauses of Axiom III"; Chapter 2, Section I, applies them to the three contexts). Standing: an axiom of the metaphysics; the directed cycle is derived from the Incommensuration Theorem in *Incommensuration*, Chapter 8, Section X, "Many-to-One, the Arrow of Time and the Bound Triple".

Claim: I identify the one-way order of findings, the order of the second axiom, with the direction of time; every record ever found follows the act it records, which the books give as the observation that bears on the identification. Where: *Comparison; The Necessary Basis*, Chapter 7, "The Order of Finding", Section I, "A Game of Chess" ("I identify that one-way order with the one direction of time"); *What the Beginning Left Behind*, Chapter 6, "The Direction in Which Comparison Proceeds"; *Incommensuration*,

Chapter 8, Section X, which states that the direction of the cycle is derived there and that its identification with the direction of time in the physical world is the identification made in *Comparison; The Necessary Basis*, Chapter 7. Standing: an identification, stated in the first person, with its observation.

Claim: of the three times of physics (geometric time, event time, evolution time), the direction belongs to event time, the order of findings. Where: *What Cannot Be*, Chapter 13, "Time as Happening, and Not Only as a Line". Standing: argued.

Two arrows, joined in every record

Definitions: the structural arrow of time is "the impossibility of a faithful time-reversal, which the Incommensuration Theorem requires, together with the direction of the cycle of Axiom II, identified with the direction of time" (*What the Beginning Left Behind*, Chapter 6, "The Direction in Which Comparison Proceeds"); the entropic arrow is the growth of entropy in a thing left to itself (same chapter, "The Arrow of Many Parts"). Standing: definitions.

Claim: the structural arrow needs no large number of parts, no coarse-graining and no low-entropy beginning; it is present in one comparison, made once. Where: *Physics Is Not Math*, "Physics Has the Arrow", Section II, "The Arrow of Time" ("This order needs no large number of parts and no special beginning of the world: it is present in one comparison, made once"); *What Cannot Be*, Chapter 13, "An Arrow Beneath the Arrow of Heat". Standing: argued from the structure of comparison.

Claim: the entropic arrow is statistical, belongs to things of very many parts, and needs a beginning of low entropy. Where: *What the Beginning Left Behind*, Chapter 6, "The Arrow of Many Parts"; *Physics Is Not Math*, "Physics Has the Arrow", Section II. Standing: established physics (Boltzmann's counting with the gap that the Past Hypothesis fills).

Claim: each act of recording joins the two arrows, because a record is a change that is not undone and making it raises the entropy of the instrument that holds it; so the two arrows point the same way wherever both

are found; and thermodynamics needs the structural arrow first. Where: *What Cannot Be*, Chapter 13, "An Arrow Beneath the Arrow of Heat"; *Physics Is Not Math*, "Physics Has the Arrow", Section II ("So each act of recording joins the two arrows in one event: the order of the act, and a growth of entropy in the record"); *What the Beginning Left Behind*, Chapter 6, "Where the Two Arrows Meet", which quotes the same sentence from *Measurement*. Standing: argued from what a record is.

Claim: the low entropy of the beginning is a condition on the entropic arrow and not the source of the structural arrow; it fixes how the direction of time is expressed in the history of this universe; the direction of time does not depend on the beginning of the world. Where: *What the Beginning Left Behind*, Chapter 6, "What the Past Hypothesis Is For", and "What This Means for the Beginning", which states: "We now know that the direction of time does not depend on the beginning of the world; only the growth of entropy does"; *What Cannot Be*, Chapter 13, "An Arrow Beneath the Arrow of Heat", which states the claim in its own words: "The argument shows that the direction of time never depended on that starting condition". Standing: argued. The reach of the structural arrow, as the books state it: it fixes that time has a direction; the size of any asymmetry, the low entropy of the early universe and the second law itself are outside its reach (*What Cannot Be*, Appendix, "For Chapter 13: The Direction of Time", "The reach of the argument"; *What the Beginning Left Behind*, Chapter 6, "What the Past Hypothesis Is For").

Claim: the low entropy at the beginning of an epoch has its own reason: every count of disorder is reckoned relative to a context, the outside world against which the states are told apart; the old context has ended at the turn, and each epoch begins its own count. Where: *At the Edge of Reality*, Chapter 18, "A Clean Slate", opening section "Why the Beginning Was So Orderly", and "Every Count Has a Context". Standing: derived in that book. Chapter 22 of this book gives the account in full: each epoch begins its own count, the space and time of a new epoch begin even, and the low entropy of the beginning is in the evenness of its geometry.

Claim: the direction of time does not rest on the growth of entropy, so a largest value of entropy does not end the direction of time. Where: *What the Beginning Left Behind*, Chapter 6; *Physics Is Not Math*, "Physics Has the Arrow", Section II; *What Cannot Be*, Chapter 13, "An Arrow Beneath the Arrow of Heat". Standing: follows from the separation of the two arrows. Chapter 30 of this book finds that time does not stop: what ends with the emptying of the universe is what a comparer can compare with, never the one-way order of comparison.

A third route, not used in the chapter

What Cannot Be, Chapter 13, "An Anchor in the Free Will Theorem", reaches the same arrow by the Epistemic Sandwich, built on the free will theorem of Conway and Kochen (2006; strong form 2009): either an arrow beneath the entropic arrow is real at all three scales of description, or there are no records and nothing is known. The book's Appendix, "For Chapter 13: The Direction of Time", states that the step from an unfixed response to a reversal that cannot be faithful is my reading, that the anchor carries the "if" of the Conway and Kochen theorem, and that this condition belongs to their theorem and to neither the Incommensuration Theorem nor the two roads to the arrow.

The weak interaction and the symmetry of time

Definitions: C (charge conjugation) swaps every particle for its antiparticle; P (parity) reflects space; T reverses time. A meson is a particle made of a bound quark and antiquark; the neutral kaons and the B mesons are mesons, the B^0 meson carrying a bottom quark or antiquark. The CPT theorem: the combined operation CPT, read "see, pee, tee together", is an exact symmetry of every local quantum field theory. So a violation of CP, read "see pee", entails a violation of T alone. Where: *What Cannot Be*, Chapter 13, "What Physics Already Shows". Standing: established physics, reported.

Claim: within any finite domain, symmetry and continuity are both present, each to a finite degree; the laws show time-reversal symmetry to an extraordinary degree, and the symmetry cannot be perfect, so there is a residual one-way character in time, small and required by structure. The phrase "perfect symmetry of time" has the meaning the book gives it: a symmetry "under which every process could be run backward faithfully, through exactly its own states to exactly its own starting condition"; the argument rules out that symmetry, and so rules out perfect time-reversal symmetry taken by itself (*What Cannot Be*, Chapter 13, "Two Ways to Run Backward" and "What Physics Already Shows"). Where: *What Cannot Be*, Chapter 13, "What Physics Already Shows". Standing: a structural exclusion, from the words "absolutely and together" of the theorem.

Claim: the argument requires that perfect time-reversal symmetry cannot be had, so that some asymmetry of time exists; I read the measured breaking of CP and of T as that impossibility become visible to instruments. Where: *What Cannot Be*, Chapter 13, "What Physics Already Shows" and "What We Now Know". Standing: the requirement is a structural exclusion; the fit of the measured violation with it is my reading of a known result. The book's Appendix, "The strength of the reading of time-reversal violation", states its exact strength: the argument says that some asymmetry must exist, gives it no size, and names no interaction and no mechanism; the requirement "would stand whether or not this particular violation had been found", and the argument finds the observed violation consistent with it; the fit of the CPT theorem with the argument (nature keeps the combined symmetry and breaks the symmetry of time alone) is stated as consistency. The same section adds that time can take part in a combined symmetry in which the other two flips make up for its one-way character, and that the exactness of the CPT theorem is exactness inside a mathematics that assumes the fully specified state, so that "What is exact in the model is not thereby perfected in the real". The coming measurements that bear on this chapter (Predictions 28 and 34 of *The Registered Predictions of Physics from Comparison; A Dated Record*) are given under its question in "What the Coming Measurements Will Find".

Measured results told in the chapter, with their primary papers

The breaking of CP in the decay of long-lived neutral kaons into two pions: J. H. Christenson, J. W. Cronin, V. L. Fitch and R. Turlay, "Evidence for the 2π Decay of the K_2^0 Meson", *Physical Review Letters* 13 (1964) 138.

The direct observation of time-reversal violation in the neutral-kaon system, by comparing the rate at which a neutral kaon turns into its anti-particle with the rate of the reverse change: CPLEAR Collaboration (A. Angelopoulos and others), "First direct observation of time-reversal non-invariance in the neutral-kaon system", *Physics Letters B* 444 (1998) 43.

The observation of time-reversal violation in the B^0 meson system: BaBar Collaboration (J. P. Lees and others), "Observation of Time-Reversal Violation in the B^0 Meson System", *Physical Review Letters* 109 (2012) 211801.

The scene: A. S. Eddington, *The Nature of the Physical World* (Cambridge University Press, 1928), the Gifford Lectures delivered at the University of Edinburgh from January to March 1927; Chapter IV, "The Running-Down of the Universe", section "Time's Arrow".

Chapter 14. Why Can't I Travel Back in Time?

Every corpus claim of Chapter 14 is listed below with the book, chapter and section that carry it, and with its standing as that book states it. The main source is *Why Time Travel Is Not a Concept; A Meditation on the Three Times and the Cauchy Horizon* (ISBN 979-8-90710-121-0, DOI https://doi.org/10.67291/SNQF5135), whose Appendix B lists every numbered statement with its kind. The plain-words version of the same chain is *What Cannot Be* (ISBN 979-8-90710-415-0, DOI https://doi.org/10.67291/KHIY2463), Chapters 15 and 16.

The claims, with their places and standing

The three times are distinct objects: geometric time (the proper time along each timelike worldline and the causal order of events, carried by the metric), event time (the order of findings for a comparer) and evolu-

tion time (the parameter t of the one-parameter unitary group U(t) that carries a quantum state). Place: *Why Time Travel Is Not a Concept*, Ch. 1, Sec. II, and Ch. 4, Sec. II, Identification 4.3, reported from *The Unquantized Arena*, Ch. 10, Definitions 10.1 to 10.3 and Proposition 10.1. Standing: definitions, with the matching of the three times to the three modalities an identification reported from *The Unquantized Arena*.

What is found of geometric time is continuous and asymmetric; what is found of event time is discontinuous and symmetric. Place: *Why Time Travel Is Not a Concept*, Ch. 1, Sec. II (with the reasons the chapter gives in words), and Ch. 4, Sec. II, Identification 4.3. Standing: reported from *The Unquantized Arena*, Definitions 10.1 and 10.2.

What exists stands as structure; what is real is given in an actual act of comparison ("A law exists; a measurement is real"). Place: *Why Time Travel Is Not a Concept*, Ch. 1, Sec. III, and Ch. 4, Sec. II, Definition 4.4. Standing: definition, quoted from *The Unquantized Arena*, premise P14.

"Going back" has exactly three readings: geometric (G), event (E) and joint (U); the joint reading is the sense in which the phrase is used. Place: *Why Time Travel Is Not a Concept*, Ch. 4, Sec. V, Definition 4.7; *What Cannot Be*, Ch. 16, "What the Phrase Asks". Standing: definition, made in *Why Time Travel Is Not a Concept*.

Under the geometric reading, a comparer that travels a closed timelike curve and returns arrives at a later finding of its own, and the occasion of its departure is not given again. Place: *Why Time Travel Is Not a Concept*, Ch. 4, Sec. VI, Proposition 4.8, parts (a) to (d). Standing: argued in that book; it rests on the causal structure of Lorentzian manifolds, Identification 4.3, Axiom II, Proposition 4.6, Proposition 5.2, Proposition 3.1, and the self-consistency principle reported from the literature. In words first: an event that a path running forward from the departure reaches lies, by definition, in the causal future of the departure; an event in both the causal past and the causal future of the departure lies on a closed causal curve, so geometric time places it both before and after; the order of findings is set by precedence, and the traveler's findings on arrival are made from

possibilities its earlier records shaped. In symbols: for events p and q, write $J^+(p)$ for the causal future of p (read "J plus of p": every event a future-directed causal curve from p reaches) and $J^-(p)$ for its causal past (read "J minus of p"). Part (a): if q is in $J^-(p)$ and q is not in $J^+(p)$, then no future-directed causal curve from p reaches q. Part (b): if q is in both $J^-(p)$ and $J^+(p)$, with q different from p, then a closed causal curve passes through p and q, and C's arrival at q is a later finding of C. The clock agrees: proper time, τ (read "tau"), increases along every timelike segment, so $\tau(q)$ is greater than $\tau(p)$ along C's worldline. Part (c) uses the self-consistency principle: a return to p requires every physical trace of C's records, the clock's state among them, to be restored on the way, and that restoration is a further act whose findings follow the findings it would undo.

Under the event reading, nothing answers, because the order of findings is the order of Axiom II, "a precedence and not a clock reading, and it cannot be reversed". Place: *Why Time Travel Is Not a Concept*, Ch. 4, Sec. IV, Proposition 4.6 (reported from *The Unquantized Arena*, Ch. 10, Definition 10.2 and Proposition 10.1, and *The Quantum Passage*, Ch. 11, Sec. III), and Ch. 4, Sec. VI, Proposition 4.9. Standing: Proposition 4.6 reported; Proposition 4.9 argued in that book.

Under the joint reading, nothing answers, because one time found in one comparison both as geometric time and as event time, each character perfected, would carry at least one of the two pairings the Incommensuration Theorem forbids. Place: *Why Time Travel Is Not a Concept*, Ch. 4, Sec. III, Proposition 4.5 (reported from *The Unquantized Arena*, Ch. 10, Definition 10.4 and Proposition 10.2), and Ch. 4, Sec. VI, Proposition 4.10. Standing: Proposition 4.5 reported (it rests on the theorem and on the characters of Definitions 10.1 and 10.2 of *The Unquantized Arena*); Proposition 4.10 argued in that book. The theorem, Theorem 4.1, quoted from *Incommensuration*, Ch. 2, Sec. VI, and proved from comparison alone in Ch. 6 of that book: "Symmetry and continuity cannot both be applied, simultaneously and fundamentally, to any event or comparison; and neither can

asymmetry and discontinuity. Any comparison, perfected at its foundation, is either continuously asymmetric or discontinuously symmetric". It is a structural fact about the nature of knowing, and it holds of every event and every comparison, under no condition.

"Time travel", in the sense in which the phrase is used, names no concept. Place: *Why Time Travel Is Not a Concept*, Ch. 4, Sec. VII, Conclusion 4.11; Ch. 7, Secs. II and V; *What Cannot Be*, Ch. 16, "The Conclusion". Standing: argued in that book, from Propositions 4.8, 4.9 and 4.10. The chain uses no result of strong cosmic censorship, no energy condition and no value of any physical constant (Ch. 4, Sec. VIII); its conclusion holds however the strong cosmic censorship conjecture is settled, because whatever lies beyond a Cauchy horizon is further geometric time (Ch. 3, Sec. IV, Proposition 3.1, argued in that book).

What the chain takes from general relativity is a complete list of three things: the definition of geometric time; two facts of Lorentzian geometry; and one principle reported from the literature. The two facts are that proper time is positive along every timelike segment, and that a causal curve from p to an event of the causal past of p, followed by a causal curve from that event back to p, is a closed causal curve. The principle is the self-consistency principle, used in Proposition 4.8, part (c). The chain also uses Proposition 3.1, which rests on none of the results of the literature listed below. Place: *Why Time Travel Is Not a Concept*, Ch. 4, Sec. VIII; *What Cannot Be*, Ch. 16, "What the Chain Uses" ("That list is complete"). Standing: stated in both books as the whole of what the chain takes from physics.

A reversal of evolution, by an inverse in a formalism or by a pulse in a laboratory, acts on a state or on physical traces; it removes no finding from the order of findings. Place: *Why Time Travel Is Not a Concept*, Ch. 5, Sec. V, Proposition 5.2, and Ch. 5, Sec. III, Proposition 5.1 ("Symmetry of the laws guarantees lawful reversal. It does not guarantee faithful reversal", reported from *The Basis of Physics*, Essay 11, Sec. III); *What Cannot Be*, Ch. 13, "What Can Be Run Backward, and What Cannot". Standing: Proposi-

tion 5.1 reported; Proposition 5.2 argued in that book. In symbols: $U(t)$ has the inverse $U(-t)$ (read "U of minus t"), which reverses the state in evolution time; a finding is a discrete record, and no inverse acts on it.

The trace and the record: what a motion leaves in one particle is a trace; a record is what a finding leaves, and it is not undone. Place: *Why Time Travel Is Not a Concept*, Ch. 5, Sec. IV, reporting *The Matter We Know*, Volume Two, Ch. 2, Sec. V. Standing: definitions of terms.

A request that names nothing is excluded in principle, and therefore in all future practice; this is a third standard beside the engineer's and the physicist's. Place: *What Cannot Be*, part "Before We Begin", section "What 'Cannot Be' Means Here" (the color of the number seven); and the closing part "What Cannot Be, and What Can", section "The Eight Exclusions". Standing: the exclusion of time travel is a structural exclusion, in the book's classification of its claims ("Three Kinds of Claim").

The picture of the road country: a traveler who drives back to her birthplace arrives at the town as it is on the day she arrives. Place: *What Comes After the Dark* (ISBN 979-8-90710-431-0, DOI https://doi.org/10.67291/IGAM1407), Ch. 10, "The Plan, Step by Step". Standing: a picture of the result of *What Comes After the Dark*, Ch. 6, that every arrival is a new finding of the traveler.

Results of the literature told as checks

None of the following is a premise of the chain; *Why Time Travel Is Not a Concept*, Ch. 7, Sec. III, states them as Barrier 4, a check, and gives what they show: "the physics, in its own terms, does not supply the door that the phrase imagines". The plain words for the results of Hawking and of Kay, Radzikowski and Wald match the technical terms as follows. "A time machine built in a limited region" is a spacetime with a compactly generated Cauchy horizon: its edge is formed by light paths that, followed back into the past, stay within a bounded region. "A slice of space that runs on without end" is a noncompact partial Cauchy surface. "Matter whose energy some observer measures as negative" is matter that violates the weak energy condition, the rule that the energy any observer measures is never

negative. “The boundary where such a machine’s loops would begin” is that Cauchy horizon, and “part of the boundary” is its base set. “The simplest quantum field” is the free scalar (Klein–Gordon) field, and “no well-behaved state” means that no Hadamard state keeps the Hadamard form there. Gödel’s solution (Rev. Mod. Phys. 21, 447, 1949) has a closed timelike curve through every point and no Cauchy surface (Ch. 2, Sec. I). Morris, Thorne and Yurtsever (Phys. Rev. Lett. 61, 1446, 1988) showed that moving one mouth of a traversable wormhole relative to the other produces closed timelike curves. Hawking (Phys. Rev. D 46, 603, 1992) proved that a compactly generated Cauchy horizon cannot form from a noncompact partial Cauchy surface if the weak energy condition holds, and proposed the chronology protection conjecture. Kay, Radzikowski and Wald (Commun. Math. Phys. 183, 533, 1997) proved that, for the free scalar (Klein–Gordon) field on a spacetime with a compactly generated Cauchy horizon, the two-point distribution of every Hadamard state fails to be of Hadamard form at every point of the base set of the horizon. The self-consistency principle is that of Friedman, Morris, Novikov, Echeverria, Klinkhammer, Thorne and Yurtsever (Phys. Rev. D 42, 1915, 1990): the only solutions admitted are those consistent everywhere, including along every closed timelike curve.

The measurement told

The spin echo: E. L. Hahn, “Spin Echoes”, Physical Review 80, 580 (1950), with pulses each turning the spins through a right angle; the single half-turn refocusing pulse is that of H. Y. Carr and E. M. Purcell, Physical Review 94, 630 (1954); the extension to the dipolar interactions of the nuclei is W.-K. Rhim, A. Pines and J. S. Waugh, Physical Review B 3, 684 (1971). Standing: reported, as *Why Time Travel Is Not a Concept*, Ch. 5, Sec. IV, reports it; it shows that a laboratory reversal runs the evolution of the spins backward, in part, while the order of findings (decay, pulse, echo) runs forward.

Chapter 15. Can We Travel Faster Than Light?

My argument in Chapter 15 of this book rests on one chapter of *What Cannot Be* (Chapter 12, "The Shape of What Can Reach What") and on the technical form of Chapter 12 of What Cannot Be, *The Basis of Physics*, Essay 10, "Causation, Connectivity, and the Domain Boundary of Comparison". Four other books supply one step each: *The Gravitational Passage* (Chapter 17, Section I), *Causality Without Determinism* (Chapter 1, Section VI), *Two Theories, One World* (Chapter 8) and *An Immanent Metaphysics*.

The claims, their places and their standing

Every cause is a comparison. Interaction, comparison and relation are one act, named three ways; a cause is the interaction whose pattern is steady and one-way; so every cause is a comparison, and the edges of comparison are the edges of causation. Where: *What Cannot Be*, Chapter 12, "Every Cause Is a Comparison", which rests on the identity that book's Chapter 1 calls the Root Tautology; *The Basis of Physics*, Essay 10, Section II. Standing: an identity (the Root Tautology) and what follows from it.

Comparison has two edges. The inner edge is marked by Planck's constant (for a given energy, no comparison is finer; the floor depends on the energy brought to the comparison and is no smallest piece of space or of time); the outer edge is marked by the speed of light (for a given elapsed time, no comparison reaches farther). Together the two edges bound the domain of comparison, "from the finest grain to the farthest reach". Where: *What Cannot Be*, Chapter 12, "The Two Edges of Comparison"; *The Basis of Physics*, Essay 10, Section IV; *An Immanent Metaphysics*, aphorism 1.89-1 ("The Planck constant and the speed of light are fundamental metrics of a domain in that they define the microscopic and macroscopic limits of a domain"). Standing: *The Gravitational Passage*, Chapter 17, Section I, states "That the domain has two limits follows from the axioms".

Space is the pattern of which events can affect which, and its edges are the edges of comparison. Where: *What Cannot Be*, Chapter 12, "What Space Is", which names Malament (1977) and Hawking and Ellis (1973) for the result that the causal structure alone fixes the topology. Standing: the book states it as the content of general relativity, stated without the container picture.

The cone comes first, and the cone at each event, unbroken and pointing one way, is what causation is. The cone is the structure of causal relatedness, "which is to say the structure of which comparisons can be made from here": an event inside the cone of a given event is an event with which a comparison can be made from it. Where: *What Cannot Be*, Chapter 12, "The Cone Comes First"; *Causality Without Determinism*, Chapter 1, Section VI ("Causation is the one-way, unbroken order at each event that physics finds at every scale: continuity with asymmetry"); *The Basis of Physics*, Essay 10, Section V. Standing: *What Cannot Be*, Chapter 12, "What Kind of Impossible", labels the claim that the cone is primary as a reading of a known result, a reading that gives the structural reason the known result holds.

Why the world is causal, in two steps. First, why there are causes: every interaction is a comparison, and the order of every comparison runs one way (the range of what is possible, then the act, then the record), so a world of interactions has causation, the one-way order at each event. Second, why causes have the cone's shape: the Incommensuration Theorem excludes perfecting symmetry with continuity, and asymmetry with discontinuity; continuity with asymmetry is one of the two pairings it allows to be carried all the way, and general relativity carries it all the way at every event. Where: *What Cannot Be*, Chapter 12, "Every Cause Is a Comparison" ("Causality is a pattern read from inside time, which is why it runs one way"), "A Signal That Would Arrive Before It Was Sent" (the order of acts) and "The Cone Comes First"; *What Cannot Be*, Chapter 13 (the order holds in every single comparison); *Causality Without Determinism*, Chapter 1, Sections VI and VII; *Incommensuration*, the chapter "The Ground as Premises", closing summary ("Two survivors: continuity with

asymmetry, and symmetry with discontinuity"). Standing: the first step follows from the Root Tautology and the second axiom; the second step is derived from the theorem, which is proved from comparison alone in *Incommensuration*, Chapter 6, with general relativity as the established physics that carries the shape.

The speed of light is invariant because it is an edge. The speeds of things are ratios of content within the domain and differ from comparer to comparer; the speed of light is the shape of the domain's edge, and an edge of comparison is the same for every comparer. Where: *What Cannot Be*, Chapter 12, "An Exchange Rate Between Time and Space"; *An Immanent Metaphysics*, the passage on time that includes "Time is not another dimension of space" ("one may understand why the speed of light is a constant if one compares it to one's horizon (as a metaphor)"). Standing: a reading of a known result (the book's own label): it gives the reason Einstein's postulate of 1905 holds, and special relativity stands as it is.

The speed of light is the conversion factor between the time side and the space side of causal connection. Where: *What Cannot Be*, Chapter 12, "An Exchange Rate Between Time and Space"; *The Gravitational Passage*, Chapter 17, Section I ("I identify it as the bridge between the omniscient and immanent modalities"). Standing: a reading of a known result in *What Cannot Be*; an identification in *The Gravitational Passage*.

Spacelike separated events have no fixed order, and events joined by a cone have one. Each comparer finds the same speed of light both ways, and the targets move relative to each comparer, so each comparer finds a different order of the two strikes; nothing joins the two strikes, because neither lies in the other's cone. Where: *What Cannot Be*, Chapter 12, "A Signal That Would Arrive Before It Was Sent" (the lamp in the middle of a moving train car, with a rider, a bystander and an overtaking passenger; the chapter uses the authors' Bertha, astronaut and Larry, an arrangement of the same kind) and "The Cone Comes First" ("Two events are spacelike

separated because there is no causal connection between them"). Standing: the relativity of simultaneity is standard physics; the reason no order is fixed is the absence of a causal connection, as the book states it.

A signal between spacelike separated events would, for some comparer, be received before it was sent, and so it is no signal. Where: *What Cannot Be*, Chapter 12, "A Signal That Would Arrive Before It Was Sent". Standing: argued from two premises: the relativity of simultaneity (standard physics) and the order of acts (what is possible, then the act, then the record), which is the second axiom and which *What Cannot Be*, Chapter 13, shows holds in every single comparison.

No signal crosses the outer edge of comparison, for any being, in any universe, that interacts with anything. Where: *What Cannot Be*, Chapter 12, "Beyond the Farthest Point", "The Silent Sky", "What Kind of Impossible" and "What We Now Know"; *The Basis of Physics*, Essay 10, Sections VI and IX. Standing: a structural exclusion (the book's term): "it says what physics will not find, and it says so before looking". The request to signal past the edge is a category error, of the kind of a request for a point beyond the antipode. The argument does not call on quantum theory, on the no-communication theorem (Ghirardi, Rimini and Weber, 1980), or on special relativity taken as postulates (*What Cannot Be*, Chapter 12, "The Edge Rests on Comparison Alone"). A preferred direction of time does not enlarge the cone ("An Arrow Opens No Door").

The kind of impossibility. Structural; it differs from a logical impossibility, since formalisms in which some quantity exceeds the speed of light (tachyons) are consistent; and it differs from an empirical impossibility, since no experiment is cited and none is needed, though every experiment is consistent with it. Where: *What Cannot Be*, Chapter 12, "What Kind of Impossible"; *The Basis of Physics*, Essay 10, "On the Kind of Impossibility Claimed".

Travel within the cone is not excluded, and no body arrives somewhere that is not in its cone. Where: *The Basis of Physics*, Essay 10, Section VIII ("A body can go anywhere its forward cone reaches"; the essay

"takes no position at all on its technological feasibility"); *What Cannot Be*, Chapter 12, "Beyond the Farthest Point" ("a place is a position in the pattern of connection"). Standing: stated scope of the exclusion. The step that a traveler is a signal uses the definition of a signal in *What Cannot Be*, Chapter 12, "A Rule on a Stage" ("anything that passes from one event to another and lets a record at the second depend on an act at the first"). The coming measurements bearing on this claim are listed under Prediction 27 in "What the Coming Measurements Will Find".

Untouched by the exclusion: everything within the cone; the expansion of the universe and the recession of distant galaxies; and the correlations of entangled particles, which are real and carry nothing ("a correlation is not a connection"). Where: *What Cannot Be*, Chapter 12, "What Stays Exactly as It Was"; *The Basis of Physics*, Essay 10, Section VIII.

A massive body never reaches the speed of light. Reaching it "would take an unbounded quantity of energy for a massive body". Where: *The Basis of Physics*, Essay 10, Section I. Standing: reported, as the standard framing of relativity, which the essay keeps and reframes. In words first: the energy of a body grows without bound as its speed approaches the speed of light, and the clock of a moving body runs slow by the same factor. In symbols: $E = \gamma mc^2$, with $\gamma = 1/\sqrt{(1 - v^2/c^2)}$; read aloud, the energy E equals gamma times the mass m times the speed of light c squared, where gamma is one divided by the square root of one minus the square of the ratio of the speed v to c. Gamma grows without bound as v approaches c. A moving clock's interval between two ticks, Δt, is gamma times its interval at rest, $\Delta\tau$: $\Delta t = \gamma\Delta\tau$.

Changes in the shape of the arena travel at the speed of light. Where: *Two Theories, One World*, Chapter 8, "What the Established Theory Adds" ("The arena carries its asymmetry smoothly, from place to place, at a finite speed"). Standing: established physics (general relativity), with the reason given in the corpus: the arena is the context whose outer edge the speed of light marks; the coming measurements bearing on it are listed under Prediction 6.

Why there is a top speed, and what its number is. The finite speed of light is required by the precedence of the second axiom, which "excludes signals that take no time, and the macroscopic boundary of the domain fixes their maximum speed": every signal takes some time, and in a given time no signal reaches past the edge. The numbers that the speed of light and Planck's constant carry "express only the units in which time, length and action are measured". Where: *The Gravitational Passage*, Chapter 17, Section I (and Chapter 10, Section III, which it cites); *What Cannot Be*, Chapter 12, "A Rule on a Stage" and "What Kind of Impossible" ("The number for the speed of light expresses a unit, fixed by the definition of the meter"); *An Immanent Metaphysics*, aphorism 1.89-2 ("The speed of light defines what is unknowable in terms of context"). Standing: the existence of the two limits is derived from the axioms; the number is a statement of units. A measurement finds a dimensionless ratio, such as the mass of a body or a particle over the Planck mass (my example in Chapter 15 of this book is the electron), or the radius of the present horizon over the Planck length (about ten to the sixty-one). *The Gravitational Passage*, Chapter 17, Section I: "This book makes no claim on the value of any such ratio".

The edge holds for any being, in any universe, that interacts with anything else. Where: *What Cannot Be*, Chapter 12, "The Silent Sky"; *The Basis of Physics*, Essay 10, Section IX. Standing: structural exclusion; it concerns the existence of the edge and states nothing about the values of dimensionless ratios in other regions. That light in empty space travels at the edge is stated for our world: "Light, which travels in empty space at exactly that speed, is the perfected example of the edge; light is not the reason the edge is where it is" (*What Cannot Be*, Chapter 12, "An Exchange Rate Between Time and Space").

Exact values

The speed of light in vacuum, c, is 299,792,458 meters per second, exact by definition: since 1983 the meter has been the distance light travels in vacuum in 1/299,792,458 of a second. One light-second is therefore

299,792.458 kilometers; one light-year (a Julian year of 365.25 days) is about 9.46×10^{15} meters. The one-way light time between Mars and the Earth runs from about 182 seconds (about 3.0 minutes, at a separation of about 54.6 million kilometers) to about 1,340 seconds (about 22.3 minutes, at about 401 million kilometers); the two times are computed from the standard extreme separations and c. Rømer's twenty-two minutes for the diameter of the Earth's orbit compares with the modern figure of two astronomical units over c: $2 \times 149{,}597{,}870.7$ km / 299,792.458 km $s^{-1} \approx 998$ s, about 16.6 minutes (computed). Rømer's league (the lieue de Paris) was about 3.9 kilometers, so his "less than a second for about three thousand leagues" states a lower bound of roughly 12,000 kilometers a second. The mean lifetime of the muon at rest is about 2.2 microseconds (2.197×10^{-6} s).

Measurements told in the chapter, with their primary papers

Rømer, the late emersion of Io: emersion observed on 9 November 1676 at 5:35:45 in the evening, ten minutes after the time reckoned from the August emersions; light's crossing of the diameter of the Earth's orbit put at 22 minutes. O. Rømer, "Démonstration touchant le mouvement de la lumière trouvé par M. Römer de l'Académie Royale des Sciences", *Journal des Sçavans* (7 December 1676) 233–236; English translation, "A Demonstration concerning the Motion of Light", *Philosophical Transactions of the Royal Society* 12, No. 136 (1677) 893–894.

Michelson and Morley: interferometer with perpendicular arms, rotated on a stone floating in mercury; the fringe shift expected from the Earth's orbital speed was about four tenths of a fringe, and the shift observed was a small fraction of that. A. A. Michelson and E. W. Morley, "On the Relative Motion of the Earth and the Luminiferous Ether", *American Journal of Science*, 3rd series, 34 (1887) 333–345.

Rossi and Hall: the decay rate of cosmic-ray mesotrons (muons) falls as their momentum rises, as relativistic time dilation requires. B. Rossi and D. B. Hall, "Variation of the Rate of Decay of Mesotrons with Momentum", *Physical Review* 59 (1941) 223–228.

GW170817 and GRB 170817A, 17 August 2017: gravitational waves from a binary neutron star merger at about 40 megaparsecs (about 130 million light-years), detected by the two detectors of the Laser Interferometer Gravitational-Wave Observatory (LIGO) in the United States and by the Virgo detector in Italy; the gamma-ray burst followed about 1.7 seconds after the merger; the difference between the speed of gravity and the speed of light is bounded between -3×10^{-15} and $+7 \times 10^{-16}$ of the speed of light. B. P. Abbott and others (LIGO Scientific Collaboration, Virgo Collaboration, Fermi Gamma-ray Burst Monitor and the International Gamma-Ray Astrophysics Laboratory, INTEGRAL), "Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A", *Astrophysical Journal Letters* 848 (2017) L13; B. P. Abbott and others, "GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral", *Physical Review Letters* 119 (2017) 161101.

Hensen and others, Delft, 2015: a Bell test with electron spins in two laboratories 1.3 kilometers apart, the choice of each measurement and the recording of each result spacelike separated from the other station's; the Bell inequality was violated. B. Hensen and others, "Loophole-free Bell inequality violation using electron spins separated by 1.3 kilometres", *Nature* 526 (2015) 682–686.

Chapter 16. Who Is Shooting Superfast Particles at the Earth?

The claims of the chapter that come from the corpus

The fastest cosmic-ray protons excite the Delta on the leftover light of the Big Bang, and this limits how far they can travel. Source: *The Alphabet of Particles*, part "The Composites and the Boundary", entry "Delta Baryon" (a baryon is a whole made of three quarks), subsection "Description". Standing: the limit is reported by the entry as established physics. The account's own statement is the Delta's place among the kinds: its quark content (uuu, uud, udd, ddd), electric charges, baryon number and isospin are given as fixed by structure, and its "Essential Nature" states that it "adds no new kind". Its mass, width and spin and parity are given as

measured. Values as the entry tabulates them (Particle Data Group 2026): mass about 1232 MeV (1230 to 1234 MeV); width about 117 MeV (114 to 120 MeV), mean life about 5.6×10^{-24} s from the width; spin and parity $3/2^+$; decay to a nucleon and a pion 99.4 percent. The entry gives the cost of aligning the three spins as about 300 MeV; the chapter's "about a third heavier than the proton" is 1232 / 938.272 = 1.313.

The energy at which a proton reaches the Delta on the leftover light is standard relativistic kinematics; no corpus book states it. In words: for a head-on meeting, the square of the proton's mass, plus four times the proton's energy times the photon's energy, must equal the square of the Delta's mass. In symbols, with the speed of light set to one, $s = {m_\mathrm{p}}^2 + 4E_\mathrm{p}\varepsilon = {m_\Delta}^2$, so $E_\mathrm{p} = ({m_\Delta}^2 - {m_\mathrm{p}}^2) \,/\, (4\varepsilon)$. Here s (read "s") is the square of the total energy in the frame where the two particles' momenta cancel; m_p ("m sub p") is the proton mass, 0.938 GeV; m_Δ ("m sub Delta") is the Delta mass, 1.232 GeV; E_p ("E sub p") is the proton's energy; ε ("epsilon") is the photon's energy. For a photon of the mean energy of the leftover light at 2.7255 K, $\varepsilon \approx 2.70\, kT \approx 6.3 \times 10^{-4}$ eV, this gives $E_\mathrm{p} \approx 0.637\ \mathrm{GeV}^2 \,/\, (2.5 \times 10^{-3}\ \mathrm{eV}) \approx 2.5 \times 10^{20}$ eV. Photons of the high-energy tail of the leftover light lower the onset of the loss to several times 10^{19} eV. The temperature of the leftover light is a measured input (Fixsen, *Astrophysical Journal* 707 (2009) 916).

The kinds of particle form a closed list, and no new kind of elementary particle exists at any energy. Source: *The Grand Synthesis*, Chapter 13, "The Cosmological Constant and the Completeness of the Kinds", Section IV, "The Dark Fire Closure" (resting on the completeness of the kinds, Section III). The list itself is the one *The Registered Predictions of Physics from Comparison; A Dated Record* states, reproduced in *Side by Side*, Volume One, Appendices, Section VII: "the kinds of the Standard Model, with a right-handed neutrino in each generation". Standing: derived; the record states that the structural claims of its Section VII "use no measured number as a premise".

Gravity is the arena, and there is no fourth force with a carrier beside the three. Source: *The Branches of the Kinds*, Chapter 4, "The Carriers", Section III, "What Is Not a Particle", subsection "No graviton among the kinds": "Gravity is the arena"; "gravity is the shape of the arena in which comparison takes place"; "There is no fourth force with a carrier in the sequence of the three". Standing: derived; the book says of each absence in that section that it "is a consequence of the structure; none is an assumption". The sense of "gravity is the arena" is that of Chapter 7's identification of gravity with the arena itself.

Our world is a world of its own, not a simulation run in some other world, so a flaw in a simulation is no candidate for the sender of the cosmic rays. Source: *What Cannot Be*, Chapter 21, "Are We Living in a Simulation?", section "What It Means for What Cannot Be": "We now know that our world is not a simulation run in some other world". The book's reason, in the same section: the arena of space and time is continuous, "and so there is something in what exists that no computation can capture". Standing: derived.

Within our era of the world, no collision in a collider or a star turns ordinary matter into dark matter; one of the reasons is energy, since the most energetic particles that reach the Earth from space each carry less than a ten-millionth of the energy one gyration holds. Source: *The Weight of the Unseen*, Chapter 3, question 3.10, quoted in full in *The Grand Synthesis*, Chapter 13, Section IV. Standing: as the book states it under "What the account holds"; the energy of one gyration is given there as the mass energy of about ten billion billion protons, about 10^{28} eV. For the Oh-My-God particle, 3.2×10^{20} eV / 10^{28} eV $\approx 3 \times 10^{-8}$, below one ten-millionth (10^{-7}). The same answer gives the largest collider's head-on collision of heavy nuclei as about a million proton masses of energy, "trillions of times too little to make one gyration". Its other two reasons are the kind of thing the dark matter is (a vibration of the space of possibility, made within an epoch only in pairs through gravity alone, in a gas hotter than about one thirtieth of the mass of a gyration) and the link a chain of conversions would need.

In this account the muon is the electron in its second generation: the same in charge, spin and every interaction, different in mass. Source: *The Alphabet of Particles*, part "Three Generations", entry "Muon" ("The electron one turn on"), subsections "Origin", "Essential Nature", "Description" and "History of Observation". Standing: charge -1, spin $1/2$ and second generation fixed by structure; heavier than the electron fixed by structure, value measured. Values (the Committee on Data of the International Science Council, CODATA 2022; Particle Data Group 2026, as the entry tabulates them): rest mass 105.658 3755(23) MeV; mass relative to the electron 206.768 2827(46), measured; mean life $2.196\,9811(22) \times 10^{-6}$ s. The entry reports a flux at the Earth's surface of about one muon per square centimeter per minute.

Our world met the particles in the order its instruments could reach them, and cosmic rays delivered the positron, the muon and the first strange particles before accelerators did. Source: *The Particular Evidence*, "The Structure of the Act", Section I, "The Case File" (cases 5, 8 and 9 of its table), and Case 5, "The Equation's Other Half", Section III, "The Resolution: The Track That Curved the Wrong Way". Standing: reported history.

The arena has no least length, area or duration, and light of every energy travels at one speed through empty space. Sources: *The Unquantized Arena*, Chapter 6, "The Category Error", Section IV, "The Exact Scope", Proposition 6.3 (resting on the law of continuity and Propositions 4.2 and 6.1); *Two Theories, One World*, Chapter 27, "What the World Will Show", section "Space and Time Will Stay Smooth". That section gives the reason: "the arena is the context of physics and is continuous; a step in the arena would give it the character of content". Standing: derived.

The reach of the timing of light, at the scope *Two Theories, One World* gives it. The timing of gamma-ray bursts reaches the pictures of a grain that make the speed of light depend on its energy. The same section states that "Some pictures of a discrete space and time keep the speed of light the same at every energy, and photon arrival times do not reach them". It continues: "The prediction reaches them too, because it is wider than any

one test: no observation will find a least step in space or time". *What Cannot Be*, Chapter 21, "The Arena Has No Least Step", states the two strengths side by side: the continuity of the arena is derived, and "Physics agrees with the derivation", since the timing of a gamma-ray burst "places any grain of space that would slow light below the Planck scale".

The simplest pictures of a grain of space and time, at about the Planck length, give light a speed that depends on its energy to first order. In words: the speed of light would differ from its usual value by a fraction equal to the light's energy divided by an energy scale of the grain, and the delay between two energies grows with the distance the light has traveled. In symbols, $v(E) \approx c(1 \pm E/E_{QG})$, where v ("v") is the speed of light of energy E, c is the usual speed of light, and E_{QG} ("E sub Q G", the energy scale of quantum gravity) is the energy scale of the grain. The measurements below place E_{QG} above a stated multiple of the Planck energy E_{Pl} ("E sub Planck"), the energy held in the Planck mass, about 1.22×10^{19} GeV, about two billion joules (*Two Theories, One World*, Chapter 27). An energy scale above the Planck energy corresponds to a length scale below the Planck length, since the length that goes with an energy scale E is $\hbar c/E$ (read "h-bar c over E": Planck's constant divided by two pi, times the speed of light, divided by the energy), and $\hbar c/E_{Pl}$ is the Planck length. The Planck length, about 1.6×10^{-35} m, against a proton's radius of about 0.84×10^{-15} m, gives the chapter's "about a hundred billion billion times smaller than a proton" (a ratio of about 5×10^{19}).

The measurements the chapter tells, with their primary papers

Victor Hess, flight of 7 August 1912, balloon *Böhmen* (1680 cubic meters of hydrogen), ascent from Aussig at 6:12, highest altitude 5350 m in the region of the Schwielochsee, landing at Pieskow at 12:15; pilot Captain W. Hoffory, meteorological observer E. Wolf. Ionization (ions per cubic centimeter per second) in the two thick-walled instruments: 40.7 and 31.8 between 9:45 and 10:45 at 4800 m (4700 m above the ground below); 15.0 and 11.6 under the landed balloon. Hess's conclusion, in the English translation: a "radiation of very high penetrating power enters from above

into our atmosphere". Primary paper: V. F. Hess, "Über Beobachtungen der durchdringenden Strahlung bei sieben Freiballonfahrten", *Physikalische Zeitschrift* 13 (1912) 1084; English translation by A. De Angelis and colleagues, "On the Observations of the Penetrating Radiation during Seven Balloon Flights", arXiv:1808.02927 (2018).

The energy of the largest collider, with its run: 13 TeV in each proton collision in Run 2 (2015 to 2018), and 13.6 TeV in Run 3 (from 2022); each proton carries half the collision energy. The chapter's "more than seven million times" is the authors' energy of the highest-energy particle, over 10^{20} eV, against one collision of Run 2: $10^{20} / 1.3 \times 10^{13} \approx 7.7 \times 10^{6}$. The authors give the Large Hadron Collider as "almost ten teraelectron volts" and the highest-energy particle as "almost two million times more energetic than the LHC's fastest particles" (*We Have No Idea*, ch. 11, "What Are Cosmic Rays?").

The Fly's Eye event of 15 October 1991: an air shower whose primary particle carried $(3.2 \pm 0.9) \times 10^{20}$ eV, about 51 joules; a baseball of 0.145 kg carries 51 joules at about 26.6 meters per second, about sixty miles (about ninety-five kilometers) an hour. Primary paper: D. J. Bird and others, "Detection of a Cosmic Ray with Measured Energy Well Beyond the Expected Spectral Cutoff due to Cosmic Microwave Radiation", *Astrophysical Journal* 441 (1995) 144.

The limit on the distance of the fastest cosmic rays, worked out after the discovery of the leftover light. Primary papers: K. Greisen, "End to the Cosmic-Ray Spectrum?", *Physical Review Letters* 16 (1966) 748; G. T. Zatsepin and V. A. Kuzmin, "Upper Limit of the Spectrum of Cosmic Rays", *JETP Letters* 4 (1966) 78. The authors name it "the GZK (Greisen-Zatsepin-Kuzmin) effect" in their notes to ch. 11.

The Delta found as the first hadron resonance, University of Chicago synchrocyclotron, 1951 to 1952. Primary paper (as *The Alphabet of Particles* cites it): H. L. Anderson, E. Fermi, E. A. Long and D. E. Nagle, "Total Cross Sections of Positive Pions in Hydrogen", *Physical Review* 85 (1952) 936.

The positron, the muon and the first strange particles, found in cosmic rays. Primary papers: C. D. Anderson, "The Positive Electron", *Physical Review* 43 (1933) 491; S. H. Neddermeyer and C. D. Anderson, "Note on the Nature of Cosmic-Ray Particles", *Physical Review* 51 (1937) 884; J. C. Street and E. C. Stevenson, "New Evidence for the Existence of a Particle of Mass Intermediate Between the Proton and Electron", *Physical Review* 52 (1937) 1003; G. D. Rochester and C. C. Butler, "Evidence for the Existence of New Unstable Elementary Particles", *Nature* 160 (1947) 855.

The timing of gamma-ray bursts: no energy-dependent delay. Fermi Large Area Telescope: E_{QG} above about 7 E_{Pl} for a first-order dependence; primary paper: V. Vasileiou and others, "Constraints on Lorentz Invariance Violation from Fermi-Large Area Telescope Observations of Gamma-Ray Bursts", *Physical Review D* 87 (2013) 122001. Large High Altitude Air Shower Observatory (LHAASO), burst of 9 October 2022 (cataloged as GRB 221009A): E_{QG} above about 10 E_{Pl} for a first-order dependence; primary paper: Z. Cao and others (LHAASO Collaboration), "Stringent Tests of Lorentz Invariance Violation from LHAASO Observations of GRB 221009A", *Physical Review Letters* 133 (2024) 071501. Both are reported in *Two Theories, One World*, Chapter 27, section "Space and Time Will Stay Smooth".

The authors' figures, given in the chapter as theirs (*We Have No Idea*, ch. 11): cosmic rays at about the collider's energy at about one per square meter per second; the highest-energy particle over 10^{20} eV; the highest energy known objects could give, about 10^{17} eV; a particle of 10^{21} eV slowed below 10^{19} eV within a few million light-years.

The chapter also draws on: *The Matter We Know, Volume One*, Chapter 6, Section III.

Chapter 17. What's Stopping Anyone from Traveling Between the Stars?

In Chapter 17 of this book I give no derivation of my own. In Chapter 17 I apply one structural exclusion, the one Chapter 15 sets out, to travel and to signals between the stars, and I give the collection's stated scope on engineering.

Each claim is given below with the book that carries it and its standing as that book states it.

Claim of the chapter	Where the collection carries it	Standing, as the book states it
Travel within the light cone, however slow, is not excluded by the structure of comparison; a body can go anywhere its forward cone reaches, and cannot arrive somewhere that is not in that forward cone, which is "a description of where 'somewhere' is".	*The Basis of Physics*, Essay 10, "Causation, Connectivity, and the Domain Boundary of Comparison", Section VIII, "What Is Not Excluded".	The stated scope of the essay's structural exclusion (Section VIII). Section X calls the central claim, "that no signal can cross the macroscopic boundary of comparison", a structural exclusion. Section IX, in its part "On the Kind of Impossibility Claimed", states what the conclusion rests on: "the identification of space with the connectivity topology of causal relations, and on the Root Tautology beneath it".

Claim of the chapter	Where the collection carries it	Standing, as the book states it
The structure of comparison does not exclude any engine or any trip within the cone; the collection makes no claim on the technological feasibility of such travel, which is a question of engineering.	*The Basis of Physics*, Essay 10, Section VIII ("the essay takes no position at all on its technological feasibility"); *The Registered Predictions of Physics from Comparison; A Dated Record* (1 November 2026), Section IX, as reproduced in *Side by Side*, Volume One: "No technological feasibility of travel within the light cone is claimed either way"; *Side by Side*, Volume Two, "The Registered Predictions Beside Stephen Wolfram", Wolfram 4: "a question of engineering on which the collection takes no side".	A statement of scope.
No signal crosses the boundary of comparison, and no body arrives somewhere that is not in its cone; travel within the cone is not excluded, nor the recession of distant galaxies faster than light.	The record, Prediction 27, "No signal faster than light, and none backward in time"; argued in *The Unquantized Arena*, Chapter 7, Section IV (Proposition 7.2), *The Basis of Physics*, Essay 10, *Measurement*, Chapter 14, Section IV, *The Quantum Passage*, Chapter 8, Section III and Chapter 11, Section III, and *Why Time Travel Is Not a Concept*, Chapter 4, Section IV (Proposition 4.6).	A registered prediction; what the coming measurements will find under it is given with Chapter 15 in "What the Coming Measurements Will Find".

Claim of the chapter	Where the collection carries it	Standing, as the book states it
The speed of light is the conversion factor between the time side and the space side of causal connection, a rate of exchange; a light-year is a distance named by a time.	*What Cannot Be*, Chapter 12, "An Exchange Rate Between Time and Space".	A reading of a known result, so named by the book in "What Kind of Impossible" ("the speed of light as the conversion factor between the time side and the space side of connection"): it gives the structural reason the known result holds.
Counted in light-seconds per second, the speed of light is one; the number 299 792 458 records the size of the meter against the second.	*Measurement*, Chapter 1, Section IV.	Stated: the number expresses a unit, fixed by the definition of the meter (also *What Cannot Be*, Chapter 12, "What Kind of Impossible").
Cosmic-ray muons reach the ground because, moving at nearly the speed of light, their clocks run slow as seen from the Earth; about one passes through each square centimeter every minute.	*The Alphabet of Particles*, entry "Muon", "Description" and "History of Observation".	Reported measurement; "one of the plainest confirmations of special relativity".

Claim of the chapter	Where the collection carries it	Standing, as the book states it
The moving away of distant galaxies at effective rates above the speed of light is a growth of the arena between them, and not a signal across it; for the most distant galaxies today's distance grows by more than a light-year each year.	*What Cannot Be*, Chapter 12, "What Stays Exactly as It Was"; *The Basis of Physics*, Essay 10, Section VIII.	Untouched by the exclusion, as both books state; the rates, and the horizons they make, are reported from Davis and Lineweaver (2004).
Space is the pattern of which events a signal can join, so any region a path from here can reach, through a wormhole, a warp drive or anything else, is part of our own world; a wormhole held open by negative energy would be a new road, and a warp drive a faster car.	*What Comes After the Dark*, Chapter 10, "No Other Sky Along Any Path" and "The Plan, Step by Step".	Structural, from the definition of space the collection uses (*What Cannot Be*, Chapter 12, "What Space Is").

Claim of the chapter	Where the collection carries it	Standing, as the book states it
A shortcut is a feature of the geometry, as a wormhole is a solution of Einstein's equations, so a body that takes it arrives within the cone of the geometry that has it.	*Side by Side*, Volume Two, "The Registered Predictions Beside Stephen Wolfram", Wolfram 4, "Travel faster than light".	Stated under Prediction 27; the register adds that whether a geometry with a shortcut can exist or be made bears on Wolfram's expectation and not on Prediction 27, and that the collection makes no claim about what engineering can do within the cone.
On this account the times the authors give for messages between civilizations stand as they are, since no signal anywhere outruns the edge.	Prediction 27 (as above); *Side by Side*, Volume Two, Wolfram 4.	A consequence of Prediction 27.
Each traversable wormhole of Morris and Thorne needs its throat held open by a material whose tension is greater than its energy, and no such material has been found.	*What Comes After the Dark*, Chapter 10, "A Bridge Between Two Sheets".	Reported physics (Morris and Thorne 1988). In their analysis, tension greater than energy density, for a material threading the throat, means that observers passing through the throat at high speed measure a negative energy density there; the chapter names that property negative energy.

Claim of the chapter	Where the collection carries it	Standing, as the book states it
The matter falling in while a real hole forms breaks up the inner passage of a spinning hole, and the inside of a real spinning hole is expected to end as every interior ends; what a traveler reaches is the end of an interior, where its matter stops being matter of our epoch's form; the counterpart of the hoped-for white hole is the beginning of a whole new epoch, which is not a region of space at the far end of any one black hole.	*What Comes After the Dark*, Chapter 10, "The Plan, Step by Step", reporting *The Gravitational Passage*, Chapter 18, "The Interior Passage": "the inner horizon of the exact solutions is unstable to the infall that forms real holes, and the generic end is expected to be of the same kind"; *At the Edge of Reality*, Chapter 9.	Reported from *The Gravitational Passage*, whose word "expected" gives the end of a real spinning hole as the generic expectation of general relativity. The end is "a limit that the path approaches and does not reach", and it "lies after every moment of the interior" (same chapter): the chapter's "end of the fall" is this limit. Developed in Chapter 21.
The six small dimensions hold the range of what a finding could be; nothing travels through them.	As Chapter 11 of this book states it, with the books it cites; also *What Comes After the Dark*, Chapter 10, "The Plan, Step by Step" ("A comparison travels through space, from here to there, and it does not travel through possibility").	As stated there.

Claim of the chapter	Where the collection carries it	Standing, as the book states it
Every signal stays within the macroscopic boundary of comparison; no civilization communicates faster than light, because no civilization can; the limit is structural and applies to any being, in any universe, that interacts with anything else; the silence of the sky needs some other explanation, and the collection offers none.	*What Cannot Be*, Chapter 12, "The Silent Sky" (the quoted sentence "So no civilization communicates faster than light, because no civilization can", and "I do not offer one"); *The Basis of Physics*, Essay 10, Section IX, "The Fermi Paradox and the Wrong Channel" (the same claim, and "The framework does not offer one. It eliminates this one").	Structural exclusion of one explanation (a signal faster than light); "no experiment is cited and none is needed, though every experiment is consistent with it" (*What Cannot Be*, Chapter 12, "What Kind of Impossible"; *The Basis of Physics*, Essay 10, Section IX).
Every place you could ever travel to, by any engine, is a part of our own world.	*What Comes After the Dark*, Chapter 10, "What This Means for You".	Structural, as the row on the road country.
No body and no signal has been found to arrive anywhere outside its light cone.	*Side by Side*, Volume Two, Wolfram 4, "Measured".	A report of the measured record.

The traveler's slow clock, in words first. A clock carried at a steady speed runs slow, against clocks at rest, by a factor that grows without bound as the speed approaches the speed of light. In symbols, the time on board, read "tau", equals the time on the Earth, read "t", multiplied by the square root of one minus the ratio of the speed squared to the speed of

light squared: $\tau = t\,\sqrt{(1 - v^2/c^2)}$, where v, read "vee", is the ship's speed and c, read "see", is the speed of light. At v equal to 0.99999999 of c, the square root is about one seven-thousandth ($1 - v^2/c^2$ is about 2×10^{-8}, whose square root is about 1.41×10^{-4}). The authors' figure of about thirty years on board for the crossing of the galaxy is quoted in the chapter as theirs.

The muon's figures. The mean life of the muon at rest is 2.196 9811(22) $\times 10^{-6}$ seconds (*The Alphabet of Particles*, "Muon", from CODATA 2022 and the Particle Data Group 2026). At nearly the speed of light, 2.2 microseconds of the muon's own time would carry it about 660 meters if its clock kept the rate of a clock on the ground; muons made ten kilometers or more above the ground reach it because, as seen from the ground, their clocks run slow by the factor above. Rossi and Hall compared the muons counted at Denver with those counted at Echo Lake, about 1,624 meters higher, as historical accounts of the experiment give the two sites; the abstract of their paper reports that the fast mesotrons (the name then used for muons) decay more slowly, "in agreement with the theoretical predictions based on the relativity change in rate of a moving clock".

The distances. A light-year is about 9.46×10^{12} kilometers. Proxima Centauri is about 4.2 light-years away; the authors give 40 trillion kilometers (*Frequently Asked Questions About the Universe*, ch. 8, "It's a Big Universe"). Voyager 1 was about 121 astronomical units from the Sun on 28 July 2012, at the first sign of the heliopause, the outer boundary of the Sun's wind (one astronomical unit being the mean distance of the Earth from the Sun); light takes about 16.8 hours to cover that distance. The plasma density measured around the probe after the crossing was about 0.08 electrons per cubic centimeter, against about 0.002 in the outer bubble of the Sun's wind.

Measured values told in the chapter, with their primary papers.

Measurement	What was found	Primary paper
Muon lifetime at different momenta, Colorado, 1941	Fast muons decay more slowly than slow ones, by the factor relativity gives for moving clocks.	B. Rossi and D. B. Hall, "Variation of the Rate of Decay of Mesotrons with Momentum", *Physical Review* 59 (1941) 223.
Voyager 1 enters interstellar space, 2012	The plasma around the probe is many times denser than in the Sun's wind, matching interstellar gas; the crossing is dated to about 25 August 2012.	D. A. Gurnett, W. S. Kurth, L. F. Burlaga and N. F. Ness, "In Situ Observations of Interstellar Plasma with Voyager 1", *Science* 341 (2013) 1489.
Recession rates and horizons of the expanding universe	Distant galaxies recede at effective rates above the speed of light, with no signal faster than light.	T. M. Davis and C. H. Lineweaver, "Expanding Confusion: Common Misconceptions of Cosmological Horizons and the Superluminal Expansion of the Universe", *Publications of the Astronomical Society of Australia* 21 (2004) 97.
Traversable wormholes, 1988	A traversable wormhole needs a throat held open by material whose tension exceeds its energy density.	M. S. Morris and K. S. Thorne, "Wormholes in spacetime and their use for interstellar travel: A tool for teaching general relativity", *American Journal of Physics* 56 (1988) 395.
Listening for signals since 1960	No message from another civilization has been found.	F. D. Drake, "Project Ozma", *Physics Today* 14 (4) (1961) 40 (the first search; told in Chapter 18).

Chapter 18. Are We Alone?

Each entry below gives one claim of the chapter that comes from the physics collection, the book, chapter and section that carry it, its standing as that book states it, and its exact values. The measured values the chapter tells follow, with their primary papers.

The hydrogen line

Claim: hydrogen gives off its twenty-one-centimeter radio waves when the spins of its electron and its proton pass from adding to opposing, and the size of that step is fixed by what the atom is. Source: *The Matter We Know*, Volume One, Chapter 8, Section VII, "The Proton Is a Magnet Too". Standing: a measured value, with its lowest-order form given in the book from standard physics (Fermi, 1930). Values: the ground state of hydrogen splits into a level of total angular momentum one (spins adding) above a level of total angular momentum zero (spins opposed), by 1420.405751768 megahertz (Hellwig and others, 1970), whose light has a wavelength of 21.106 centimeters. In words first: the splitting is four thirds of the proton's g-factor, times the ratio of the electron's mass to the proton's, times the fourth power of the fine-structure constant, times the electron's rest energy. In symbols: $\Delta E = (4/3)\ g_p\ (m_e/m_p)\ \alpha^4\ m_e c^2$, read "delta E equals four thirds g sub p times m sub e over m sub p times alpha to the fourth times m sub e c squared", with $g_p = 5.5856946893$ the proton's g-factor (CODATA 2022), m_e/m_p the ratio of the electron's mass to the proton's, and α the fine-structure constant.

Claim: astronomers read the small shifts of the hydrogen line as the motion of the gas, and drew from them the first map of the galaxy's spiral arms. Source: *The Matter We Know*, Volume One, Chapter 8, "In Use". Standing: reported measurements (Ewen and Purcell, 1951, first detection of the line from the galaxy; Oort, Kerr and Westerhout, 1958, the map).

What is the same in every star

Claim: the amounts of the elements in the stars are known because each element's levels are fixed by structure and are the same in every star. Source: *The Matter We Know*, Volume One, Chapter 6, "In Use"; the levels themselves are derived in Chapters 7 to 10 of that volume. Standing: stated as a consequence of structure (the levels are derived from the kinds and the electric force with measured constants); the line positions are measured.

Claim: structure is whatever follows from the form of comparison and from the kinds of particle and their forces, with no measured number. Source: *The Matter We Know*, Volume One, Chapter 1, Section II, "The Kinds and Their Masses". Standing: a definition (the book's own term).

Claim: which wholes exist is structure, which last is structure and measured values, and how many there are is history. Source: *The Matter We Know*, Volume One, "The Ladder in Brief"; Chapter 1, Section VI, "The Ladder of Levels", and Summary. Standing: stated as the volume's organizing result, argued rung by rung through the volume. The rule of lasting: a whole lasts when it is the lightest thing that carries its counts, which the book names as its electric charge, its number of baryons and its number of leptons, three numbers that every change at the temperatures of the present universe keeps. In The Matter We Know I state the rule for any set of particles: a particle lasts when "nothing lighter has its charge, its baryon number and its lepton number at once, and it has nothing lighter to turn into" (Volume One, Chapter 1, Section II, "The Kinds and Their Masses"). In Chapter 18 of this book I say "particles of the proton's family" for baryons (wholes of three quarks, such as the proton and the neutron) and "particles of the electron's family" for leptons. The rule is structure, and which whole is lightest is set by measured masses: the free neutron is heavier than the proton by a measured 1.293 MeV, and decays to a proton, an electron and an electron antineutrino, which together carry its charge (zero), its baryon number (one) and its lepton number (zero, the antineutrino counting minus one) and weigh 0.782 MeV less.

Claim (recalled from Chapter 4): every particle of a kind is found exactly like every other, and the list of kinds is closed. Source: *The Matter We Know*, Volume One, Chapter 1, Chapter Overview and Section II, citing *The Story of the Particles*, which derives the kinds from the structure of comparison. Standing: derived (in *The Story of the Particles*).

What each place holds is its history

Claim: the first minutes made hydrogen and helium-4 with traces of deuterium, helium-3 and lithium-7, and stopped at the gaps at masses five and eight; every heavier nucleus was made in stars. Source: *The Matter We Know*, Volume One, Chapter 6, Chapter Overview and Section I (the gaps from Chapter 5, Section VI). Standing: the gaps are derived (helium-4's lowest level is filled, so a proton, a neutron or another helium-4 nucleus added to it makes nothing that stays bound); the amounts are measured. Values: helium-4 carries 0.245 ± 0.003 of the mass of ordinary matter (Particle Data Group, 2026, as *The Coming of the Kinds*, Chapter 12, gives it); deuterium $(2.508 \pm 0.029) \times 10^{-5}$ for each hydrogen nucleus; lithium-7 about one in ten billion.

Claim: every nucleus carries a positive charge, nuclei push each other apart, and in a star's core they join only at energies that the fastest nuclei reach; each fuel, by its charge, burns at its own temperature. Source: *The Matter We Know*, Volume One, Chapter 6, Chapter Overview ("In a star's core, nuclei cross their electric barrier by tunneling"; "So each fuel, by its charge, burns at its own temperature") and Section II, "Stars Burn Hydrogen", with Box 6.1. Standing: standard nuclear physics with measured values, computed in the book. Values: two protons must come within about 1.4 femtometers for the strong force to act, where their electric push is about 1.0 MeV; in the Sun's core, at about 15.7 million kelvin, the temperature as an energy is 1.35 keV; the nuclei meet in a narrow band of energies, the Gamow peak, about 6 keV for protons in the Sun's core. The chapter's plain phrase "they join only where they move fast enough to

come close" stands for this: the share of nuclei falls with energy as the Boltzmann factor, the chance of tunneling through the electric barrier rises with energy, and the joining happens in the band between.

Claim: three helium-4 nuclei join into carbon-12 through the short-lived beryllium-8, at a rate made large enough by the Hoyle state; carbon-12 and another helium-4 nucleus make oxygen-16; the carbon of living things and the oxygen of breath were made in this way. Source: *The Matter We Know*, Volume One, Chapter 6, Section III, "Across the Gaps: Three Alpha Particles Make Carbon". Standing: reported nuclear physics with measured masses and levels, computed in the book. Values: three helium-4 atoms exceed one carbon-12 atom by $3 \times 4.00260325\ \text{u} - 12\ \text{u} = 0.00780976\ \text{u}$, which is 7.275 MeV; the Hoyle state lies about 7.65 MeV above carbon-12's ground state, so $7.65 - 7.275 = 0.38$ MeV above three separate helium-4 nuclei and 0.29 MeV above beryllium-8 and a helium-4 nucleus; beryllium-8 comes apart in about 10^{-16} seconds; helium burns near a hundred million kelvin (0.18×10^9 kelvin in the core of a star of fifteen solar masses, Woosley and Janka, 2005), where the Gamow peak for two helium-4 nuclei is at 83 keV.

Claim: the amounts of the elements are history, and the measured abundance curve records it (the notch after helium, the even-over-odd sawtooth, the peak at iron). Source: *The Matter We Know*, Volume One, Chapter 6, Section VII, "The Amounts Are History". Standing: measured values, read by the book as the record of the processes of Sections I to VI. Values: the Sun's surface, for every hydrogen nucleus, 0.085 helium nuclei, and in parts per hundred thousand of the hydrogen, oxygen 49, carbon 27, nitrogen 6.8, silicon 3.2, iron 3.2, sulfur 1.3 (Asplund and others, 2009); helium 0.2485 of the mass of the Sun's outer layers; boron 5×10^{-10} of the hydrogen.

Claim: the heavy elements that life needs are made in stars over billions of years, and habitable planets depend on that history. Source: *The Last Turtle*, Chapter 5, Section VII, "The Universe as a Process". Standing: stated (an argument from the universe as process; independent of the nuclear physics of *The Matter We Know*).

Claim (this chapter, first person): every factor of the Drake equation is a count or a share, so each is an amount, set by history place by place and read by measurement; how often life arises on a planet with the right materials is an amount of this kind, and so is the count of places that hold life. Source: my application, made in this chapter, of the rule of *The Matter We Know*, Volume One, Chapter 1, Summary ("how many there are is history"), and of Chapter 6, Section VII (the amounts of the elements are history). Standing: my application; *The Matter We Know* states the rule for wholes and for the amounts of the elements, and the chapter applies it to the authors' factors.

Claim: our epoch is followed by another, which grows by the same law and begins with the same structure and the same orderly start under which stars, planets and people became possible in ours; the structure is the same in every epoch. Source: *What Comes After the Dark*, Chapter 7, "Where Thinking Begins Again" ("The structure this physics derives is the same in every epoch"; the reason is taken up in its Chapter 8); Chapter 10, "The Cosmic Egg" ("The next epoch grows by the same law that ours grew by"). Standing: stated in that book, on the cycle of epochs that it and *At the Edge of Reality* argue. In Chapter 18 of this book I draw one result from the claim that the structure is the same in every epoch. The result is that the rules that make the materials of life are the same in every epoch, as the rules are at every star.

Is there another Earth?

Claim: ice is less dense than liquid water because each molecule in ice holds four neighbors at the corners of a tetrahedron by hydrogen bonds, an open arrangement; so ice floats, water is densest near 4 degrees Celsius, and the ice lid keeps the deep water of a lake liquid. Source: *The Matter We Know*, Volume Two, Chapter 4, Section VI, "Water", Box 4.4. Standing: derived from the tetrahedral arrangement and a measured distance, and set in the book beside the measured densities. Scope: the derivation's first premise is the open tetrahedral framework of ordinary ice, and its densities are those at 0 degrees Celsius and the pressure of the air; the chapter

states the result for water that freezes into that framework, on the Earth or on any other world. In words first: in an arrangement where each point has four neighbors at the corners of a regular tetrahedron at distance d, each point has to itself eight times d cubed over three times the square root of three. In symbols: $v = 8d^3/(3\sqrt{3})$, read "v equals eight d cubed over three root three", with d = 0.276 nanometers the distance between neighboring oxygen centers (Petrenko and Whitworth, 1999); this gives 0.0324 cubic nanometers for each molecule and a density of 924 kilograms per cubic meter, against the measured 916.7 for ice and 999.84 for liquid water at 0 degrees Celsius (*CRC Handbook of Chemistry and Physics*, 97th edition, Harvey, 2017).

Claim (this chapter, first person): the levels of a molecule of water are fixed by structure as the levels of an atom are, so water vapor marks starlight with the same colors at any distance. Source: an application made in this chapter of *The Matter We Know*, Volume One, Chapter 6, "In Use" (levels fixed by structure) to the molecules of Volume One, Chapter 11, "In Use" (each bond takes up infrared light at its own notes; carbon dioxide near 667 waves per centimeter). Standing: my application; *The Matter We Know* states the rule for the elements in stars, and the chapter applies it to the air of a planet.

Life is rare, and it is here

Claim: life is rare in the universe as a share of all its matter, and it is here. Source: *Home in the World*, Chapter 8, "A Village That Is Alive". Standing: stated; "rare" is measured against all the matter of the universe, and the sentence concerns that share, as distinct from the number of planets that carry life.

Claim: a true choice is a selection made with nothing before the selecting fixing it; a living being is made of the same matter as a stone, and differs from it in kind because in it true choice is gathered into a self, carried forward as its own, and known from inside; from outside, a true choice and chance look the same. Source: *Home in the World*, Chapter 8, "A Village That Is Alive" ("what is new in kind is the gathering of choice into a self

that knows it from within"; the gift, the thermostat and the bacterium), resting on its Chapter 4 (the two kinds of knowing) and Chapter 7 (true choice). Standing: the book's argument; *Side by Side*, Volume One, Section XIV, "What Are Life and Mind to Physics?", places the questions of what life and experience are among differences of kind, which falsification does not reach.

Measured values told in the chapter, with their primary papers

Project Ozma, Green Bank, from 8 April 1960: the 85-foot Howard Tatel telescope, tuned near the hydrogen line, pointed at Tau Ceti and Epsilon Eridani; a strong burst on the first day was found about ten days later to be local radio interference; two months of searching found no signal from either star (Drake, 1961; Drake's reminiscence in *Cosmic Search*, 1979).

Fraunhofer's dark lines, mapped in 1814 (Fraunhofer, 1817); their identity with the bright lines of heated elements (Kirchhoff, 1860, with Bunsen); the stars mostly hydrogen and helium (Payne, 1925).

The Hoyle state predicted (Hoyle, 1954) and found (Dunbar, Pixley, Wenzel and Whaling, 1953; Cook, Fowler, Lauritsen and Lauritsen, 1957).

The composition of the Sun's surface (Asplund, Grevesse, Sauval and Scott, 2009).

The first planet found around a star like the Sun, 51 Pegasi b, by the periodic shift of the star's lines (Mayor and Queloz, 1995). The figures for transits from 2002, the Kepler telescope, "about one in five stars" with an Earth-sized rocky planet, and water vapor on a mini-Neptune about 120 light-years away are told in the authors' terms, as *We Have No Idea*, ch. 17, and *Frequently Asked Questions About the Universe*, ch. 7, give them.

The chapter also draws on: *The Matter We Know, Volume One*, Chapter 6, Section III; *The Matter We Know, Volume Two*, Chapter 4, Section VI.

Chapter 19. Why Are We Made of Matter, Not Antimatter?

Every particle that carries an additive quantum number has an antiparticle, with every such number reversed. *The Story of the Particles*, Level 4, Section I, carries it, restated in *The Coming of the Kinds*, Chapter 1, Section IV. Standing: derived from the first axiom (the thing compared and the thing compared against are conjugate) together with a definition (the photon is the act of comparing, Level 0), as the book states it in two steps. An additive quantum number is a label that comes in whole units and adds up when things are put together: electric charge Q, baryon number B, lepton number L, color. In Chapter 19 of this book I call the additive quantum numbers "labels", and I call B and L the baryon count and the lepton count.

A state of content holds its two terms, the relation toward the thing compared and the relation toward the thing compared against, in one order; its conjugate, the antiparticle, holds them in the other order. *The Story of the Particles*, Level 4, Section I; *The Alphabet of Particles*, Terms, "Two terms of a state". Standing: an argument from Axiom I; the chapter's picture of a battery set into a flashlight one way round or the other carries the order of the two terms.

The conjugate of the electron is not the proton: the electron and the proton carry opposite charges, but they differ in kind, the one pointlike and the other composite, and neither is the other state reversed. *The Story of the Particles*, Level 4, Section I. Standing: stated in that section as a consequence of the definition of the conjugate.

The act of comparing, when it creates content, creates the state and its conjugate together. *The Story of the Particles*, Level 4, Section I. Standing: an argument from Axiom I; an act that carries no order cannot produce one order of two conjugate terms without the other.

The minimum energy for making a pair is twice the rest mass of one member. *The Story of the Particles*, Level 4, Sections I and III. Standing: derived; the values are measured. In words: the threshold energy equals two times the rest mass times the speed of light squared; in symbols, $E_{th} =$

$2mc^2$, read "E threshold equals two m c squared". Values: 1.022 MeV for the electron and positron; about 1,876 MeV for the proton and antiproton; about 346 GeV for the top quark and its antiquark.

Annihilation is the reversal of pair creation, with the energy released equal to the energy required. *The Story of the Particles*, Level 4, Section III. Standing: stated as the reversal of the derived creation; the energy accounting is standard physics. For the authors' raisin: two grams of rest mass give 2×10^{-3} kg $\times$ $(2.998 \times 10^8 \text{ m/s})^2 = 1.80 \times 10^{14}$ J, which at 4.184×10^{12} J per kiloton of TNT is about 43 kilotons.

A particle and its antiparticle have equal mass, equal lifetime and equal and opposite magnetic moments, because C, P and T taken together are an exact symmetry of any theory with the five properties of the CPT theorem. *The Story of the Particles*, Level 4, Section II; *The Branches of the Kinds*, Chapter 3, Section III and Box 3.4. Standing: derived (the CPT theorem, with the structure supplying its premises). C is charge conjugation, the exchange of every particle with its antiparticle; P is parity, the exchange of left and right; T is time reversal. No one of the three, and no pair of them, is guaranteed alone: the weak force breaks C and P, and CP is broken by the irremovable phase of quark mixing. In the words of the same section, the comparison treats both standings of a state alike in what they are, and it does not follow that every force treats them alike in what it does.

Electric charge and color are conserved because the act of comparing cannot change the total of what it compares; baryon number and lepton number are kept by every single transformation because no single transformation turns a quark into a lepton. *The Story of the Particles*, Level 4, Sections I and V; *The Branches of the Kinds*, Chapter 2, Section II ("no X or Y boson at any scale", Section V). Standing: derived. The chapter's "single change" is a single transformation in this sense: one reaction among the kinds, such as the decay of a neutron to a proton, an electron and an antineutrino.

The twelve carriers of force fall into two classes. A reading carrier leaves a state where it is and reads it, and each is its own antiparticle: the two neutral gluons (gluon three and gluon eight), the hypercharge boson and the neutral weak boson. A transition carrier moves a state from one value to another and carries the difference it makes, so it comes in pairs of particle and antiparticle, one for each direction: the six color-changing gluons, in three pairs, and the W^+ and W^- bosons. The settled Higgs field mixes the hypercharge boson and the neutral weak boson into the photon and the Z boson, so both are their own antiparticles. *The Alphabet of Particles*, Appendix, "The Primitive Particles by the Six Metrics", Sections VI and VII, Tables A2 and A3. Standing: stated in that appendix from the structure of the three ways of force (eight, three, one).

The photon is its own antiparticle because it is the act of comparing and carries no additive number; the Z boson and the Higgs boson are their own antiparticles because they are columns of context, not states of content; no state of content is its own antiparticle, so the neutrino is a Dirac particle and no Majorana mass exists for either chirality. *The Story of the Particles*, Level 4, Section I; *The Branches of the Kinds*, Chapter 1, Chapter Overview and Section II, Box 1.1. Standing: derived. A Dirac mass joins the left-handed component of a particle to the right-handed component of the same particle; a Majorana mass joins a particle to its own antiparticle and would change L by two units.

The existence of antiparticles is structural; the excess of matter belongs to the history of the universe. *The Story of the Particles*, Level 4, Section IV; *The Strengths of the Kinds*, Chapter 1, Section I (as quoted in *The Coming of the Kinds*, Chapter 1, Section VI). Standing: derived (structure); the excess is classed as a number of history.

In balance, a kind and its antiparticle are equal in number when no conserved quantity carries an excess. *The Coming of the Kinds*, Chapter 3, Box 3.1, and Chapter 4, Section V. Standing: standard physics (Kolb and Turner, 1990, Chapter 3), with the equality of masses from the CPT theorem. In symbols, for a kind X and its antiparticle $\bar{X}$ in balance, $\mu_X + \mu_{\bar{X}} = 0$,

read “the chemical potential of X plus the chemical potential of X bar equals zero”; with every conserved charge zero, both vanish and $n_X = n_{\bar{X}}$, “the number of X equals the number of X bar”.

Of Sakharov’s three conditions, the kinds supply a process that changes B (the sphaleron) and a breaking of C and CP; the third, a departure from equilibrium, is absent at the electroweak transition, which is a crossover. *The Coming of the Kinds*, Chapter 4, Sections II to IV, Boxes 4.1 to 4.3. Standing: derived from the closed list of kinds together with standard physics and lattice computations, as cited. The chapter’s “collective passage” is the sphaleron transition: a change of the winding of the weak field by one unit, which changes the number of each of the twelve left-handed doublets by one unit, all with the same sign (’t Hooft, 1976). A sphaleron transition changes B by 3 and L by 3 and keeps $B - L$: $\Delta B = 9 \times 1/3 = 3$, $\Delta L = 3 \times 1 = 3$, $\Delta(B - L) = 0$. The transitions run in balance from about 10^{12} GeV down to $T_* = 131.7 \pm 2.3$ GeV (D’Onofrio, Rummukainen and Tranberg, 2014), about 1.3×10^{-11} s after the start of our history; at zero temperature their rate carries a factor $\exp(-4\pi/\alpha_W) \approx 10^{-161}$, with α_W the weak fine-structure constant. The crossover is centered at $T_c = 159.5 \pm 1.5$ GeV (D’Onofrio and Rummukainen, 2016); a first-order transition occurs only for a Higgs mass below the endpoint 72.4 ± 1.7 GeV (Csikor, Fodor and Heitger, 1999), against the measured 125.13 ± 0.11 GeV (Particle Data Group, 2026).

The strength of CP violation from the quark phase at the crossover is about 4.4×10^{-22}, more than a trillion times smaller than the measured baryons per photon. *The Coming of the Kinds*, Chapter 4, Section III, Box 4.2. Standing: computed from measured inputs, following Cline (2006, Section 4.1). The chapter’s “phase” of quark mixing is the Kobayashi and Maskawa phase (1973), whose size, independent of any choice of basis, is measured by the Jarlskog invariant J. In words: the strength is J times the product of the differences of the squared masses of the up-type quarks, times the same product for the down-type quarks, divided by the twelfth power of the temperature. In symbols, $\delta_{CP} = J \prod (m_i^2 - m_j^2)_u \prod (m_i^2 - m_j^2)_d / T^{12}$, read “delta CP equals J times the product over up-type pairs

of m i squared minus m j squared, times the same product over down-type pairs, over T to the twelfth". With J = $(3.16 \, +0.13 \, -0.11) \times 10^{-5}$ (Particle Data Group, 2026) and T = 159.5 GeV, $\delta_{CP} = 1.20 \times 10^{41}$ MeV^{12} / 2.71×10^{62} MeV$^{12} = 4.4 \times 10^{-22}$, and $\eta/\delta_{CP} = 1.4 \times 10^{12}$. An excess made through a breaking of CP is in proportion to the strength of that breaking, which is why the two numbers are set side by side. The kinds break CP through two phases only, one in quark mixing and one in lepton mixing; the strong angle is zero by structure, and the measured angle is below 1.8×10^{-10} (Abel and others, 2020).

Every process among the kinds keeps B − L, and the excess of baryons today requires a B − L present from the earliest moment our history reaches; that value is a residue the turn leaves, kept by every change after it. *The Coming of the Kinds*, Chapter 5, Sections II to IV, Boxes 5.1 and 5.2; restated in *What the Beginning Left Behind*, Chapter 20. Standing: derived from the closed list of kinds (no X or Y boson, no Majorana mass, no further kind) and the anomaly structure of the Standard Model; the placing of the value with the turn follows from it. The turn is the beginning of our epoch, which the chapter names in those words; Chapter 20 introduces the word. In symbols: $\partial_\mu(j_B{}^\mu - j_L{}^\mu) = 0$, read "the divergence of the baryon current less the lepton current is zero". The windings of the color field change the difference between the numbers of left-handed and right-handed quarks and leave B and L unchanged (*The Branches of the Kinds*, Chapter 2, Section III and Box 2.3). No bending or twisting of space and time changes B − L either: with the right-handed neutrino counted, B − L summed over the left-handed states of one generation is $6 \times 1/3 + 2 \times (-1) = 0$, and over the right-handed states $6 \times 1/3 + 2 \times (-1) = 0$, so the gravitational anomaly of B − L vanishes (Alvarez-Gaumé and Witten, 1984; Montero and Pleitez, 2009, as cited in *The Coming of the Kinds*, Chapter 5, Section II and Box 5.1). While the sphalerons are in balance, B = c(B − L), "B equals c times B minus L", with c fixed by the kinds; an excess with B − L = 0 is erased (Harvey and Turner, 1990).

The three routes of baryogenesis each need one thing the kinds do not hold: grand unification (Yoshimura, 1978) needs a carrier of both color and the weak charge; leptogenesis (Fukugita and Yanagida, 1986) needs a Majorana mass; electroweak baryogenesis needs a first-order transition. *The Coming of the Kinds*, Chapter 5, Section V. Standing: derived from the closed list.

The kinds fix the share of the residue held as baryons, about one third, and the leptons carry the rest as an excess of antileptons; in the words of *The Coming of the Kinds*, "The residue is history; the share is structure" (Chapter 7, Summary), which *What the Beginning Left Behind* quotes in Chapter 20. The share is $28/79 = 0.3544$ before the Higgs field has a value, $12/37 = 0.3243$ deep in the broken phase, and 0.3328 ± 0.0005 where the sphalerons leave balance. *The Coming of the Kinds*, Chapter 7, Section V, Table 7.1 and Box 7.3. Standing: $28/79$ from the count $(8N_f + 4N_H)/(22N_f + 13N_H)$ with $N_f = 3$ generations and $N_H = 1$ Higgs doublet (Harvey and Turner, 1990); $12/37$ from Laine and Shaposhnikov (2000); 0.3328 from Benso, Bödeker, Kamada, Mukaida, Sagunski, Schicho and Schmitz (2026), as cited. With the measured η, the residue is $B - L = \eta/0.3328 = (1.84 \pm 0.01) \times 10^{-9}$ per photon today, and $L \approx -2.0$ B.

With no residue, annihilation would have left about 10^{-18} baryons per photon. *The Coming of the Kinds*, Chapter 5, Section VII. Standing: standard physics (Kolb and Turner, 1990, Chapter 5), as cited.

The excess has one sign everywhere: nowhere in the observable universe do antibaryons outnumber baryons. *The Coming of the Kinds*, Chapter 5, Section VI; *What the Beginning Left Behind*, Chapter 20. Standing: derived from the adiabatic form of the first departures from evenness (*At the Edge of Reality*, Chapter 19) together with the conservation of $B - L$; confirmed by measurement.

Antimatter falls as matter does; gravity, as the context of physics, couples to every content, and to energy, which is positive for matter and antimatter alike. *The Unquantized Arena*, Chapter 5, Sections II and III, and Chapter 19, Section IV; *Two Theories, One World*, Chapter 9. Standing: de-

rived given the identification of gravity as the context of physics (*The Unquantized Arena*, premise P18), made in Chapter 7 of this book; confirmed in direction by measurement. The Eötvös parameter, twice the difference of the free-fall accelerations of two bodies divided by their sum, is zero for every pair of materials.

Measured values told in the chapter, with their primary papers.

The positron: Anderson, C. D., "The Positive Electron", *Physical Review* 43 (1933) 491–494 (photograph of 2 August 1932; magnetic field 15,000 gauss; the photograph shows a positron of about 63 million electron volts crossing a 6 mm lead plate and emerging with about 23 million electron volts, the two energies with which the Science Museum Group catalog describes the print). Pairs in showers: Blackett, P. M. S., and Occhialini, G. P. S., *Proceedings of the Royal Society A* 139 (1933) 699–726. The antiproton: Chamberlain, O., Segrè, E., Wiegand, C., and Ypsilantis, T., "Observation of Antiprotons", *Physical Review* 100 (1955) 947–950. Antihydrogen trapped: Andresen, G. B., and others (ALPHA), "Trapped Antihydrogen", *Nature* 468 (2010) 673–676. The 1S–2S transition of antihydrogen equal to hydrogen's to 2 parts in 10^{12}: Ahmadi, M., and others (ALPHA), *Nature* 557 (2018) 71–75. The free fall of antihydrogen, $a_g = (0.75 \pm 0.13 \pm 0.16)$ g, repulsion of size g excluded: Anderson, E. K., and others (ALPHA-g), "Observation of the Effect of Gravity on the Motion of Antimatter", *Nature* 621 (2023) 716–722. Baryons per photon from the microwave background, $\eta = (6.13 \pm 0.04) \times 10^{-10}$, from $\Omega_b h^2 = 0.02237 \pm 0.00015$ with $\eta = 274 \times 10^{-10}\ \Omega_b h^2$: Planck Collaboration, "Planck 2018 results. VI. Cosmological parameters", *Astronomy and Astrophysics* 641 (2020) A6, with the conversion of the Particle Data Group (2026), review "Big-Bang Nucleosynthesis". Baryons per photon from deuterium, $(6.04 \pm 0.12) \times 10^{-10}$: Particle Data Group (2026), review "Big-Bang Nucleosynthesis", Eq. (24.5); $D/H = (2.527 \pm 0.030) \times 10^{-5}$: Cooke, R. J., Pettini, M., and Steidel, C. C., *The Astrophysical Journal* 855 (2018) 102. No antimatter domains: Cohen, A. G., De Rújula, A., and Glashow, S. L., "A matter-antimatter universe?", *The Astrophysical Journal* 495 (1998) 539–549; isocurvature departures no more than 1.55 percent of the temperature variation: Planck

Collaboration, "Planck 2018 results. X. Constraints on inflation", *Astronomy and Astrophysics* 641 (2020) A10, Table 14. No neutrinoless double beta decay, half-life above 3.8×10^{26} years in xenon-136 at 90 percent confidence: Abe, S., and others (KamLAND-Zen Collaboration), "Search for Majorana Neutrinos with the Complete KamLAND-Zen Dataset", *Physical Review Letters* 135 (2025) 262501. Above 1.9×10^{26} years in germanium-76 at 90 percent confidence, from LEGEND-200, GERDA and the MAJORANA DEMONSTRATOR together: LEGEND Collaboration, "First results from LEGEND-200 on the search for neutrinoless double beta decay", arXiv:2509.21166. Both limits as *The Registered Predictions of Physics from Comparison; A Dated Record* reports them (Prediction 32).

Chapter 20. What Happened During the Big Bang?

Each paragraph below gives one claim of the chapter, the corpus book that carries it, its standing as that book states it, and its exact values.

The reconstructed history and its limit. The past is known by its impression on the present, and the history reconstructed from that impression, traced backward, approaches a limit and takes it for its beginning. The reconstruction reports what it finds as located events, so it draws the limit as a point in time. Source: *At the Edge of Reality*, Chapter 17, sections "Yes, as Our History Finds It", "How a History Is Made" and "The Limit Rendered as a Point"; *What the Beginning Left Behind*, Chapter 1, section "A History Made from What Arrives Now"; the walker picture is *The Coming of the Kinds*, Chapter 2, Section I. Standing: a stated premise ("I take a reconstruction to report what it finds as content"), then an identification.

The turn, and the Big Bang of our epoch as its appearance. The turn is the limit between the collapse inside the black holes of one epoch and the reconstructed history of the next. At the turn the smooth description and the stepwise description each reach the edge of their domains, and no description takes over; no comparison registers the turn as an event. Two identifications are made in the first person in *At the Edge of Reality*: "I identify this restoration of the outside context with the Big Bang of the

new epoch" (Chapter 16, "The Identification"), and "I identify the Big Bang of the equations of cosmology with that appearance", namely "the turn, which no comparison registers as an event, rendered as an event in a history reconstructed from inside" (Chapter 17, "The Limit Rendered as a Point"). The chapter makes the identification in one sentence: the Big Bang of our epoch is the turn as it appears in the reconstructed history. Source: as above; *What the Beginning Left Behind*, Chapter 1, section "The Turn". Standing: a stated premise (the turn as the limit of both descriptions) and an identification.

The singularity as the edge of the smooth description. General relativity holds below the Planck curvature; the corrections to Einstein's equations are negligible far below it and of order one at it. The singularity is what the smooth equations produce when carried past that edge; the structure of comparison, the three axioms and the Incommensuration Theorem hold beyond it; asking for the geometry at the singularity is a category error. A single description carrying both characters at the Planck scale would need a pairing the Incommensuration Theorem forbids: continuity with symmetry, or asymmetry with discontinuity. Source: *At the Edge of Reality*, Chapter 15, all sections; the two forbidden pairings as Chapter 8 of this book, in its part of this appendix, states them. Standing: argued from the Incommensuration Theorem; the singularity theorems (Penrose 1965; Hawking 1966; Hawking and Penrose 1970) are established general relativity, as the book cites them in its Chapter 1. The Incommensuration Theorem, in its exact wording: "Symmetry and continuity cannot both be applied, simultaneously and fundamentally, to any event or comparison; and neither can asymmetry and discontinuity" (*Incommensuration*, Chapter 2, Section VI; quoted in *The Coming of the Kinds*, The Ground in Brief).

What the turn passes on, and one origin. The content does not cease at the end of the black-hole interiors (Chapter 16, "Content Needs a Context"); "What passes the turn is the form of the content, and it passes as one form" (Chapter 18, "Why the Beginning Was So Orderly"), and "no total of the old content passes the turn, since no comparison of the new

epoch registers the mass of the old interiors" (Chapter 19, "Why Space Is Flat"). The new four-dimensional geometry "re-forms from a ten-dimensional geometry in which it had no separate identity" and so "has no prior identity". The new context inherits no record, no length and no mark that sets one of its parts apart from another. The corpus books name the single origin of the new world "one domain", the chapter's "one origin": the ends of all black-hole interiors of an epoch are one, because no comparison anywhere can tell them apart, and the new outside world re-forms from that one end. The ends of the interiors, and their place on the far side of the turn, are walked in Chapters 21 and 22 of this book. Source: *At the Edge of Reality*, The Story in Brief, Chapter 11, Chapter 16 ("Content Needs a Context" and "The Six Are Released, and the Split Re-forms") and Chapter 19 ("One Origin, Not a Signal"); *What the Beginning Left Behind*, Chapter 12, opening; *The Gravitational Passage*, Chapter 18, Questions. Standing: argued (from the principle that a difference no comparison can register is no difference, and from the third axiom, which excludes content without a context).

The horizon problem answered. Regions of the sky that no signal within the epoch's history has connected are alike because they come from one origin. The departures from uniformity are required by the Incommensuration Theorem, since perfect sameness in every direction and at every place would make symmetry and continuity both perfect. Source: *At the Edge of Reality*, Chapter 19, "One Origin, Not a Signal", and Chapter 18, "Even From the Start"; *What the Beginning Left Behind*, Chapter 12, "One Origin, One Cloth", and Chapter 13, "The Sameness and the Flatness, Answered From the Turn". Standing: argued. The separation of the regions, about a degree on the sky (twice the width of the full Moon), is the standard history's figure, as *What the Beginning Left Behind*, Chapter 12, gives it.

The universe "too big". The authors' second mystery assumes matter moving outward from a small region through a static space. In Chapter 20 of this book I answer the authors' second mystery from two statements of *At the Edge of Reality*. The first statement is that the expansion is the

stretching of space itself, which carries the galaxies apart (Chapter 2, "The Expanding Universe"). The second statement is that at the turn "what reforms is the outside world itself", neither a creation from nothing nor a fluctuation in a vacuum already there (Chapter 16, "What the Turn Is Not"). A geometry with no prior identity "inherits no large-scale unevenness from the old outside world" (Chapter 18, "Even From the Start"), and an outer edge of the matter would be such an unevenness, so the matter of the epoch has no outer edge. Standing: the first two statements are standard cosmology and the corpus book's statement; the last step is my application, made in this chapter, of the premise of no prior identity to the authors' picture. In Chapter 23 of this book I take up the size of space as measured from inside. I find space flat, with no short loop, and, for every finding made from inside, the same as a space without end.

Flatness. In the Friedmann equation for a homogeneous universe, the spatial curvature enters as a constant of integration set once by the initial state; the curvature share then grows relative to matter and radiation as the universe expands, which is the flatness problem of the standard history. The state set at the turn holds one length, the length of the turn, of the order of the Planck length, and only pure numbers of order one. The de Sitter radius, about 17.53 billion light-years, belongs to the law (the cosmological constant) and not to the state, and at the turn the constant "acts as nothing at all" (*The Gravitational Passage*). The de Sitter radius is the horizon radius of a universe holding only the energy of the vacuum; it is a different length from the present distance of the cosmological event horizon, which Chapter 23 gives. A radius between the two lengths would need a pure number near ten to the thirty, and the only numbers that large are counts, none of which passes the turn. A radius of the Planck length would close the epoch within a few Planck times or leave it curvature-dominated, and is excluded by the cycle. So the homogeneous model is spatially flat, curved only by its departures, of order ten to the minus five. In symbols: the curvature share is Ω_K (read "omega K"), the share of the critical density that the curvature term carries in the Friedmann equation; the account gives $\Omega_K = 0$ for the homogeneous model,

and a curvature found within one horizon of order 10^{-5}. A radius equal to the de Sitter radius would leave Ω_K about 2.5×10^{-64} today (*At the Edge of Reality*, Appendix C, as *What the Beginning Left Behind*, For the Physicist, Chapter 12, reports it). Source: *At the Edge of Reality*, Chapter 19, "Why Space Is Flat"; *What the Beginning Left Behind*, Chapter 12, "Flat Space"; *The Compactification*, Chapter 6, Section VI; *The Gravitational Passage*, Chapter 18, Section IX. Standing: argued, in the form "must", given the premise that the new context has no prior identity; the argument uses nothing of the cosmological constant's value or sign. No measurement can test the curvature more finely than about 1.5×10^{-5}, the size of the departures (Waterhouse and Zibin, "The Cosmic Variance of Omega", arXiv: 0804.1771, 2008).

The first ripples identified. "I identify the primordial departures from uniformity with the form of the content carried from one side of the turn to the other, the distinctions of the old epoch averaged and not erased". The form of the content is "which alternatives the content has taken, the specification of what has been selected". Source: *What the Beginning Left Behind*, Chapter 11, "What Passes the Turn"; *At the Edge of Reality*, Chapter 19, "The Departures"; the worn steps are *What the Beginning Left Behind*, Chapter 11. Standing: an identification, made in the first person, with the observation that bears on it (the pattern of the first ripples).

The vacuum adds almost nothing. Traced back to near the turn, a length observed today lay some 10^{27} times beyond the horizon of that time. The vacuum of a wave so far beyond the horizon carries a power below 10^{-51}, against the observed power of about 2.1×10^{-9}. *What the Beginning Left Behind*, Chapter 11, states the shortfall as more than ten to the forty-two; *At the Edge of Reality*, Chapter 19, states it as more than ten to the forty; both statements follow from the two powers just given. Source: *What the Beginning Left Behind*, Chapter 11, "Empty Space Adds Almost Nothing", and For the Physicist, Chapter 13; computed in *The Gravitational Passage*, Chapter 18, Section IX. Standing: computed.

The pattern: one form, near the same strength at every length. Because the form passes the turn as one form, the departures are correlated across the whole new sky and nearly scale invariant. Independent pieces, averaged, would leave white noise, with a spectral index of 4 in the curvature (or 0 in the density), far from the observed value near 1. In symbols: the power spectrum of the curvature perturbation is $P_\zeta(k) = A_s(k/k_*)^{n_s-1}$, read "the power at wavenumber k equals the amplitude A sub s times the ratio of k to the reference wavenumber k star, raised to the power n sub s minus one", with $k_* = 0.05\ \text{Mpc}^{-1}$; n_s is the spectral index. Source: *What the Beginning Left Behind*, Chapter 11, "How the Ripples Are Described", Chapter 12, "One Origin, One Cloth", and For the Physicist, Chapters 11 and 12 (from *The Compactification*, Chapter 6, Sections I and III, and *The Gravitational Passage*, Chapter 18, Section IX). Standing: the description is the standard one (definitions); the correlation and the exclusion of white noise are argued in the form "must".

The strength and the tilt. A_s and n_s are measured inputs, and the direction of the tilt and the running are also taken from measurement. *The Gravitational Passage* names what sets each: "The amplitude is set by the count of states over which the form of the content is shared as it becomes the departures of the new metric; the tilt, by the length to which the departures refer and by the way the departures depend on it". The length to which the departures refer lies between the length of the turn and the de Sitter radius; near the turn an observed length was some 10^{27} Planck lengths and some 10^{-34} of the de Sitter radius. Source: *What the Beginning Left Behind*, Chapter 12, "The Strength and the Tilt" and "The Marks Beside the Sky"; *At the Edge of Reality*, Chapter 19, "The Tilt". Standing: measured inputs, each with its question (what count of states sets the amplitude; what length sets the tilt).

Ripples of density, and waves of space only at second order. Content close to equilibrium has no anisotropic stress at first order, so the first departures of the geometry are scalar, and tensor departures arise only at second order. The ratio of tensor to scalar power, $r = P_t(k_*)/P_\zeta(k_*)$ (read "r equals the tensor power at k star divided by the curvature power at k

star"), is far below 10^{-6}. Source: *At the Edge of Reality*, Chapter 19, "Only Departures of Density"; *What the Beginning Left Behind*, Chapter 12, "Ripples of Density, and Waves Only Later". Standing: argued, in the form "must", given the identification and the premise.

No inflationary phase needed; a long one excluded. "The account therefore needs no inflationary phase for the horizon and flatness problems". On the identification of the first ripples, an inflationary phase long enough to stretch the scales observed today from within the early horizon to beyond it is excluded, since the departures on those scales would then be those of the inflationary vacuum. A shorter phase, which leaves the observed scales outside the early horizon throughout, "is neither required nor excluded by the account"; the temperature at which the history of the new epoch begins bounds it. Source: *The Gravitational Passage*, Chapter 18, Questions; *At the Edge of Reality*, Chapter 19, "What This Says About Inflation"; *What the Beginning Left Behind*, Chapter 13, "A Long Inflation Is Excluded", and For the Physicist, Chapter 13. Standing: argued, in the form "must", relative to the identification. Inflation itself is cited from Guth, "Inflationary Universe: A Possible Solution to the Horizon and Flatness Problems", *Physical Review D* 23 (1981) 347–356.

The second route, from the dark matter. Gyrations have a mass of $\sqrt{2}$ Planck masses at the classical level and about 0.6 Planck masses at first order (Planck mass 1.221×10^{19} GeV). A plasma formed at once must never have been hotter than about one thirtieth of a gyration's mass (the divisor runs from about 28 to 34 with the coupling), about 5×10^{17} GeV and 2×10^{17} GeV for the two masses. If the turn's energy reached the plasma gradually, through a stage that behaved as matter and decayed into the content, the condition falls instead on the end of that stage: "the reheating that ended it must lie below about one hundredth of the mass of a gyration". In an epoch whose observed departures were made by inflation, the bound on primordial gravitational waves (BICEP/Keck 2021) would keep the temperature far below this limit, and gyrations could not be made after that inflation in the measured amount. The gyrations of the turn could not supply that amount in such an epoch, because an inflation di-

lutes whatever was made before it, as it dilutes the monopoles of grand unified theories (*What the Beginning Left Behind*, Chapter 13, "No Monopoles, No Strings, No Walls"). Source: *The Weight of Possibility*, Chapter 4, Section VI; *What the Beginning Left Behind*, Chapter 13, "How Hot the Beginning Could Have Been" and "A Second Reason, From the Dark Matter". Standing: computed (the ceiling, from the method and cross sections of Garny, Sandora and Sloth 2016); argued (the exclusion).

Nothing to drive a slow-roll inflation. The two moduli of the internal space (its overall size and the ratio of its two radii) have masses of 2.25 and 3.09 Planck masses at first order. The slow-roll condition $|\eta| = m^2/(3H^2) \ll 1$ (read "the absolute value of eta, equal to the square of the field's mass over three times the square of the expansion rate, is much less than one") would need an expansion rate far above the Planck mass, beyond the edge of the description of the large world. The authors' unstable substance with negative pressure is the inflaton of the usual version: a scalar field whose potential energy gives a negative pressure and drives the expansion. Source: *The Gravitational Companion*, Comparisons at Single Steps, Section IX, as *What the Beginning Left Behind*, Chapter 13, "Nothing for Inflation to Work With", and For the Physicist, Chapter 13, report it; the masses are from *The Gravitational Passage*. Standing: established physics (the slow-roll condition, and the inflaton as the source of negative pressure); computed at first order (the masses); argued (the conclusion).

Growth of structure. The gyrations are cold whatever speed the turn gives them, because the momentum of each gyration falls as the universe expands. A gyration moving with the speed that the gyration would have in a plasma at one thirtieth of the gyration's mass travels about two centimeters in the whole history of the universe. So on the scales of galaxies they cluster exactly as standard cold dark matter does. For matter held together by its own gravity, clumping raises the count of states; the content's count began at most about fifteen percent of the largest count of its region, and the room above it widened as the epoch grew. Source: *The Weight of Possibility*, Chapter 5, Section VI; *What the Beginning Left Behind*, Chapter 10, "Gravity Turns the Order Around" and "Room to Grow". Standing: ar-

gued (the coldness of the gyrations); established physics (the reversal of the order of counts under self-gravity; the growth of the ceiling), computed in *The Compactification*.

Measured values told in the chapter, with their primary papers.

Quantity	Value	Primary paper
Excess antenna temperature at 4080 Mc/s, isotropic, unpolarized, no seasonal change (July 1964 to April 1965)	about 3.5 K	Penzias and Wilson, "A Measurement of Excess Antenna Temperature at 4080 Mc/s", *Astrophysical Journal* 142 (1965) 419–421; explanation in Dicke, Peebles, Roll and Wilkinson, "Cosmic Black-Body Radiation", *Astrophysical Journal* 142 (1965) 414–419
Temperature of the microwave background	2.73 K (the authors' figure); 2.72548 $\pm$ 0.00057 K	Fixsen, "The Temperature of the Cosmic Microwave Background", *Astrophysical Journal* 707 (2009) 916–920
Temperature differences of the microwave background	about one part in 10^5	Smoot and others, *Astrophysical Journal Letters* 396 (1992) L1–L5
Spectral index n_s; amplitude A_s; running	0.9649 $\pm$ 0.0042; 2.10 $\times 10^{-9}$ ($\ln(10^{10} A_s) = 3.044 \pm 0.014$); -0.0045 ± 0.0067	Planck Collaboration (Aghanim and others), "Planck 2018 results. VI. Cosmological parameters", *Astronomy and Astrophysics* 641 (2020) A6; Planck Collaboration (Akrami and others), "Planck 2018 results. X. Constraints on inflation", *Astronomy and Astrophysics* 641 (2020) A10

Quantity	Value	Primary paper
Curvature share Ω_K	0.0007 ± 0.0019 (about 0.001 ± 0.002 rounded)	Planck Collaboration (Aghanim and others) 2020, A6, with baryon acoustic oscillations, as *What the Beginning Left Behind*, Chapter 11, and *The Compactification*, Chapter 6, give it
Flatness as the authors give it	within 0.4 percent	their source: WMAP results, as their source notes for ch. 7 give them
BICEP2 B-mode polarization reported	a detection read as primordial tensor modes	BICEP2 Collaboration (Ade and others), "Detection of B-Mode Polarization at Degree Angular Scales by BICEP2", *Physical Review Letters* 112 (2014) 241101 (arXiv: 1403.3985)
Joint analysis with Planck	"strong evidence for dust and no statistically significant evidence for tensor modes"; $r_{0.05} < 0.12$ at 95 percent confidence	BICEP2/Keck Array and Planck Collaborations, "A Joint Analysis of BICEP2/Keck Array and Planck Data", *Physical Review Letters* 114 (2015) 101301
Tensor-to-scalar ratio r	< 0.036 (95 percent); < 0.032	BICEP/Keck Collaboration (Ade and others), *Physical Review Letters* 127 (2021) 151301; Tristram and others, "Improved limits on the tensor-to-scalar ratio using BICEP and Planck data", *Physical Review D* 105 (2022) 083524

Chapter 21. What Happens If I Fall into a Black Hole?

The chapter's black-hole account is the one set out for the general reader in *At the Edge of Reality*, Part III, and for physicists in *The Gravitational Passage*, Chapters 18 and 19. Every number below with no other source be-

side it is the value that *At the Edge of Reality* prints in its appendix "The Numbers", Part III, where each is marked with its source. Throughout, G is Newton's constant (the measured strength of gravity), c is the speed of light, M is the mass of the hole, and $M_\odot$ (read "M sun") is the mass of the Sun.

The black hole and its horizon

Claim: a heavy enough star whose fuel is spent collapses without limit; a region in which the bending of space and time is so steep that nothing, not even light, can climb back out is a black hole. Where: *At the Edge of Reality*, Ch. 1, "How a Black Hole Forms". Standing: standard general relativity (Oppenheimer and Snyder 1939), as the book states it.

Claim: the horizon is the surface from inside which no signal can reach the outside, and inside it every direction a light cone allows leads inward. Where: *At the Edge of Reality*, Ch. 1, "How a Black Hole Forms" and "The Lean of the Light Cones" (Figure 1 draws the cones with time running up the page). Standing: standard general relativity, as the book states it.

Claim: the horizon is a feature of the shape of the geometry, no material lies there, and a falling body meets nothing special at it. Where: *Two Theories, One World*, Ch. 25, "What a Black Hole Is" and the firewall paragraph of "Small Holes and the Page Curve". Standing: stated; the book keeps the smooth horizon against the firewall argument of Almheiri, Marolf, Polchinski and Sully (2013), giving up only the assumption that the partners inside the horizon are independent of the early radiation, "as the equivalence principle of Chapter 9 requires".

Values: the radius of the horizon of a hole that does not rotate is the Schwarzschild radius, two times G times M divided by the square of c, in symbols $r_s = 2GM/c^2$. For one solar mass it is 2.95 km; for four million solar masses it is 1.18×10^7 km (standard, as *At the Edge of Reality*, "The Numbers", gives them). The gravitational size of Chapter 8 is GM/c^2, half of r_s.

The equivalent density and the layers

Claim: the tidal pull at each depth inside the hole equals the tidal pull just outside a body of the hole's whole mass and a radius equal to that depth, so each depth has an equivalent density, which rises inward as the cube of the inverse radius. Where: *At the Edge of Reality*, Ch. 10, "A Density for Every Depth". Standing: standard physics used as a marker of depth, as the book states ("this book uses them only as markers of depth"). In symbols, the equivalent density at radius r is $\rho(r) = 3M/(4\pi r^3)$, read as: rho of r equals three times M divided by four pi r cubed.

Claim: the interior passes the densities of the early universe in the opposite order; for a solar-mass hole the hadron density is already exceeded at the horizon; for a hole of four million solar masses a faller crosses the horizon "with little to feel". Where: *At the Edge of Reality*, Ch. 10, "Densities in the Opposite Order", "The Layers" and "Big Holes and Small Holes"; values from *The Gravitational Passage*, Ch. 19, Sec. II. Values: hadrons dissolve at about 10^{18} kg/m^3; the electroweak symmetry returns at 10^{30} to 10^{31} kg/m^3 (a temperature of 159.5 ± 1.5 GeV, about 1.85×10^{15} K; D'Onofrio and Rummukainen 2016); the Planck density is 5.16×10^{96} kg/m^3. Depths as fractions of the horizon's radius: one solar mass, electroweak 1.2×10^{-4} to 2.6×10^{-4}, Planck density 1.5×10^{-26}; four million solar masses, hadrons 1.05×10^{-4}, electroweak 1.05×10^{-8}.

Claim: near the end of the interior of a hole that neither rotates nor carries charge, a falling body is stretched along one axis and squeezed along the other two, by amounts that, for a fall from rest far away, depend only on the proper time left before the end; so the faller's own measure of the stretching tells one hole from another less and less as the end comes near, and the mass stays registered only in how long the fall has lasted and in the records the faller carries. Where: *At the Edge of Reality*, Ch. 10, "The End Has No Size"; Ch. 11, "The Faller's View"; *The Gravitational Passage*, Ch. 18, Sec. II. Standing: exact in general relativity for that fall, as the book states it ("these values are exact, whatever the mass of the hole"); on other radial paths the mass-dependent part fades as the end is ap-

proached. In symbols, with τ (tau) the proper time left before the end and the speed of light set to one, the stretching is $4/(9\tau^2)$ (four ninths over tau squared) and the squeezing along each other axis is $2/(9\tau^2)$ (two ninths over tau squared), both in units of inverse time squared.

Claim: the six small dimensions are a few Planck lengths across, so their curvature is close to the curvature of the Planck scale, and they begin to change when the curvature of the large world approaches their own, near the Planck density; at the end of the interior both conditions that hold them compact fail (the large world present as a context; a reference for inertia fixed in it), so the hold ends there; the forms of matter, which last only while the hold stands, end there; the content does not cease, and no body arrives at the end as a body. Where: *At the Edge of Reality*, Ch. 10, "Where the Six Begin to Change"; Ch. 13, "The Form of Matter Is Not Held" and "Both Conditions Fail"; *What Comes After the Dark*, Ch. 10, "What Reaches the Turn" and "The Plan, Step by Step" ("So the way down leads to the turn, where no body arrives as a body"). Standing: stated in the collection from the two conditions that hold the six compact, both of which fail at the end of an interior, and from the third axiom, which excludes content without a context (*At the Edge of Reality*, Chs. 8 and 13).

Two clocks

Claim: in the time of a distant observer the faller approaches the horizon without end, the crossing takes an infinite coordinate time, and no signal from inside reaches the outside. Where: *At the Edge of Reality*, Ch. 9, "The View from Outside"; *The Gravitational Passage*, Ch. 18, Sec. I. Standing: standard general relativity; both books state these facts for holes whose evaporation takes far longer than the outside world takes to empty, which is every hole that astronomers observe.

Claim: a hole of the mass of the Sun evaporates in about ten to the sixty-seven years, and its outside world empties first, in 10^{11} to 10^{12} years. Where: *What the Beginning Left Behind*, For the Physicist, "Chapter 9, Black Holes Within an Epoch", section "The glow of a black hole and the Page

curve", which states that the evaporation "takes about 2.1×10^{67} years for one solar mass, emitting photons only, as a black body without greybody factors"; the computation is *The Unquantized Arena*, Ch. 17, "Black-Hole Information and the Page Curve", Sec. II; the emptying is *At the Edge of Reality*, Ch. 12, "Two Timescales", and *The Gravitational Passage*, Ch. 18, Sec. III. Values: Hawking temperature of a solar-mass hole, $T_H = \hbar c^3/(8\pi G M k_B)$, read as: T sub H equals h-bar c cubed over eight pi G M k sub B, where $\hbar$ (h-bar) is the reduced Planck constant and k_B is Boltzmann's constant; about 6.2×10^{-8} K (*The Gravitational Passage*, Ch. 18, Sec. X). Primary paper of the method of the emission rates: Page (1976). A graybody factor is the probability that a wave of given frequency and angular momentum, leaving the neighborhood of the horizon, passes the barrier of the geometry and reaches far away (*The Unquantized Arena*, Ch. 17, Sec. II).

Claim: the faller crosses at a definite moment of proper time, and the end comes a finite proper time later. Where: *At the Edge of Reality*, Ch. 9, "The View from Inside"; *The Gravitational Passage*, Ch. 18, Sec. I. Standing: standard general relativity. Values: the longest proper time from the horizon to the end, for a faller starting from rest at the horizon, is pi times G times M divided by c cubed, $\pi GM/c^3$: 1.55×10^{-5} s for one solar mass and 62 s for four million solar masses; every other path takes less. For a fall from rest far away, the proper time left at the horizon is four thirds of G times M divided by c cubed, $4GM/(3c^3)$: 6.6×10^{-6} s for one solar mass (*The Gravitational Passage*, Ch. 18, Sec. II). *Frequently Asked Questions About the Universe*, ch. 5, "What's Inside?", gives "about twenty seconds" for a hole like the one at the center of the Milky Way and states no starting condition for the fall.

Claim: inside the horizon of a non-rotating hole the direction toward the center is the direction of time, so the singularity is a moment, the future end of every path inside, and not a place at the center. Where: *At the Edge of Reality*, Ch. 1, "The Center Is in the Future"; Ch. 9, "The End Is a Moment" and "What This Changes"; *The Gravitational Passage*, Ch. 18, Sec.

I. Standing: the direction is "a standard result of general relativity"; the placing of the end as a limit after every moment of the interior is the book's statement from it.

Claim: the end is a limit that each path approaches and does not reach. The end lies after every moment of the interior, and the end lies before, at or after no moment of the exterior. For the outside world the end never happens at any finite external time, and from the standpoint of the interior the end is the end of time. Where: *At the Edge of Reality*, Ch. 9, "Two Clocks, One Structure" and "The End Is a Moment"; *The Gravitational Passage*, Ch. 18, Sec. I ("and never happens at any finite external time"). Standing: derived from the two facts of general relativity just stated; in the words of *At the Edge of Reality*, "Both statements are true, and they are one structure". Scope: the end of the interior is the end of time on the faller's own clock, finite and with no last tick; for the outside world it never happens; and time does not stop (*What Comes After the Dark*, Ch. 6, "No Last Tick": "No clock records a last tick beyond which it ticks no more").

Claim: the ends of all black-hole interiors lie on a boundary that the outside world's time does not order. Where: *At the Edge of Reality*, Ch. 9, "All the Ends, Unordered"; *The Gravitational Passage*, Ch. 18, Sec. I. Standing: derived (no signal from any end reaches any exterior observer).

The singularity as the edge of the smooth description

Claim: the singularity theorems show that some paths cannot be continued within the smooth geometry beyond a finite proper time; they show that the smooth description has an edge to its domain and are silent about what lies beyond. Where: *At the Edge of Reality*, Ch. 1, "The Singularity Theorems"; Ch. 15, "What the Singularity Is"; *Two Theories, One World*, Ch. 26, "'The Singularities Demand a Quantum Gravity'". Primary papers: Penrose (1965); Hawking (1966); Hawking and Penrose (1970).

Claim: general relativity holds below the Planck curvature; along a path into a hole the curvature it gives reaches the Planck curvature before the path ends; the infinity is what the smooth equations give when carried past the edge of their domain; at the singularity a description reaches its

edge and physics does not break down; asking for the geometry there is a category error. Where: *At the Edge of Reality*, Ch. 15, "A Description Reaches Its Edge", "How Far the Smooth Description Holds" and "A Question Without an Answer"; *Two Theories, One World*, Ch. 26 ("To ask for the geometry at the singularity is to apply a concept where the concept does not belong"). Standing: derived in the collection from the Incommensuration Theorem, which places the edge of both descriptions at the Planck scale, where the gravitational size and the quantum size of an object are equal (*At the Edge of Reality*, Ch. 15, "Where Two Descriptions Meet" and "What the Theorem Can See"). Beyond the edge, in the words of the same chapter, "the three roles still operate, the axioms still hold, and the theorem still holds" ("What the Theorem Can See").

Claim: while a black hole stands, the black hole hides what falls in and destroys nothing. In neither of the two descriptions, quantum theory and general relativity, is the information destroyed. Quantum theory carries the matter's state forward without loss on the geometry of the black hole. General relativity carries what falls in forward to the end of the interior. Where: *Two Theories, One World*, Ch. 25, opening and "Information Is Not Destroyed". Scope, as the book states it for holes formed from stars: the information is not destroyed and is not accessible from outside while the hole stands, and "The account asserts neither that this information returns to the outside world nor that it is lost to the outside world" (Ch. 25, "Holes Formed From Stars").

One end

Claim: the ends of all black-hole interiors are one; the interiors stay distinct. Where: *At the Edge of Reality*, Ch. 11, all sections; *The Gravitational Passage*, Ch. 18, Sec. II. Standing: the step rests on three facts of physics (merger, in which the merged hole has one interior containing the interiors that merged; the no-hair theorem, by which nothing about the collapse beyond mass, spin and charge can be registered from outside; and the unordered ends of *At the Edge of Reality*, Ch. 9) and one principle of comparison, "a difference that no comparison can register is no differ-

ence". Stated exactly: two things are one when, for every possible comparison and every thing whatever, the comparison of the first with that thing gives the same verdict as the comparison of the second with it. In At the Edge of Reality I state two premises in the first person: "I take a comparison to register nothing that it only predicts", and "I take that context to register no distinction that the old outside world drew" (Ch. 11, "The Principle" and "The Ends Are One"). *The Gravitational Passage* (Ch. 18, opening) lists this step, which it names "the identity of interiors", among the three steps of the chapter that rest on principles of comparison, and states: "Each holds at the standing of its principle". No-hair theorem, primary papers as the book cites them: Israel (1967); Carter (1971).

Claim: the inner horizon of the exact rotating and charged solutions is unstable to the matter that falls in as real holes form, so the end of a real hole is expected to be of the same kind; the white hole of the authors' speculation has its counterpart in the beginning of a whole new epoch, taken as one beginning, which is no region of space at the far end of any one black hole. Where: *At the Edge of Reality*, Ch. 9, "All the Ends, Unordered"; *What Comes After the Dark*, Ch. 10, "The Plan, Step by Step"; *The Gravitational Passage*, Ch. 18, Sec. I ("the generic end is expected to be of the same kind"). Standing: reported from general relativity (the instability), with the expectation stated as an expectation in *The Gravitational Passage*; the counterpart is stated by the collection, with the identification of the new beginning with the Big Bang made in *At the Edge of Reality*, Ch. 16, and made in this book in Chapter 20.

Measured values and primary papers

Oppenheimer and Snyder, the scene: J. R. Oppenheimer and H. Snyder, "On Continued Gravitational Contraction", *Physical Review* 56, 455–459 (1939), received 10 July 1939, from the University of California, Berkeley: for a collapsing pressureless star, the collapse time for an observer comoving with the matter is finite (about a day for their example), while an external observer sees the star approach its gravitational radius asymptotically.

The first merger of two black holes seen by its gravitational waves: B. P. Abbott and others (LIGO Scientific Collaboration and Virgo Collaboration), "Observation of Gravitational Waves from a Binary Black Hole Merger", *Physical Review Letters* 116, 061102 (2016), the event of 14 September 2015.

The shadow of the black hole in M87: Event Horizon Telescope Collaboration, "First M87 Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole", *Astrophysical Journal Letters* 875, L1 (2019).

The shadow of the black hole at the center of our Galaxy: Event Horizon Telescope Collaboration, "First Sagittarius A* Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole in the Center of the Milky Way", *Astrophysical Journal Letters* 930, L12 (2022); mass about 4×10^6 $M_\odot$, ring diameter 51.8 ± 2.3 microarcseconds.

Singularity theorems: R. Penrose, "Gravitational Collapse and Space-Time Singularities", *Physical Review Letters* 14, 57–59 (1965); S. W. Hawking, "The Occurrence of Singularities in Cosmology", *Proceedings of the Royal Society of London A* 294, 511–521 (1966); S. W. Hawking and R. Penrose, "The Singularities of Gravitational Collapse and Cosmology", *Proceedings of the Royal Society of London A* 314, 529–548 (1970).

Black-hole emission rates: D. N. Page, "Particle Emission Rates from a Black Hole: Massless Particles from an Uncharged, Nonrotating Hole", *Physical Review D* 13, 198–206 (1976).

Chapter 22. What Came Before the Big Bang?

Each claim of the chapter that comes from the corpus is given here with the book that carries it, its standing as that book states it, and its exact values.

Claim, in one plain sentence	Where the corpus carries it	Standing as the book states it
The past is known only by its impression on the present, and the history reconstructed from that impression, traced back, approaches a limit and takes it for its beginning, the Big Bang as our history finds it.	*At the Edge of Reality*, Chapter 2, "The Answer of This Book"; Chapter 17, "How a History Is Made" and "The Limit Rendered as a Point"; source given there: *The Gravitational Passage*, Chapter 19, Section III.	Argued; the rendering of the limit as time zero is named "the projection" and stated in the first person ("I identify the Big Bang of the equations of cosmology with that appearance", Chapter 17).
The answer that the question has no meaning rests on one assumption: that the beginning our history finds is a first moment in the structure of things.	*At the Edge of Reality*, Chapter 2, "Why 'Before' Seems Meaningless".	Argued.
I identify what lies on the other side of the limit that our history takes for its beginning with the collapse of the interiors of the black holes of the epoch before ours.	*At the Edge of Reality*, Chapter 2, "The Answer of This Book"; Chapter 20, "A Creation Story With No First Moment".	An identification, stated in the first person in Chapter 2 ("I identify what lies on the other side of the limit with the collapse of the interiors of the black holes of the epoch before ours").

Claim, in one plain sentence	Where the corpus carries it	Standing as the book states it
The ends of the interiors of all black holes are one end, while the interiors stay distinct.	*At the Edge of Reality*, Chapter 11, "The Principle", "Stated Exactly", "The Ends Are One".	Argued from three facts of physics (merger, the no-hair theorem, the ends lying on a boundary the outside time does not order) and the principle that a difference no comparison can register is no difference, with an explicit statement that the new context registers no distinction the old drew ("I take that context to register no distinction ...").
Near the end of an interior, Einstein's equations in ten dimensions allow a form on which the three directions of space shrink together while the six small directions grow; the ordinary interior, with one direction stretched and two squeezed and the six at constant size, is also a valid ten-dimensional form, and it lies off that curve.	*At the Edge of Reality*, Chapter 14, "The Ordinary Interior", "One Loop", "The Arc at the Upper End"; Appendix A.	Exact (vacuum solutions of Einstein's equations of Kasner form).

Claim, in one plain sentence	Where the corpus carries it	Standing as the book states it
The end of every interior is placed at the upper end of the arc of the Kasner curve, chosen by what happens on it: read toward the end, the three collapse while the six grow; read away from the end, three open out while the six close up.	*At the Edge of Reality*, Chapter 14, "Where the Story Is Placed".	A placement, stated in the first person ("I place the end of every interior on the upper end of this arc").
The six are held compact as content of a large world under two conditions: the large world is present as a context for the six, as a domain of the smooth description of space and time, and a reference for inertia is fixed in it.	*At the Edge of Reality*, Chapter 8, "No Content Without a Context" and "The Two Conditions"; *The View from Inside*, Chapter 16, "Context Must Be Restored".	Argued from the third axiom (content and context distinct and inseparable) and the principle that a difference no comparison can register is no difference.
At the end of an interior both conditions that hold the six compact fail, because the outside world has no moment there and no reference for inertia survives.	*At the Edge of Reality*, Chapter 13, "The Conditions Fail" and "Both Conditions Fail".	Argued from the third axiom and the conditions of Chapter 8 of that book.

Claim, in one plain sentence	Where the corpus carries it	Standing as the book states it
The content does not cease at the end, content needs a context, so the ten-dimensional geometry restores a large outside context: the restoration of context.	*At the Edge of Reality*, Chapter 16, "Content Needs a Context"; source given there: *The Gravitational Passage*, Chapter 18, Section VII.	Argued from the third axiom (no content without a context) and the edge of the descriptions at the Planck scale (Chapter 15 of that book).
The restoration of the outside context is the Big Bang of the new epoch.	*At the Edge of Reality*, Chapter 16, "The Identification".	An identification ("I identify this restoration of the outside context with the Big Bang of the new epoch"), made in this book in Chapter 20.
The far future reaches the same condition: when the large world no longer serves as a context, a final featureless emptiness would be perfectly symmetric and perfectly continuous at once, which the Incommensuration Theorem excludes, so context must be restored.	*The View from Inside*, Chapter 16, "Nowhere Else to Be" and "Context Must Be Restored".	Argued from the third axiom and the Incommensuration Theorem; a separate route from the one through the black-hole interior.
The restoration is neither a creation from nothing, nor a fluctuation in a vacuum that was already there, nor a breakdown.	*At the Edge of Reality*, Chapter 16, "What the Turn Is Not".	Argued from the restoration being a transition in a cycle.

Claim, in one plain sentence	Where the corpus carries it	Standing as the book states it
"Before" names the order of a cycle; no comparison measures a time across the turn, since the outside world has no moment at the end of an interior and the interior's clock ends at the limit.	*At the Edge of Reality*, Chapter 2, "The Question Has an Answer"; Chapter 17, "No Comparison Across the Turn".	Argued.
The history of the world is a cycle of epochs with no first iteration; the epochs follow one another in a single sequence; the comparisons of an epoch register the turn they came from and not the turn their own interiors will reach.	*At the Edge of Reality*, Chapter 20, "No First Iteration" and "The Cycle"; Chapter 11, "The Ends Are One".	Argued from the steps of Chapters 11, 12, 16 and 17 of that book.
The accelerating expansion does not prevent the cycle: the cosmological constant belongs to the description of the outside world and has no purchase at the end of an interior.	*At the Edge of Reality*, Chapter 20, "The Expansion Does Not Stop It".	Argued.

Claim, in one plain sentence	Where the corpus carries it	Standing as the book states it
The derived structure (the shape of the internal space, the ratio of its radii, its size at the Planck scale, the count of three degrees of freedom of the accessible share) is the same in every epoch; the strength of gravity is the one scale taken from measurement.	*At the Edge of Reality*, Chapter 20, "What Carries Over".	Derived structure; the strength of gravity is a measured input.
Every entropy is a count reckoned relative to a context: the entropy of a black hole counts the states of its interior that the outside cannot tell apart, and the count of the states of the matter is reckoned relative to the same outside world; at the turn the old context has ended, so no count is carried over (the reset); each epoch begins its own count, which meets Tolman's difficulty.	*At the Edge of Reality*, Chapter 18, "Every Count Has a Context" and "The Old Objection to Cycles"; *The Compactification*, Chapter 3, Sections V and VII; source given there: *The Gravitational Passage*, Chapter 18, Section VIII.	"The reset at the turn: argued, by principle" (*The Compactification*, Chapter 3, Section X). The Bekenstein and Hawking formula is established physics; what it counts is an identification (*The Unquantized Arena*, Chapter 17, Proposition 17.3, as quoted in *The Compactification*, Chapter 3, Section V). *The Compactification* states that a count of states across the turn, in numbers, is not given in that book or in *The Gravitational Passage*; the reset is stated by principle.

Claim, in one plain sentence	Where the corpus carries it	Standing as the book states it
The new geometry has no prior identity, so it begins even up to the departures the Incommensuration Theorem requires; the matter begins hot and near equilibrium, so its entropy is high, and the low entropy is in the gravitational part.	*At the Edge of Reality*, Chapter 18, "The Question of Entropy" and "Even From the Start"; Chapter 16, "The Six Are Released, and the Split Re-forms"; *The Compactification*, Chapter 3, Section VI.	"The even beginning, and the Weyl curvature hypothesis as its consequence: argued from the restoration of context and the absence of a prior identity" (*The Compactification*, Chapter 3, Section X).
Penrose's Weyl curvature hypothesis (1979), that the part of curvature which distorts shapes, as distinct from the part that changes volumes, was near zero at the Big Bang, follows here as a consequence of the restoration of context and is not a separate postulate.	*At the Edge of Reality*, Chapter 18, "Even From the Start"; *The Compactification*, Chapter 3, Section VI; *Side by Side*, Volume One, chapter "Two Roads to Reality", Section V.	Argued (as in the row above).

Claim, in one plain sentence	Where the corpus carries it	Standing as the book states it
Inside a black hole near the end, three directions shrink and six grow on an exact arc of Kasner solutions in ten dimensions; the same exponents, read in the opposite direction of time, describe three growing and six contracting at the beginning of the new epoch.	*At the Edge of Reality*, Chapter 14, "The Arc at the Upper End" and "The Same Arc, Read Backward"; Chapter 16, "The Same Arc, Read Away From the End"; Appendix A; *The Compactification*, Chapter 1, Section VI.	Exact (a vacuum solution of Einstein's equations of Kasner form); its placement at the end of every interior is argued.
There is one next epoch from all the black holes of an epoch together, not one universe for each black hole, with no inheritance of constants and no selection; this is the difference from Lee Smolin's cosmological natural selection (1992), in which every black hole begins a universe of its own with constants changed slightly from its parent's, so that universes rich in black holes leave the most descendants.	*Side by Side*, Volume Two, chapter "Time Is Real", Section V; *At the Edge of Reality*, Chapter 20, "What Is New Here".	Argued from the identity of the ends.

Claim, in one plain sentence	Where the corpus carries it	Standing as the book states it
Penrose's conformal cyclic cosmology (2010) shares six features with the account and differs in six; its bridge is the remote future after every black hole has evaporated, joined to the beginning of the next era, with no black hole as the bridge.	*Side by Side*, Volume One, chapter "Two Roads to Reality", Section V, "The turn and Penrose's crossover".	Reported comparison.
Pocket universes from endless inflation are excluded: the account needs no inflation and excludes a long one, and the internal space is one space, so there is no landscape of vacua among which constants could vary.	*Side by Side*, Volume Two, chapter "The Structure and the Act", Section VI (Level II); *At the Edge of Reality*, Chapter 19, "What This Says About Inflation"; *The Compactification*, Chapter 2, Section IX, as quoted there.	Argued; the exclusion of a long inflation holds on the identification of the first ripples with the form of the content carried through the turn (*At the Edge of Reality*, Chapter 19).
The arena of space and time is the context of every quantum state, and it is not derived from the entanglement structure of a state: Carroll "derives the arena from the state, and the collection holds that the arena is the setting of every state".	*Side by Side*, Volume One, chapter "The Wave Function and the One Who Finds", Section VI.	Argued, from the Incommensuration Theorem's two characters (a common source, two descriptions, no merger).

Claim, in one plain sentence	Where the corpus carries it	Standing as the book states it
A law exists; a measurement is real; the world that comparisons find is not a mathematical structure.	*Side by Side*, Volume Two, chapter "The Structure and the Act", quoting *Comparison; The Necessary Basis*, Chapter 10, Section II.	Argued (developed in Chapter 27 of this book).
The energy of empty space in each unit of volume stays the same as space grows (the ratio of its pressure to its energy in each unit of volume is exactly minus one).	*What the Beginning Left Behind*, Chapter 10, "The Largest Count".	Derived (the cosmological constant as the accessible share).
Creation is a side of every event and is not confined to a first moment; the degree of interaction is always above zero, because zero is the edge of the domain and not a state inside it, which is why there is something rather than nothing.	*What Cannot Be*, Chapter 19, "Interaction, Existence and Creation"; the domain is the one bounded by the two constants of "The Width Between the Edges" in the same chapter.	Argued from the three axioms (the order among the modalities is an order of presupposition, not of clock time); "in the framework's terms", as the book states.
The form of the content passes the turn as one form and re-emerges as departures from uniformity correlated across the whole new world.	*At the Edge of Reality*, Chapter 18, "Information Is Not Destroyed"; Chapter 19, "One Origin, Not a Signal" and "The Departures".	The departures are identified with the form of the content in the first person (*At the Edge of Reality*, Chapter 19); that identification is made in this book in Chapter 20.

The Kasner curve, in words first. A Kasner geometry is an empty space in which each direction stretches or shrinks as a fixed power of the time; the powers are called the exponents. Einstein's equations for empty space allow only those sets of exponents whose sum is one and whose sum of squares is one. In ten dimensions, with three directions sharing one exponent and six sharing another, the upper end of the arc has the three at five ninths and the six at minus one ninth. In symbols, write p (read "p") for the exponent of each of the three directions and q (read "q") for the exponent of each of the six, with t (read "t") the time counted from the limit. Each of the three scales as t to the power p, and each of the six as t to the power q, with $p = 5/9$ and $q = -1/9$. The first condition is $3p + 6q = 1$, and here $3 \times 5/9 + 6 \times (-1/9) = 15/9 - 6/9 = 1$. The second condition is $3p^2 + 6q^2 = 1$, and here $3 \times 25/81 + 6 \times 1/81 = 75/81 + 6/81 = 1$. When t falls by a factor of 10^9, each of the three changes by the factor $(10^{-9})^{5/9} = 10^{-5}$, a hundred-thousandfold shrinking, and each of the six by $(10^{-9})^{-1/9} = 10$, a tenfold growth. Read toward the end inside a black hole, t is the time remaining, and the three shrink while the six grow; read away from the turn in the new epoch, t is the time since the limit, and the three grow while the six contract (*At the Edge of Reality*, Chapters 14 and 16 and Appendix A; *Side by Side*, Volume One, chapter "Two Roads to Reality", Section V). The ordinary interior has the exponents $-1/3$, $2/3$ and $2/3$ for its three directions of space, with 0 for each of the six; its sums are $-1/3 + 2/3 + 2/3 = 1$ and $1/9 + 4/9 + 4/9 = 1$ (*At the Edge of Reality*, Chapter 14, "The Ordinary Interior").

Values behind the chapter's steps, with their exact form.

Quantity	**In the chapter**	**Exact value and source**
Entropy of a black hole of one solar mass	not stated in words	1.05×10^{77}, in units of Boltzmann's constant (*At the Edge of Reality*, Appendix C, citing *The Gravitational Passage*, Appendix B, Section VI)

Quantity	In the chapter	Exact value and source
Entropy of all black holes in the observable universe, against the count of the particle horizon	not stated in words	about 10^{104}, against 2.29×10^{123} (same sources)
Bekenstein and Hawking entropy	a count made relative to the outside world	$S = k_B c^3 A / (4 G \hbar)$: Boltzmann's constant times the cube of the speed of light times the area of the horizon, divided by four times Newton's constant times the reduced constant of action; in words, one quarter of the area of the horizon in units of the Planck area (*The Compactification*, Chapter 3, Section V, equation 3.1)
Strength of the first ripples, and their power	about one part in a hundred thousand	about 10^{-5}; power about 2×10^{-9} (*At the Edge of Reality*, Appendix C)
Temperature of the microwave background today	about 2.7 degrees above absolute zero	about 2.7 kelvin (*At the Edge of Reality*, Chapter 2); Cham and Whiteson give "about 2.73 K" (*We Have No Idea*, ch. 14, "Big Mystery #3: The Universe Is Too Smooth")

Measured values the chapter tells, with their primary papers.

Measurement	What was found	Primary paper
Hubble, Mount Wilson Observatory, 1929	The recession speeds of galaxies rise roughly in proportion to their distances.	E. Hubble, "A Relation between Distance and Radial Velocity among Extra-Galactic Nebulae", *Proceedings of the National Academy of Sciences* 15 (1929) 168–173.

Measurement	What was found	Primary paper
Penzias and Wilson, Bell Telephone Laboratories, Holmdel, New Jersey, 1964 to 1965	An excess antenna temperature of 3.5 ± 1.0 kelvin at 4080 megacycles per second, isotropic, unpolarized and free from seasonal variation within the limits of their observations.	A. A. Penzias and R. W. Wilson, "A Measurement of Excess Antenna Temperature at 4080 Mc/s", *Astrophysical Journal* 142 (1965) 419–421.
Differential Microwave Radiometer of the Cosmic Background Explorer satellite (COBE), first-year maps, 1992	Structure well described as scale-invariant fluctuations: a root-mean-square sky variation of 30 ± 5 microkelvin at 10 degrees smoothing, a root-mean-square quadrupole amplitude of 13 ± 4 microkelvin, and a spectral index of 1.1 ± 0.5.	G. F. Smoot and others, "Structure in the COBE Differential Microwave Radiometer First-Year Maps", *Astrophysical Journal Letters* 396 (1992) L1–L5.

The opening scene's papers. S. W. Hawking, "The Boundary Conditions of the Universe", in *Astrophysical Cosmology: Proceedings of the Study Week on Cosmology and Fundamental Physics* (Vatican City: Pontificia Academia Scientiarum, 1982), 563–574; the study week was held 28 September to 2 October 1981. J. B. Hartle and S. W. Hawking, "Wave Function of the Universe", *Physical Review D* 28 (1983) 2960.

The proposals compared in the table above. R. Penrose, "Singularities and Time-Asymmetry", in S. W. Hawking and W. Israel (eds), *General Relativity: An Einstein Centenary Survey* (Cambridge University Press, 1979), 581–638. L. Smolin, "Did the Universe Evolve?", *Classical and Quantum Gravity* 9 (1992) 173–192. R. Penrose, *Cycles of Time* (London: The Bodley Head, 2010), ISBN 978-0-224-08036-1. R. C. Tolman, *Relativity, Thermodynamics and Cosmology* (Oxford: Clarendon Press, 1934).

The chapter also draws on: *Side by Side, Volume Two*, chapter "Time Is Real", Section V; *Side by Side, Volume Two*, chapter "The Structure and the Act", Section VI; *Side by Side, Volume One*, chapter "The Wave Function and the One Who Finds", Section VI.

Chapter 23. How Big Is the Universe?

Every observer has its own horizon, centered on itself. Where stated: *What Comes After the Dark*, Chapter 1, "The Edge of What You Can Ever See"; *The View from Inside*, Chapter 15, "One Map, One Scale", where the observer-centered horizon is used to show that the cosmological constant cannot follow the horizon from era to era. Standing: stated as established physics, and used as a premise of the argument in *The View from Inside*.

The particle horizon is the only horizon a measurement made here and now holds. Where stated: *The Gravitational Passage*, Chapter 13, Section II ("the only horizon a first-person measurement holds"); *The View from Inside*, Chapter 12, "The Edge of What Has Reached Us". Standing: argued from the first-person character of measurement; *The Gravitational Passage*, Chapter 13, Section VI, gives a second, separate reason: only the particle horizon grows past the de Sitter radius. Values, with the parameters of the Planck satellite (*The View from Inside*, appendix section "The Horizon"; *What the Beginning Left Behind*, Chapter 10, "The Largest Count"): particle horizon R = 46.14 billion light-years; cosmological event horizon 16.68 billion light-years today; Hubble radius 14.51 billion light-years; de Sitter radius r sub Lambda, read "r lambda", equal to the square root of three over Lambda, 17.53 billion light-years. The de Sitter radius is the edge that a universe holding only the energy of empty space would have; the event horizon is smaller than it at every epoch and approaches it as the epoch grows without bound (*The Gravitational Passage*, Chapter 13, Section VI; *What the Beginning Left Behind*, Chapter 10). The authors give 46.5 billion light-years (14.26 gigaparsecs in their source notes to *We Have No Idea*, ch. 15, citing arXiv astro-ph/0310571). Both figures are results of the same standard calculation of the distance light has covered since the beginning, stretched by the expansion; they differ by the measured values of the cosmological parameters each source puts into it.

Any one horizon can be passed by moving or by waiting; the horizon as a class is permanent, and for the horizon as a class "beyond" has no meaning. Where stated: *What Cannot Be*, Chapter 18, "The Horizon of the

Very Large". Standing: a structural statement of the account about the edge of the knowable; the cosmological event horizon is cited there from the measured acceleration (Riess and others 1998; Perlmutter and others 1999).

Space itself stretches, and galaxies not bound together are carried apart by it, which gives Hubble's linear relation. Where stated: *At the Edge of Reality*, Chapter 2, "The Expanding Universe"; *What Comes After the Dark*, Chapter 1, "Twenty-Four Islands", and Chapter 3, "Binding Lives Where the Matter Is" (the raisin bread). Standing: reported as established physics.

The new outside world of an epoch carries no mark that sets one of its parts apart from another, so no place in our space is the place of the beginning. Where stated: *What the Beginning Left Behind*, Chapter 11, "What the Pattern Must Show" (the premise that the new context has no prior identity, which *The Gravitational Passage* argues from the re-forming of the four-dimensional geometry); *At the Edge of Reality*, Chapter 19, "One Origin, Not a Signal". Standing: a premise argued in *The Gravitational Passage*; the chapter's statement about the center is its direct consequence.

The space of our epoch is flat, curved only by its first departures from uniformity, of order ten to the minus five. Where stated: *The Gravitational Passage*, Chapter 18, Section IX, "Spatial flatness"; *What Comes After the Dark*, Chapter 2, "The First Way: Space Is Flat"; registered as Prediction 9 of *The Registered Predictions of Physics from Comparison; A Dated Record* (1 November 2026), reproduced in *Side by Side*, Volume One, Appendix B. Standing: derived. The argument in words: the radius of spatial curvature is a constant of integration of the expansion equation, set once by the state from which the history begins; that state holds no length and no count of the old epoch, so the only length it holds is the length of the turn, of the order of the Planck length; a radius of that size would close the epoch within a few Planck times or leave it dominated by curvature, and neither epoch makes the black holes the cycle requires; so the homogeneous model is spatially flat. The argument uses nothing of the cosmological con-

stant, neither its value nor its sign (the Passage's own words). *Side by Side*, Volume One, "Is Space Flat?", adds that no measurement can settle flatness finer than about 1.5 times ten to the minus five, the size of the departures themselves (Waterhouse and Zibin 2008), so exact flatness is settled by argument.

How the measurement states a curvature. In the Friedmann equation, the equation of Einstein's theory for the rate of expansion of a space that is the same everywhere, a spatial curvature enters as a term of the same form as a density of energy. Astronomers state it as a share of the critical density, Omega sub K, read "omega K": the curvature term divided by the whole, so that a flat space has Omega sub K equal to zero. The measured value is 0.001 plus or minus 0.002: zero to within about two thousandths of the whole.

No short loop exists anywhere in space: no closed path that goes around the universe, and so cannot be shrunk to a point, is shorter than the diameter of the horizon, at any location. Where stated: *The Weight of Possibility*, Chapter 3, Section II, "The Count: Six Against One"; Prediction 23 of the dated record (*Side by Side*, Volume One, Appendix B); *Side by Side*, Volume Two, "The Registered Predictions Beside George Ellis", entry Ellis 3. Standing: derived from the account's principle of counting (a measurement counts the independent classes of what it counts), which *The Weight of Possibility* names as the account's principle. The mathematics in words: the region a measurement holds is the ball within its horizon, which has one independent class; the dark residue ranges over both factors of the internal space and is counted by three classes times two classes, six; the share of the curvature of the complex projective plane that holds fast in the count is two over pi; so the ratio of the density of the dark matter to that of the ordinary matter is six less two over pi. In symbols: Omega sub c over Omega sub b, read "the dark matter's share over the ordinary matter's share", equals $6 - 2/\pi = 5.3634$. If the region within the horizon held N independent classes, the ratio would be $6 - 2/(N\pi)$, read "six minus two over N pi"; a region with a short loop counts N of at least two, which gives $6 - 1/\pi = 5.682$ or more. The ratio is an identity of the

present measurement: "The identity fixes the ratio for every registration, wherever it is made" (*The Weight of Possibility*, Chapter 3, Section II, citing Section I). So the count of one, and with it the absence of a short loop, holds at every location; it is a consequence of the identity, and the measured ratio is its check. The circle searches show the region within our horizon to be a ball out to 96.5 percent of the horizon's radius (*The Weight of Possibility*, Chapter 3, Section II).

For any measurement, space is infinite up to the limit of distinguishability, and the open space counts as one, whatever it is beyond the horizon. Where stated: *The Weight of Possibility*, Chapter 3, Section II ("so, for a registration, space is infinite up to the limit of distinguishability"; "So the open space counts as one, whatever it is beyond the horizon"). Standing: derived, from the count of one and the principle of identity (two descriptions that no comparison can tell apart are one). The sense of the claim, as the book argues it: within the bound of what a measurement has compared, which is its horizon, no comparison tells the ball it holds apart from a ball of an infinite flat space, so for that measurement the two descriptions are one; the claim holds of every measurement and is made at that scope. "Counts as one" there is the count of one class: the region within the horizon is a ball, a ball has one independent class, and the count a registration makes of the open space is one, whatever space is beyond the horizon. Scope, as the books state it: a flat space closed on a scale beyond every horizon also meets Predictions 9 and 23 (*Side by Side*, Volume One, "Is Space Flat?"; Volume Two, "The Participant and the Act", Section VIII, "A flat space or a closed one"); the account states no further claim about what lies beyond every horizon. Regions beyond a horizon interact with what is near them, so they exist as further parts of one world (*Side by Side*, Volume Two, "The Structure and the Act", Section VI, on Tegmark's Level I; and "The Registered Predictions Beside Max Tegmark", "Regions beyond every horizon: Levels I and II", which quotes the principle of existence from *Incommensuration*, Chapter 9, Section I).

The number of the speed of light expresses only the units of length and time. Where stated: *The Gravitational Passage*, Chapter 17, Section I ("express only the units in which time, length and action are measured"); *What Cannot Be*, Chapter 12. Standing: derived (the existence of the limit follows from the axioms; its number is a choice of units, exact by definition in the International System since 2019).

The magnitude of the cosmological constant in Planck units follows from the size of the present particle horizon. Where stated: *The Gravitational Passage*, Chapter 13, Section VI: the vacuum density is 3f divided by the count of the present horizon, about ten to the minus one hundred twenty-three of the Planck density, because the particle horizon now spans about ten to the sixty-one Planck lengths. Standing: derived given the identification of the cosmological constant with the share of the vacuum's energy open to a measurement made from inside (made in Chapter 3 of this book; *The View from Inside*, Chapter 11). The absolute epoch, the age of the universe at which the act of measurement falls, about ten to the sixty-one Planck times after the beginning of the reconstructed history, is a question about when comparers exist, which *The Gravitational Passage* (Chapter 13, Questions) takes from the measured particle horizon.

The span between the two edges of the physical domain is about sixty-one powers of ten, and the degree of structure a domain allows rises with that span. Where stated: *What Cannot Be*, Chapter 19, "What a Domain Is", "The Two Constants" and "The Width Between the Edges". The book's words for the levels: "each level able to serve as content for the level above it and as context for the level below it". Standing: the existence of two edges of two kinds is derived from the Incommensuration Theorem; the values of the edges are quoted from physics, and the book states that nothing in its framework says what they are. Values: the Planck length, about 1.6 times ten to the minus thirty-five meters; the radius of the observable universe, about 4.4 times ten to the twenty-six meters.

Measured values told in the chapter, with their primary papers.

Measurement	Value told	Primary paper
Cepheids in the Andromeda Nebula (plate H335H, night of 5 to 6 October 1923)	distance about 285,000 parsecs, a little under a million light-years	E. Hubble, "Cepheids in Spiral Nebulae", *The Observatory* 48 (1925) 139–142; also *Popular Astronomy* 33 (1925) 252–255
Period and luminosity of Cepheids	the longer the period, the greater the true brightness	H. S. Leavitt and E. C. Pickering, "Periods of 25 Variable Stars in the Small Magellanic Cloud", *Harvard College Observatory Circular* 173 (1912) 1–3
"The Scale of the Universe", 26 April 1920	Shapley: galaxy about 300,000 light-years across; Curtis: about 30,000, spirals separate galaxies	H. Shapley and H. D. Curtis, "The Scale of the Universe", *Bulletin of the National Research Council* 2, part 3 (May 1921)
Velocities and distances of galaxies	46 radial velocities, 24 distances, a roughly linear relation	E. Hubble, "A Relation between Distance and Radial Velocity among Extra-Galactic Nebulae", *Proceedings of the National Academy of Sciences* 15 (1929) 168–173
Spatial curvature	Ω sub K = 0.001 $\pm$ 0.002 (microwave background with baryon acoustic oscillations); told as zero to within about two thousandths of the whole	Planck Collaboration (N. Aghanim and others), "Planck 2018 results. VI. Cosmological parameters", *Astronomy and Astrophysics* 641 (2020) A6

Measurement	Value told	Primary paper
Circle searches for topology	every non-contractible loop through our location longer than 98.5 percent of the comoving diameter of the last-scattering surface	P. Petersen, Y. Akrami, C. J. Copi, A. H. Jaffe, A. Kosowsky, D. P. Mihaylov, G. D. Starkman, A. Tamosiunas, J. R. Eskilt, Ö. Güngör, S. Saha, Q. Taylor, "Cosmic topology. Part I. Limits on orientable Euclidean manifolds from circle searches", *Journal of Cosmology and Astroparticle Physics* 2023 (01) 030
Ratio of dark to ordinary matter	5.370 ± 0.048 (South Pole Telescope, Atacama Cosmology Telescope and Planck combined); told as within about a tenth of a percent of $6 - 2/\pi$	E. Camphuis and others, *Physical Review D* 113 (2026) 083504, as in Chapter 1

Chapter 24. Is There Another You?

The principle of identity: what no comparison can distinguish, in any way at all, is one thing and not two. It is stated in *The Last Turtle*, Chapter 25 ("Two Atoms in an Empty Universe"), Section VI, and in the form "what no comparison can distinguish, in any way at all, even in principle, is one thing and not two" in *The Quantum Passage*, Chapter 8, Section VI, as *The Matter We Know* quotes it. Its standing in those books: a principle of the ground (the account's starting principle about sameness), from which *The Last Turtle* derives exclusion for content and addition for context.

The principle stated exactly, with its scope: two things are one when, for every possible comparison and for every thing whatever, the two themselves included, the comparison of the first with that thing gives the same verdict as the comparison of the second with that thing. It is stated in *At the Edge of Reality*, Chapter 11 ("Every Ending Is the Same Ending"), sections "The Principle" and "Stated Exactly"; its standing there is a prin-

ciple of comparison, with its scope stated by the book (it counts every possible comparison, and a comparison registers what reaches it, never what it only predicts). In words first: a thing's pattern of verdicts is the list of what every comparison finds when it sets that thing beside every other thing, and two things are one exactly when their lists agree. In symbols: for things a and b, $a = b$ if and only if, for every possible comparison C and every thing x, $C(a, x) = C(b, x)$. Read aloud: "a is b exactly when, for every comparison C and every thing x, the verdict of C on a and x is the verdict of C on b and x". The example of *At the Edge of Reality*, used in the chapter: "Two identical coins, one in each hand, are not one". *At the Edge of Reality* adds that sameness so stated is transitive (two patterns each the same as a third are the same as each other).

A copy of a person elsewhere is a second person, told apart at least by place. The claim that a copy of a person elsewhere is a second person is the principle of identity as stated, applied in the way that I apply the principle of identity to the two coins in *At the Edge of Reality*, Chapter 11. In both cases, place is the comparison that gives the two different verdicts.

The principle of existence: "Existence without any interaction whatsoever is indistinguishable from non-existence, and therefore is non-existence". It is stated in *Incommensuration*, Chapter 9 ("Each Axiom Derived Again"), Section I ("Axiom I: The Asymmetry of the Relational"), part "The Scope of the Derivation", where it follows from the principle of identity.

Regions beyond a horizon are further parts of one world: "Regions beyond a horizon interact with what is near them, so they exist; they are further parts of one world, and not another universe". It is stated in *Side by Side*, Volume Two, "The Structure and the Act" (the chapter on Max Tegmark), Section VI ("The Four Levels, Level by Level"), on the principle of existence. The same section states the agreement with Tegmark's Level I: "Tegmark's Level I is the same space, with the same laws, beyond our horizon", with the difference only in whether those regions are called an-

other universe; the same volume's register beside Tegmark, Section V ("Regions beyond every horizon: Levels I and II"), adds "Both accounts hold that space continues beyond our horizon".

Space is infinite for a registration up to the limit of distinguishability, and the open space counts as one whatever it is beyond the horizon. It is stated in *The Weight of Possibility*, Chapter 3, Section II ("The Count: Six Against One"). The steps there: the region a registration holds is the ball within its particle horizon; that horizon is "defined by a limit of comparison: 'the bound of what has been compared is the bound of the information available to the comparison'" (the inner words quoting *The Gravitational Passage*, Chapter 13, Section II); within the limit of comparison the ball cannot be told apart from a ball of an infinite flat space; by the principle of identity the two are one. "Counts as one" there is the count of one class: a ball has one independent class, and the count a registration makes of the open space is one, whatever space is beyond the horizon. Standing: derived from the principle of identity. Scope, as the book states it: the statement is made for a registration, a measurement made from inside, and it says nothing of the number of stars or people in the regions beyond every horizon. The same section records the circle searches of the microwave background (Petersen and others 2023: every closed path through our location that goes around the universe is longer than 98.5 percent of the diameter of the last-scattering surface), which Chapter 23 tells.

The different-constants multiverse is excluded: "The multiverse is excluded by the collection on a structural ground: one internal space, one vacuum, no landscape". It is stated in *Side by Side*, Volume Two, "The Open Future" (the chapter on George Ellis), Section VIII, Key Concepts, and argued in Section VI ("The Multiverse"), which quotes *The Compactification*, Chapter 2, Section VI ("the account has no flux sectors, and the landscape of flux vacua has no counterpart in it"). In plain words, from *What Comes After the Dark*, Chapter 4, sections "The Six Small Dimensions" and "No Threads, No Landscape": the action is the geometry alone, and no field is threaded through the six small dimensions, so there is no in-

teger to choose and there is one valley. The two quantities of the six that could change (overall size and the ratio of the radii), which *What Comes After the Dark* calls "settings", are fixed at the Planck scale, with radii of one Planck length (the sphere) and the square root of six Planck lengths (the four-dimensional factor); "One space, two settings, one held size and shape: the six have one vacuum". Standing: derived, given the identifications those books state (each factor homogeneous; every direction of the six bending by the Planck-scale amount), which *What Comes After the Dark* states in the first person. *Side by Side*, Volume Two, Tegmark chapter, Section VI, gives the three routes by which Level II is excluded: no long inflation ("there is no eternal inflation to make the regions"); one internal space (*The Compactification*, Chapter 2, Section IX); the cosmological constant given without selection (*The View from Inside*).

The cosmological constant is given without selection among universes: *The View from Inside*, Preface ("On the Purpose of This Book"), names the alternative ("one setting among countless others in a vast multiverse") and gives its own answer, the share of the vacuum's energy open to a comparison made from inside. The standing and values of the cosmological constant are those of Chapter 3 (observed energy density of empty space 2.52×10^{-47} GeV^4, as that Preface prints it; matter fraction 0.311 and cosmological-constant fraction 0.689 as *The Registered Predictions of Physics from Comparison; A Dated Record* (1 November 2026), Prediction 7, states them).

No long inflationary phase occurred: Prediction 13 of *The Registered Predictions of Physics from Comparison; A Dated Record* (1 November 2026), argued in *The Compactification*, Chapter 6, Section VIII, as *Side by Side*, Volume Two, Tegmark chapter, Section VIII, sets it out. Standing, as *The Compactification* states it: "The kind of this step is must , relative to the identification: if the identification of Section II holds, a long phase cannot have occurred". The identification is that of *The Compactification*, Chapter 6, Section II: the departures on the observed lengths (the first ripples) are the form of the content carried through the turn, to which the vacuum of the new epoch adds almost nothing. The one origin, which the corpus

books call the one domain (the ends of the interiors are one, *The Gravitational Passage*, Chapter 18), is a separate premise, and it answers the horizon problem: "The account therefore needs no inflationary phase for the horizon and flatness problems" (*The Gravitational Passage*, Chapter 18, Questions). A second route to the exclusion rests on the dark matter: "So the dark matter, too, requires that the observed ripples were not made by inflation" (*What the Beginning Left Behind*, Chapter 13). A shorter phase, which leaves the observed lengths outside the early horizon throughout, "is neither required nor excluded by the account" (*The Gravitational Passage*, Chapter 18, Questions).

The epochs follow one another in a single line, under one law, with no journey between the epochs: *What Comes After the Dark*, Chapter 9 ("What Returns") and Chapter 10 ("No Other Sky Along Any Path"). In *At the Edge of Reality*, Chapter 20, I add that there is one new epoch from all the black holes of an epoch together. The contrast with Smolin's branching family of universes is drawn in *What Comes After the Dark*, Chapter 9 (L. Smolin, "Did the universe evolve?", *Classical and Quantum Gravity* 9 (1992) 173). "Nothing of you crosses as you": *What Comes After the Dark*, Chapter 9, "What This Means for You"; developed in Chapter 28 of this book.

Many worlds keeps only evolution time and absorbs the finding into branching; its two difficulties (which branches; what the odds mean) are where the finding returns. It is stated in *Two Theories, One World*, Chapter 19 ("The Interpretations as Choices About Time"), section "Many Worlds" (the achievement, the two difficulties, and "On this account the debate is the finding asserting itself: odds are odds of findings, and an interpretation without findings must rebuild them from inside evolution") and the chapter's Key idea, after the section "The Pattern" ("many worlds keeps only evolution"). *Two Theories, One World* names Deutsch (1999) and Wallace (2012) as the arguments that a rational agent in a branching world should weigh branches by Born's rule. The technical form is in *The Quantum Passage*, Chapter 9, Section VIII (many worlds "eliminates measurement time entirely"), as *Side by Side*, Volume Two, Tegmark chapter, Section VI, quotes it.

No whole world is completely fixed by a law: "A whole world completely fixed by a law perfects symmetry and continuity together, whichever account describes it, and the theorem forbids that pairing". It is stated in *Physics Is Not Math*, Chapter 8 ("Physics Has the Arrow"), Section VII ("Three Grounds"), which names the many-worlds account of Hugh Everett and the pilot-wave theory of David Bohm as accounts that describe a whole world as completely deterministic. The step, as the same section gives it: complete determinism needs the same law carrying every state into its successor everywhere and at every time, which is symmetry perfected, and every state specified at every point with no gap, so that nothing sudden and nothing new enters between one state and the next, which is continuity perfected. Standing: a consequence of the Incommensuration Theorem, a structural fact about the nature of knowing: "Symmetry and continuity cannot both be applied, simultaneously and fundamentally, to any event or comparison; and neither can asymmetry and discontinuity". *The Registered Predictions of Physics from Comparison; A Dated Record* (1 November 2026) registers the exclusion as Prediction 28 ("no world is purely and completely deterministic"), as *Side by Side*, Volume Two, register beside Tegmark, Section V, quotes it.

Measured and calculated values told in the chapter, with their primary papers.

Measured or calculated value told in the chapter	**Value**	**Primary paper**
Upper limit on the ratio r (read "r", the tensor-to-scalar ratio) of the power in primordial waves of the metric (tensor modes) to the power in the primordial density departures (scalar modes), from Planck PR4 data combined with BICEP/ Keck 2018 data and baryon acoustic oscillations	$r < 0.032$	M. Tristram and others, "Improved limits on the tensor-to-scalar ratio using BICEP and Planck data", *Physical Review D* 105 (2022) 083524; arXiv: 2112.07961

Measured or calculated value told in the chapter	Value	Primary paper
Tegmark's calculation for inflation on potentials with many minima, in its limit of high energy (inflation at a high characteristic energy scale; at fixed scalar power the tensor power grows in proportion to the energy density during inflation)	$r \approx 0.15$ (read "r about 0.15"), spectral index $n_s \approx 0.96$	M. Tegmark, "What does inflation really predict?", *Journal of Cosmology and Astroparticle Physics* 2005, issue 04, article 001; arXiv:astro-ph/0410281

The authors' figures, given as theirs: the odds of you, one in $2^{10^{15}}$ (two raised to the power ten to the fifteen; the ebook text prints "21,000,000,000,000,000"); the cosmological constant, 10^{-122} (printed "10-122"); about 250 billion stars in our galaxy (*Frequently Asked Questions About the Universe*, ch. 3). The pocket universes with other values of the basic numbers: *We Have No Idea*, ch. 14, "Maybe There Are Lots of Universes", and ch. 16, "How Will We Know If We Are Done?".

The chapter also draws on: *Side by Side, Volume Two*, the chapter on Max Tegmark, Section VI.

Chapter 25. Why Can't We Teleport?

Every corpus claim of Chapter 25 is listed below with the book, chapter and section that carry it, and with its standing as that book states it. The books are *The Quantum Passage* (ISBN 979-8-90710-073-2, DOI https://doi.org/10.67291/TKSP9901), *Why the Quantum Is the Way It Is* (ISBN 979-8-90710-417-4, DOI https://doi.org/10.67291/NNXH9990), *The Quantum Bridge* (ISBN 979-8-90710-107-4, DOI https://doi.org/10.67291/NHFX3629), *What Cannot Be* (ISBN 979-8-90710-415-0, DOI https://doi.org/10.67291/KHIY2463), *The Last Turtle* (ISBN 979-8-90710-215-6, DOI https://doi.org/10.67291/ONZV8400), *What Comes After the Dark* (ISBN 979-8-90710-431-0, DOI https://doi.org/10.67291/IGAM1407), *The Matter We Know*, Volume One (ISBN 979-8-90710-079-4, DOI https://doi.org/10.67291/BSFF2866), *At the Edge of Reality* (ISBN

979-8-90710-058-9, DOI https://doi.org/10.67291/BWNG7504), and *Incommensuration* (ISBN 979-8-90710-063-3, DOI https://doi.org/10.67291/ARTV2404).

The claims, with their places and standing

No process makes an exact copy of an arbitrary quantum state (the no-cloning theorem). Place: *The Quantum Passage*, Ch. 10, "Quantum Information from the Comparison Algebra", Sec. III and Sec. IV; *Why the Quantum Is the Way It Is*, Ch. 15, "Entanglement and Bell's Limit", section "What Can Be Copied". Standing: derived; the linearity the theorem needs is derived from the comparison algebra, and the theorem then follows by the standard argument of Wootters and Zurek (1982). In words first: the construction of Gelfand, Naimark and Segal applied to the comparison algebra gives a space of states on which every operation of the algebra acts linearly, and so does every evolution that keeps sizes; a linear map cannot send every state to two copies of itself. In symbols: write A_F (read "A sub F") for the comparison algebra, the direct sum of the complex numbers, the quaternions and the three-by-three complex matrices, $A_F = \mathbb{C} \oplus \mathbb{H} \oplus M_3(\mathbb{C})$. The construction gives a Hilbert space H_F (read "H sub F") and a linear representation π (read "pi") of A_F on it. Suppose a unitary U (a change that keeps sizes) and a blank state $|0\rangle$ (read "ket zero") satisfied $U(|\psi\rangle|0\rangle) = |\psi\rangle|\psi\rangle$ (read "U of psi, zero equals psi, psi") for every state $|\psi\rangle$. For $|\psi\rangle = |0\rangle$ and $|\psi\rangle = |1\rangle$ this gives $|0\rangle|0\rangle$ and $|1\rangle|1\rangle$; by linearity the sum state $(|0\rangle + |1\rangle)/\sqrt{2}$ (read "zero plus one, over root two") is sent to $(|0\rangle|0\rangle + |1\rangle|1\rangle)/\sqrt{2}$, an entangled state, whereas a copier would have to give the product $(|0\rangle + |1\rangle)(|0\rangle + |1\rangle)/2$. The two differ, so no such U exists. In the chapter the two states are "upright" and "level" polarization, and the sum state is polarization at forty-five degrees. In the chapter I show the sum with a walk to the north-east (a step north and a step east in equal parts). I show linearity with a turn of the map, which turns the walk by turning each step. Both pictures are my own pictures of the vector sum and the linear map stated above.

The outcomes of one question (one basis of perfectly distinguishable states; in the words of those books, one setting) can be copied, and a state that lies between them cannot be, because a comparison finds only the outcomes of its own question and the finding replaces the state between them. Place: *The Quantum Passage*, Ch. 10, Sec. III ("States that are outcomes of one setting can be copied, as the CNOT copies $|0\rangle$ and $|1\rangle$, which is why classical records can be copied"); *Why the Quantum Is the Way It Is*, Ch. 15, "What Can Be Copied". Standing: derived, as a statement of which states the theorem excludes; the books use a silver atom after a magnet along z, and the chapter uses a photon after a polarizing filter, which is the same case in another two-state system.

No-cloning is the information-theoretic expression of the fact that comparison is constitutive: "a comparison makes its finding, and does not only report something already there". Place: *Why the Quantum Is the Way It Is*, Ch. 15, "What Can Be Copied"; *The Quantum Passage*, Ch. 10, Sec. III. Standing: stated in both books as the meaning of the derived result.

A copier of every state would treat the state purely as content; the state is also context, and content and context cannot be separated, so the attempt to extract pure content disturbs the state. Place: *The Quantum Passage*, Ch. 10, Sec. III, "Cloning and the six intrinsics"; *Why the Quantum Is the Way It Is*, Ch. 15, "What Can Be Copied". Standing: stated as the reason for the theorem in the terms of the six intrinsics of comparison, resting on the inseparability of content and context (*The Quantum Passage*, Ch. 3, Sec. III). In Chapter 25 of this book I quote *The Quantum Passage*, Ch. 10, Sec. III, for the state as context: it "defines the framework within which measurement outcomes are possible". Content and context are used in the sense this book's Chapter 1 gives them: the content of a finding is what it finds, and the context is where the content is found.

A reading that learns anything about which of two states, neither equal nor orthogonal, is held changes at least one of them. Place: *The Quantum Bridge*, Ch. 4, "Quantum Error Correction Across the Bridge", Sec. VII, paragraph "Copying, reading and moving a state". Standing:

proved there from the preservation of inner products. In words first: if the reading left both states unchanged, the reading device would end in the same state whichever was held, and so would learn nothing. In symbols: let the reading device start in $|e\rangle$ (read "ket e"); if $U(|\psi\rangle|e\rangle) = |\psi\rangle|e_\psi\rangle$ and $U(|\varphi\rangle|e\rangle) = |\varphi\rangle|e_\varphi\rangle$ (read "e sub psi", "e sub phi"), then, since U keeps inner products, $\langle\psi|\varphi\rangle = \langle\psi|\varphi\rangle\langle e_\psi|e_\varphi\rangle$, and with $\langle\psi|\varphi\rangle$ (read "the inner product of psi and phi") neither zero nor of size one, $\langle e_\psi|e_\varphi\rangle = 1$.

Teleportation moves an unknown state from sender to receiver by a joint measurement in a basis of four entangled states, two classical bits sent over an ordinary channel, and one of four known corrections; the state arrives only when the two bits do, at no more than the speed of light; the entangled pair is used up; and the sender no longer holds the state, so nothing is copied. Place: *The Quantum Bridge*, Ch. 4, Sec. VII, paragraph "Copying, reading and moving a state", citing Bennett, Brassard, Crépeau, Jozsa, Peres and Wootters (1993) and Bouwmeester, Pan, Mattle, Eibl, Weinfurter and Zeilinger (1997). Standing: stated with the protocol and its proof; the protocol itself is standard (Bennett and others 1993). In words first: the sender's joint measurement has four outcomes, which take two bits to name, and each outcome leaves the receiver's half holding the unknown state turned by one known gate. In symbols: the four gates are the identity I, the bit flip X, the phase flip Z, and X and Z together; the receiver applies the inverse of the gate the two bits name. Before the bits arrive, the receiver's half alone is in the completely mixed state I/2 (read "the identity over two"), whatever the unknown state; this is standard quantum mechanics and is stated in the chapter in words ("gives each answer to any question half the time").

The limit on the arrival is the edge of comparison: "the limit of every causal signal". Place: *The Quantum Bridge*, Ch. 4, Sec. VII (the quoted words); the edge of comparison as glossed in this book's Chapter 15. Standing: stated.

Two electrons are always found exactly alike, whatever their origin. Place: *The Matter We Know*, Volume One, Ch. 1, "From Kinds to Wholes", Sec. II, "The Kinds and Their Masses". Standing: stated as a finding about the kinds; the closed list of kinds is derived in *The Story of the Particles*, as that section reports.

A thing is classical when it can be virtualized, that is, when a model of it can be built that behaves as the original does for every purpose that matters; what cannot be replicated without destroying the original is quantum. Place: *The Last Turtle*, Ch. 26, "What Can Be Modeled", Sec. III and Sec. IV. Standing: definition of the classical, made in that chapter ("That is the single defining feature of the classical"). In Chapter 25 of this book I apply the definition of the classical to a cup of coffee and the recipe for the coffee. That application of the definition is my own picture.

Two things are one only when no comparison anywhere tells them apart; two identical coins, one in each hand, are two. Place: *At the Edge of Reality*, Ch. 11, "Stated Exactly"; the principle of identity as this book's Chapter 24 glosses it. Standing: the principle of identity, stated exactly there in terms of patterns of verdicts.

Computation, perfected as computation, is symmetry with discontinuity applied absolutely; the first-person stance is continuity with asymmetry; a continuity cannot be composed of purely symmetric steps, as a curve cannot be composed of tiles; the Incommensuration Theorem, which forbids perfecting symmetry with continuity, therefore forbids perfecting computation with subjectivity; "A person is not a very large file". Place: *What Cannot Be*, Ch. 22, "Why No Computation Is Everything", sections "Why a Computation Cannot Be What Consciousness Is" and "A Person Is Not a File"; *The Last Turtle*, Ch. 33, "Against Computationalism", Sec. VII, "Mind Uploading Is a Category Error". Standing: a structural exclusion, in the words of *The Last Turtle*, Ch. 33, Sec. VIII ("The exclusions ... are structural exclusions, resting on that binding and on the theorem"); the first-person stance as asymmetry with continuity is the second surviving mode of the theorem (*Incommensuration*, Ch. 6, Sec. XI). In symbols, with S for symmetry, C for continuity, A for asymmetry and D for discon-

tinuity: the theorem excludes S and C perfected together, and A and D perfected together; the two surviving compounds are S with D (the third person, content) and A with C (the first person, context).

Experience has three conditions that experience cannot do without: something new arriving that nothing before the arrival fixed, time running one way, and a point of view from inside; computation is what remains when the three conditions are factored out. Place: *What Cannot Be*, Ch. 22, "A Person Is Not a File" and "What Computation Takes Away". Standing: stated; the three are the bound triple (hard randomness, directed time, subjectivity), derived in that chapter as mutually requiring.

A device that carries a description of a person carries a map of that person, and the person is not in it; the ramp and the staircase of tiles. Place: *What Comes After the Dark*, Ch. 10, "No Message, No Record, No Identity". Standing: stated; in that book the first-person stance is matched to the ramp as a first-person identification ("I identify the first-person stance, the inside of a life, with the ramp"), and the chapter uses the ramp as the picture of that stance.

A system can be built that behaves as a person behaves, to any degree of behavioral faithfulness, and it would not be that person, or any person, because being a person is not exhausted by any exterior description. Place: *What Cannot Be*, Ch. 22, "A Person Is Not a File"; *The Last Turtle*, Ch. 33, Sec. VII. Standing: stated as the scope of the exclusion.

Whether a thing has a self depends on whether the thing is a physical process that makes comparisons in the world, with an inside. Whether a thing has a self does not depend on what program the thing runs. In the sense of copying, self-identity is quantum and not classical. Identity in the sense of a single unitary consciousness is not something a copy can carry. Place: *The Last Turtle*, Ch. 26, Sec. IV, "What Cannot Be Copied", and Sec. IX, "Summary". Standing: stated, with the no-cloning theorem (Wootters and Zurek 1982; Dieks 1982) as the physical correlate.

Mind uploading, and so the request to send a person as information, is a category error and not an engineering problem: impossible in principle, and therefore in all future practice. Place: *What Cannot Be*, Ch. 22, "A Person Is Not a File"; *The Last Turtle*, Ch. 33, Sec. VII and Sec. VIII. Standing: structural exclusion. In Chapter 25 of this book I apply the exclusion of mind uploading to the authors' scanned and transmitted description. In the corpus books I state the exclusion of a description of a person carried by a device or a computation.

Measured values told in the chapter, with their primary papers

Teleportation of the polarization of a photon, Innsbruck: photons of wavelength 788 nanometers from type II parametric down-conversion, pumped by ultraviolet pulses of 200 femtoseconds at 76 megahertz; one of the four Bell states (the antisymmetric state, ψ^-, read "psi minus") identified by a coincidence of two detectors behind a beam splitter, so teleportation succeeded in a quarter of the cases; input polarizations $+45°$, $-45°$, $0°$, $90°$ and circular. Primary paper: D. Bouwmeester, J.-W. Pan, K. Mattle, M. Eibl, H. Weinfurter and A. Zeilinger, "Experimental quantum teleportation", *Nature* 390 (1997), 575 to 579, published 11 December 1997.

Ground-to-satellite teleportation: single-photon states teleported from the ground station at Ngari, Tibet (altitude 5,100 meters), to the satellite Micius (launched 16 August 2016), over distances from about 500 to 1,400 kilometers; average fidelity 0.80 ± 0.01 over six input states, which the paper states is "well above the classical limit". Primary paper: J.-G. Ren and 31 co-authors, "Ground-to-satellite quantum teleportation", *Nature* 549 (2017), 70 to 73, published 7 September 2017. The fidelity F of a received state ρ (read "rho") to the sent pure state $|\psi\rangle$ is $F = \langle\psi|\rho|\psi\rangle$ (read "the expectation of rho in psi"): the probability that a test for the sent state, made on the received photon, answers yes; the chapter gives 0.80 in words as "about four times in five". The classical limit for a single two-state system is an average fidelity of two thirds, the best that measuring the unknown

state and preparing a new one from the result can reach without entanglement: S. Massar and S. Popescu, "Optimal extraction of information from finite quantum ensembles", *Physical Review Letters* 74 (1995), 1259 to 1262.

The theorem and the protocol: W. K. Wootters and W. H. Zurek, "A Single Quantum Cannot Be Cloned", *Nature* 299 (1982), 802 to 803; D. Dieks, "Communication by EPR Devices", *Physics Letters A* 92 (1982), 271 to 272; C. H. Bennett, G. Brassard, C. Crépeau, R. Jozsa, A. Peres and W. K. Wootters, "Teleporting an unknown quantum state via dual classical and Einstein–Podolsky–Rosen channels", *Physical Review Letters* 70 (1993), 1895 to 1899.

Chapter 26. Are Humans Predictable?

Each line below gives a claim of the chapter, the corpus book, chapter and section that carries it, and its standing as that book states it.

Claim of the chapter	Where the corpus carries it	Standing as the book states it
Causation is a one-way relation between findings, in which the first makes a difference to the second; science establishes causation every day and never establishes determinism.	*Two Theories, One World*, Ch. 18, "Causation Established, Determinism Never"; *Causality Without Determinism*, Ch. 1, Sec. VI (causation as the one-way, unbroken order at each event, the cone of precedence).	Stated as a consequence of what a finding is (one comparison from one place inside the world); derived.

Claim of the chapter	Where the corpus carries it	Standing as the book states it
Determinism is the claim that a complete description of everything at one moment fixes everything at every other moment; Laplace's intellect (1814) is its picture.	*Two Theories, One World*, Ch. 18; *Causality Without Determinism*, Ch. 1, Sec. II (the definition of *An Immanent Metaphysics*: a complete and absolute specification of all values of the three content metrics for all values of the three context metrics); *Physics Is Not Math*, Ch. 11, Sec. III.	Definition.
Determinism asks for symmetry and continuity perfected together, the pair the Incommensuration Theorem forbids; no world is purely and completely deterministic.	*Causality Without Determinism*, Ch. 1, Secs. VIII and IX (quoting *Incommensuration*, Ch. 15, Sec. IV); *Physics Is Not Math*, Ch. 8, Sec. VII.	Derived from the Incommensuration Theorem.
Pure randomness, asymmetry and discontinuity perfected together, is excluded by the theorem's second clause; every world lies between determinism and pure randomness and is causal to a non-zero degree (the non-polarization principle).	*Causality Without Determinism*, Ch. 1, Secs. VIII and IX; Ch. 2, Secs. I to III (the player piano, the radio hiss, the music).	Derived.
A computation is determinism within its own discrete states; the determinism of a rule is run by a physical process in a world, and what is impossible is a whole world fixed completely by a law, whichever account describes it.	*Physics Is Not Math*, Ch. 8, Sec. VII ("Three Grounds"); *Causality Without Determinism*, Ch. 5, Sec. II.	Derived.

Claim of the chapter	Where the corpus carries it	Standing as the book states it
Soft randomness is unpredictability from a limit of knowledge; hard randomness is an outcome that no description of what came before fixes, however complete, for any comparer; the single quantum outcome is its plainest instance, and atomic decay shows it directly.	*What Cannot Be*, Ch. 8, "Two Meanings of Random" and "One Atom, One Avalanche, Three Balls"; *Causality Without Determinism*, Ch. 5, Sec. V (quoting *Measurement*, Ch. 14, Sec. I).	Definitions; "Hard randomness is the irreducible residual guaranteed by the ICT", the ICT being the Incommensuration Theorem (*Incommensuration*, Ch. 8, Sec. X, as quoted in *Causality Without Determinism*, Ch. 5, Sec. V).
The radioactive lump: the half-life is exact for the many, and which atom goes next is fixed by nothing.	*Two Theories, One World*, Ch. 18, "An Open Future Is Real"; *Causality Without Determinism*, Ch. 1, Sec. I (the Geiger counter).	Measured regularity of the many; openness of each outcome derived.
A law that gives the odds of findings, with a direction from one finding to the next, is causal without being deterministic; quantum theory has had that form from Born onward.	*Two Theories, One World*, Ch. 18, "Causation Established, Determinism Never".	Stated as the correct form of a law made of findings.

Claim of the chapter	Where the corpus carries it	Standing as the book states it
The free will theorem: if the experimenters' choices are not determined by prior information, the particles' responses are not either; four assumptions, each supported by established physics and practice, and together among the most securely established starting points in the history of physics; the experimenter's freedom secured by the Incommensuration Theorem and, independently, by the presupposition of every experiment.	*Causality Without Determinism*, Ch. 3, Secs. I to III; *What Cannot Be*, Ch. 9.	A mathematical result (Conway and Kochen); the strength of the assumptions as Ch. 3, Sec. II states it; the independence of the two grounds stated in Ch. 3, Sec. III.
Two independent routes to one result (the free will theorem, and the Incommensuration Theorem), each enough alone, are stronger together than either alone, as a cable is stronger than its strongest strand.	*Causality Without Determinism*, Ch. 3, Sec. VI; the cable that holds when one strand is cut, *Physics Is Not Math*, Ch. 12, Sec. I.	Stated (each route alone is enough).
The catastrophic theorem of determinism: indeterminism anywhere means no scale is completely deterministic; amplification (Lorenz 1963) is the physical process that magnifies small differences, and it carries a microscopic outcome up.	*Causality Without Determinism*, Ch. 3, Sec. VI.	Derived from the definition of determinism; amplification as its physical picture.

Claim of the chapter	Where the corpus carries it	Standing as the book states it
Many worlds gives up the single outcome the free will theorem speaks of; a whole world completely fixed by a law perfects symmetry and continuity together whichever account describes it.	*Causality Without Determinism*, Ch. 3, Sec. IX; *Physics Is Not Math*, Ch. 8, Sec. VII.	Derived.
Superdeterminism asks for everything determinism asks for and more, and is excluded by the Incommensuration Theorem a fortiori; the rational position is that indeterminism is real.	*Causality Without Determinism*, Ch. 3, Secs. VII and VIII.	Derived (a fortiori from the theorem); also excluded as removing the conditions under which any observation is evidence.
The brain operates near criticality, so that microscopic indeterminacy enters causal chains that reach the macroscopic scale and bear on choice; the mesoscopic behavior of a brain is modeled by approximately deterministic computation, and the single choice carries indeterminacy no such model fixes.	*The Last Turtle*, Ch. 15, Sec. VIII; *Causality Without Determinism*, Ch. 5, Sec. IX.	Stated by the book; the physical support is the measurement of Beggs and Plenz (2003), which the book cites with the words "as the study of neuronal avalanches suggests".

Claim of the chapter	Where the corpus carries it	Standing as the book states it
The criticality of the brain is the physical circumstance under which the relation of the inside to the outside of an undetermined outcome is expressed in us; it is not that relation itself. *The Last Turtle* names the relation as the subjective being the interior face of a process that, from the exterior, presents as entanglement and hard randomness; *Causality Without Determinism* names it as the bound triple (the arrow of time, hard randomness and the subjective, which Chapter 27 sets out).	*The Last Turtle*, Ch. 15, Sec. VIII; *Causality Without Determinism*, Ch. 5, Sec. IX.	Stated.
People are fairly predictable; however good a compression of a person's behavior, a residue remains that cannot be told from randomness, and that residue is the person's choosing.	*What Cannot Be*, Ch. 7, "From Outside, Chance; From Inside, Choice"; *The Last Turtle*, Ch. 14, Sec. III.	An argument from observation (the compression argument).
Choice and causality are conjugate, and at the scale of a person their proportion varies from act to act: a habit runs almost wholly as causality; a turning point is causality bent almost wholly by choice; "the life of a person is the movement of that proportion".	*Causality Without Determinism*, Ch. 6, Sec. IV; *What Cannot Be*, Ch. 7, "Choice and Cause at Every Scale".	Stated (conjugacy of choice and causality).

Claim of the chapter	Where the corpus carries it	Standing as the book states it
Hard randomness and choice are one event described from two positions: from outside (the omniscient position, the position of law) a gap without pattern or meaning; from inside (the transcendent position, of the one engaged) a choice, meaningful to the process from which it came; neither description replaces the other. A role belongs to a position of description and never to a thing. The particle's undetermined response is choice described from the position of the process from which it came.	*Causality Without Determinism*, Ch. 5, Sec. V; *What Cannot Be*, Ch. 7, "From Outside, Chance; From Inside, Choice" (the modal rotation), and Ch. 8, "Chance From Outside, Choice From Inside"; *The Last Turtle*, Ch. 14, Sec. IV (by the principle of identity).	Derived (a consequence of the theorem and the principle of identity).
Choice lies between the completely random (noise) and the completely determined (execution); a choice is potentiality, selection and consequence; the one who chose is responsible and could have chosen otherwise.	*Causality Without Determinism*, Ch. 6, Secs. III and VIII; *What Cannot Be*, Ch. 7, "Decision, Choice and Creation".	Stated (from the definition of choice in *An Immanent Metaphysics*).

The Incommensuration Theorem, as the chapter uses it, in the short form of *Incommensuration*, Chapter 2, Section VI, quoted in *Causality Without Determinism*, Chapter 1, Section VII: "Symmetry and continuity cannot both be applied, simultaneously and fundamentally, to any event or comparison; and neither can asymmetry and discontinuity".

The free will theorem in its authors' terms. Conway and Kochen named their assumptions SPIN, TWIN and FIN in 2006, and replaced FIN with the weaker MIN in 2009. The chapter's first assumption is what SPIN

and TWIN take from quantum mechanics; its second is the locality half of MIN, and its fourth the freedom half of MIN; Conway and Kochen give the third, no backward causation, no name of its own, since it is part of what they take for granted in their assumptions of locality and freedom (*Causality Without Determinism*, Chapter 3, Section II). SPIN: for a spin-one particle, the squared spin components measured along any three mutually perpendicular directions are 1, 0 and 1 in some order. TWIN: two such particles can be prepared so that the squared spin components measured along the same direction agree. MIN: the experimenters' choices of direction, made at spacelike-separated places (no signal at light speed can pass between them), are free, and neither choice affects the other side's response. The conclusion: the particles' responses are not functions of information available to them before the measurement.

The brain and quantum coherence. The account of the chapter depends on no specific biological mechanism, and it needs no sustained entanglement in the brain; its claim holds for any system in which novelty enters, time is directed, and there is a point of view (*The Last Turtle*, Ch. 15, Sec. VIII; *Causality Without Determinism*, Ch. 5, Sec. IX). It is distinct from the hypothesis of orchestrated objective reduction of Stuart Hameroff and Roger Penrose (1996), which places consciousness in quantum coherence, a quantum state kept whole and undisturbed by its surroundings, sustained in the microtubules of the brain's cells.

Lorenz's numbers, from his own account (*The Essence of Chaos*, 1993, p. 134, as quoted by Motter and Campbell, 2013): the restarted run first repeated the old values, then differed by one and then several units in the last decimal place, and the differences "more or less steadily doubled in size every four days or so", until all resemblance disappeared in the second month of model weather. The 1963 paper studies a three-variable model of convection (in symbols, the variables X, Y and Z, read "ex", "why" and "zee") and finds that its nonperiodic solutions are unstable to small modifications of the initial state.

Measured values told in the chapter, with their primary papers.

Measurement	Value	Primary paper
Sensitivity of a deterministic model to its initial state	Slightly differing initial states evolve into considerably different states; prediction of the sufficiently distant future impossible unless the present conditions are known exactly.	E. N. Lorenz, "Deterministic Nonperiodic Flow", *Journal of the Atmospheric Sciences* 20 (1963) 130–141.
Loophole-free Bell test, electron spins in diamond, Delft	Separation about 1.3 kilometers; Bell inequality violated (CHSH value about 2.42, as *Why the Quantum Is the Way It Is* reports it).	B. Hensen and others, "Loophole-Free Bell Inequality Violation Using Electron Spins Separated by 1.3 Kilometres", *Nature* 526 (2015) 682–686.
Loophole-free Bell test with entangled photons, Vienna	Bell inequality violated with detection and locality loopholes closed.	M. Giustina and others, "Significant-Loophole-Free Test of Bell's Theorem with Entangled Photons", *Physical Review Letters* 115 (2015) 250401.
Loophole-free Bell test with entangled photons, Boulder	Bell inequality violated with detection and locality loopholes closed.	L. K. Shalm and others, "Strong Loophole-Free Test of Local Realism", *Physical Review Letters* 115 (2015) 250402.
Neuronal avalanches in rat cortex (organotypic cultures and acute slices, 60-channel multielectrode array)	Avalanche sizes follow a power law with exponent about $-3/2$ (in words, the number of avalanches falls as the size raised to the power minus three halves); branching parameter close to the critical value 1 (each active site sets off, on average, about one further site).	J. M. Beggs and D. Plenz, "Neuronal Avalanches in Neocortical Circuits", *Journal of Neuroscience* 23 (2003) 11167–11177.

Works named in the chapter and in this part, besides the papers above: J. Conway and S. Kochen, "The Free Will Theorem", *Foundations of Physics* 36 (2006) 1441; J. Conway and S. Kochen, "The Strong Free Will Theorem", *Notices of the American Mathematical Society* 56 (2009) 226; J. S. Bell, "On the Einstein Podolsky Rosen Paradox", *Physics* 1 (1964) 195; P.-S. Laplace, *Essai philosophique sur les probabilités* (Paris, 1814); S. Hameroff and R. Penrose, "Orchestrated Reduction of Quantum Coherence in Brain Microtubules", *Mathematics and Computers in Simulation* 40 (1996) 453; E. N. Lorenz, *The Essence of Chaos* (Seattle: University of Washington Press, 1993), ISBN 0-295-97270-X.

The coming measurement that bears on this chapter (Prediction 25 of the dated record, that the statistics of quantum theory hold, including in the tests proposed for superdeterminism) is listed in "What the Coming Measurements Will Find".

Chapter 27. Do We Live in a Computer Simulation?

In Chapter 27 of this book I give two routes to my answer, and a third route stands beside the two routes in the corpus. The first route runs through the bound triple and gives the fenced region; the second runs through the continuum and gives the difference of kind; *Physics Is Not Math* adds a route through determinism and the cross-modal principle. *What Cannot Be*, Ch. 21, "Randomness, Halving, and the Smallest Length", states of the first two: "The two roads arrive at the same place; neither road rests on any step of the other, and each road is the stronger for that". The same book, section "Symmetry, Continuity and the Self", places both roads under one theorem: "the two roads are the two survivors of the same theorem, seen from opposite ends".

Each claim of the chapter is listed below with the book that carries it and its standing as that book states it.

Claim of the chapter	Where the corpus carries it	Standing as the book states it
A computation is deterministic: given its present state and its rule, its next state is fixed, and run twice from the same start, it gives the same sequence.	*Measurement*, Ch. 14, Sec. X; *Physics Is Not Math*, Ch. 8, Sec. IV; *What Cannot Be*, Ch. 21, "A Simulated World Is a Region of the One World" (after Turing 1936).	Definition (the definition of a deterministic process).
A pseudo-random generator is a fixed rule whose output looks random and is set by its starting value; it gives no hard randomness.	*Causality Without Determinism*, Ch. 5, Sec. VII; *Physics Is Not Math*, Ch. 8, Sec. IV.	Definition, and a consequence of determinism.
A computation's list of states is an indexing and can be read backward as readily as forward; a computation has no arrow of its own; the arrow its running shows is lent by the physical process that carries it out.	*Physics Is Not Math*, Ch. 8, Secs. IV and V; *Causality Without Determinism*, Ch. 5, Sec. II.	Argued from what a computation is.
Whatever happens in this world draws its information from earlier states, through cause and effect, and from hard randomness entering at the inner edge of the domain, which sensitivity magnifies.	*What Cannot Be*, Ch. 21, "One Level Only".	Argued. The application to the steam of the reader's cup is this chapter's example of the book's storm.

Claim of the chapter	Where the corpus carries it	Standing as the book states it
The bound triple (the arrow of time, hard randomness, the subjective) is distinct, inseparable and non-interchangeable.	*Causality Without Determinism*, Ch. 5, Secs. III and IV; *Measurement*, Ch. 14, Sec. VI; *Incommensuration*, Ch. 8, Sec. X.	Derived from the Incommensuration Theorem, and found in physics (every interpretation of quantum mechanics keeps the three together or drops them together).
Each of the three requires the next. The arrow requires hard randomness: a direction needs the next moment to hold something the present does not. Hard randomness requires the subjective: a third-person description cannot tell an outcome no prior state fixes from one fixed and unknown, and the difference lies in the finding, made by a comparer. The subjective requires the arrow: perceiving, remembering and anticipating each run one way.	*Measurement*, Ch. 14, Sec. VI; reported in *Causality Without Determinism*, Ch. 5, Sec. IV.	Argued, link by link. The friend's story, the paper roll and the timed click are this chapter's pictures; the corpus pictures the triple with a piece of music heard for the first time (*Causality Without Determinism*, Ch. 5, Sec. III).

Claim of the chapter	Where the corpus carries it	Standing as the book states it
A computation on ordinary digital machinery cannot be what consciousness is; strong computationalism is false.	*Causality Without Determinism*, Ch. 5, Sec. VI; *What Cannot Be*, Ch. 22, "Why a Computation Cannot Be What Consciousness Is".	Argued from the theorem (first clause) and the bound triple. The match of Bostrom's assumption of substrate-independence with strong computationalism is this chapter's comparison.
A simulated world with pseudo-random randomness has an indexing and no arrow, and so no subjective: a program running on a machine with no one in it.	*Measurement*, Ch. 14, Sec. X; *What Cannot Be*, Ch. 21.	Argued from the bound triple. The chapter's walk of why the machine's running lends that world no arrow (the running reads out states already fixed) applies the first link of the triple, *Measurement*, Ch. 14, Sec. VI.
A simulated world fed hard randomness from the world that runs it shares that world's randomness, arrow and subjectivity, and is a restricted region of the one world (this book's word: a fenced region).	*Measurement*, Ch. 14, Sec. X; *Causality Without Determinism*, Ch. 5, Sec. VIII (third argument); *What Cannot Be*, Ch. 21; *Physics Is Not Math*, Ch. 8, Sec. VII (third ground).	Argued from the bound triple; the hypothesis "that we are real subjects in a world that is not real" is "excluded by the structure of comparison, in principle and therefore in all future practice" (*Causality Without Determinism*, Ch. 5, Sec. VIII).

Claim of the chapter	Where the corpus carries it	Standing as the book states it
Bostrom's count treats each simulation as a separate world with its own observers.	*Measurement*, Ch. 14, Sec. X; *Causality Without Determinism*, Ch. 5, Sec. VIII; *What Cannot Be*, Ch. 21.	Argued (a reading of Bostrom 2003 against the bound triple).
The principle of identity: what no comparison can distinguish is one; a simulation no conceivable test could tell from a continuous world would make the hypothesis empty, and a test in principle makes the two different in kind.	*The Basis of Physics*, Essay 18, Sec. II; *What Cannot Be*, Ch. 21, "The Principle of Identity".	A consequence of what comparison is (stated there as not a law of physics).
No list reaches the continuum; everything a computation could ever produce can be listed.	*What Cannot Be*, Ch. 21, "What No List Can Hold" and "The Consequence, and the Amplifier"; *The Basis of Physics*, Essay 18, Secs. V and VI.	Theorem of mathematics (Cantor 1874, 1891); the listability of every output of a Turing machine is a standard fact (Turing 1936).
The arena of space and time has no least step: sameness and difference are inseparable in every comparison, so every difference between two positions holds some sameness and can be split by a finer comparison; a least step would be a difference with no sameness within it.	*What Cannot Be*, Ch. 21, "The Arena Has No Least Step" (full derivation in *Incommensuration*); *The Unquantized Arena*, Ch. 6, Sec. IV, Proposition 6.3.	Derived from what comparison is, and found by physics at every scale yet probed. The chapter joins this step to Chapter 10's form of the same reason (a least step would be a break in the arena).

Claim of the chapter	Where the corpus carries it	Standing as the book states it
As a very general rule, real systems are sensitive to how they start; sensitivity turns the structural gap into two different histories; no fixed precision follows a sensitive system forever.	*What Cannot Be*, Ch. 21, "The Consequence, and the Amplifier"; *The Basis of Physics*, Essay 18, Sec. VI.	Argued; the order of quantifiers is stated in the book (name a time and a closeness first, and some precision suffices; name a precision first, and some time carries the simulation as far as the system can go).
A model reaches what it describes as closely as one wishes and never contains it; every computation carried out is a physical process, and physics needs no computation.	*Physics Is Not Math*, Ch. 11, Secs. I and V; Ch. 8, Sec. VI; Ch. 5, Sec. V; *Measurement*, Ch. 8, Proposition 8.1 (the cross-modal principle).	Argued (the order of presupposition: metaphysics, physics, computation, mathematics).
The behavior of a brain at the middle scale can be simulated in principle; its particles cannot be simulated as what they are, since no earlier state fixes their outcomes; a whole-universe simulation that is a world of its own is impossible in principle.	*Causality Without Determinism*, Ch. 5, Sec. VIII (the paradox of embedding); *What Cannot Be*, Ch. 21, "No Outside, and the Brain That Can Be Copied".	Argued.

Claim of the chapter	Where the corpus carries it	Standing as the book states it
Each fixed rule has a least step and sets a precision beyond which its statistics differ from the world's; for any one fixed program, beyond its smallest step, a sensitive enough measurement eventually tells the program's statistics from the world's.	*Causality Without Determinism*, Ch. 5, Sec. VIII; *What Cannot Be*, Ch. 21, "The Quantum Wave as Evidence"; *The Basis of Physics*, Essay 18, Sec. VII.	Argued. "Beyond its smallest step" means at a precision finer than the rule's least step (*What Cannot Be*: "With enough trials, and enough sensitivity to reach below that step"). Its coming tests are Prediction 29 of the appendix "What the Coming Measurements Will Find".
A deterministic program can reproduce the statistics of entangled pairs to any precision chosen in advance, and cannot be what their outcomes are, since its outputs are fixed by its rule and its start and the outcomes are fixed by nothing before them.	*What Cannot Be*, Ch. 21, "The Quantum Wave as Evidence"; *Causality Without Determinism*, Ch. 5, Sec. VIII (first argument).	Argued, with the free will theorem (Conway and Kochen) as its physical premise.
A law of physics states what stays the same when the circumstances of a measurement change; lawfulness is a finding of comparison.	*Comparison*, Ch. 2, Sec. II, "What a Law Is".	Definition, with its consequence stated there.
Why the laws hold at all (the deep why) steps outside measurement within the world.	*The Basis of Physics*, "The Deep Why", Sec. IV.	Argued (each of the three usual responses leaves the method of measurement).

Claim of the chapter	Where the corpus carries it	Standing as the book states it
Inside a black hole the two descriptions do not clash; the smooth one reaches its edge.	As given for Chapters 8 and 21 of this book: Chapter 8 found quantum theory and general relativity to be two descriptions of one world, joined side by side; Chapter 21 found that inside a black hole the smooth description reaches the edge of its domain at the Planck curvature (*At the Edge of Reality*, Ch. 15; *Two Theories, One World*, Ch. 26).	Derived in the collection from the Incommensuration Theorem, as the entries for Chapters 8 and 21 state it.
Interference in quantum theory comes in pairs of paths: with three paths open, the pattern is fixed by the single paths and the pairs, with no third-order term.	Standard quantum theory (the Born rule: the probability of a finding is the square of the size of its amplitude); *Side by Side*, Volume One, Appendix B, Prediction 25 ("Three-slit experiments find the third term consistent with zero (Sinha and others 2010)").	Definition of the third-order term, and a measured fact to the precision given below.

The third route, in the words of *Physics Is Not Math*, Ch. 8, Sec. VIII ("Summary"): "The thesis that the world is a computation is excluded on three independent grounds: determinism, which the theorem forbids, since cyclicity perfected and sequentiality perfected are symmetry and continuity perfected together; the cross-modal principle, which excludes a description of one character at both levels; and the bound triple, by which a simulated world with real subjects is a region of the one world". The

same book argues the three grounds in Ch. 8, Sec. VII (“Three Grounds”). *Side by Side*, Volume Two, chapter “The Structure and the Act” (beside Max Tegmark), Sec. IX, gathers the same three grounds.

The diagonal argument, in words first: given any list of numbers between zero and one written as endless decimals, a number built to differ from the n-th number of the list in its n-th digit, using no zero and no nine, lies between zero and one and is on no line of the list. In symbols: let the list be the sequence x_1, x_2, x_3, and so on (read “x one, x two, x three”), and let $d_n(x)$ (read “the n-th digit of x”) be the n-th decimal digit of a number x; choose y with $d_n(y)$ in the set {1, ..., 8} and $d_n(y) \neq d_n(x_n)$ for every n (read “the n-th digit of y differs from the n-th digit of x n”); then $y \neq x_n$ for every n. The restriction to the digits one to eight removes the numbers with two decimal spellings, such as one half, written both 0.5000... and 0.4999....

Measured values told in the chapter, with their primary papers:

Measurement	**Value**	**Primary paper**
Three-slit interference with single photons (Institute for Quantum Computing, Waterloo)	Any third-order (three-path) term bounded below about 10^{-2} of the expected two-path interference.	U. Sinha, C. Couteau, T. Jennewein, R. Laflamme and G. Weihs, “Ruling out multi-order interference in quantum mechanics”, *Science* 329, 418–421 (2010).
Arrival times of photons of different energies from GRB 090510 (Fermi)	Any linear energy dependence of the speed of light placed beyond the Planck scale.	A. A. Abdo and others, “A limit on the variation of the speed of light arising from quantum gravity effects”, *Nature* 462, 331–334 (2009). As told in Chapter 10.
Loophole-free Bell tests, 2015	Violation of a Bell inequality with the detection and locality loopholes closed.	B. Hensen and others, *Nature* 526, 682–686 (2015); M. Giustina and others, *Physical Review Letters* 115, 250401 (2015); L. K. Shalm and others, *Physical Review Letters* 115, 250402 (2015). As told in Chapter 26.

The scene: N. Bostrom, "Are You Living in a Computer Simulation?", *Philosophical Quarterly* 53, no. 211, 243–255 (2003). The authors' footnote quoted in the chapter stands in *Frequently Asked Questions About the Universe*, ch. 14, "Could You Tell?", at the paragraph on particles from the Andromeda Galaxy.

Chapter 28. Is an Afterlife Possible?

Information has two senses: the form of the content, which is carried with the matter wherever the matter goes, and a count of states, which is always a count made against some context. *What Comes After the Dark*, Chapter 9, "Two Things Called Information" and Key idea. Standing: a definition (the two senses are named and kept apart). The form of the content is "what the matter is, and which alternatives it has taken"; the count is the entropy, the number of arrangements that the comparisons available from a context cannot tell apart. For the counts of that chapter, the context is the outside world of an epoch: the sky and everything in it, against which the comparisons of that epoch are made.

Hawking's calculation of 1976 found that the glow of a black hole, as he computed it, carries away the hole's mass with nothing in it that records what went in; in the words of his abstract, "part of the information about the state of the system is lost down the hole". *What Comes After the Dark*, Chapter 9, "A Paper Sent from Pasadena". Standing: reported (the history of the information paradox).

Information in the first sense is not destroyed in a black hole. Within the range where each holds, the quantum description and the smooth description of gravity each carry what the matter is without loss. The loss in Hawking's 1976 calculation sits where the falling matter meets the singularity, the edge of the smooth description's range. *What Comes After the Dark*, Chapter 9, "Two Things Called Information"; *Two Theories, One World*, Chapter 25, "Information Is Not Destroyed". Standing: derived, given the book's premise that the geometry of space and time is no entry in the quantum state of the matter (*Two Theories, One World*, Chapter 25,

"The Premise Underneath"). In words: the state of the matter, laid out on its geometry, evolves without loss; the Hawking radiation alone is mixed because its entangled partner lies inside the horizon.

While a black hole stands, it hides what falls into it from everything outside, and it destroys nothing. For a hole formed from a star, the account asserts neither the return of the information to the outside world nor its loss to it. *Two Theories, One World*, Chapter 25, opening and "Holes Formed From Stars"; *The Registered Predictions of Physics from Comparison; A Dated Record* (1 November 2026), Section IX, as reproduced in *Side by Side*, Volume One. Standing: derived (first sentence); a stated scope (second sentence).

At the end of a black hole's interior the content does not cease, and by the third axiom a context forms again around it. By two of the three clauses of the third axiom, content and context are distinct and inseparable: "there is no content without a context in which it is content, and no context without a content". *What Comes After the Dark*, Chapter 8, "What Is Left When the Sky Is Empty" and "The First Ground: No Content Without a Context"; Chapter 9, "What Crosses". Standing: derived from the third axiom together with the statement that the edge at the Planck scale belongs to the descriptions and is no ending of what they describe.

At the turn, every count (every entropy), every length, every record, the shape of the old large space and the fields of its matter stay behind, and every thing stays behind as the thing it was. *What Comes After the Dark*, Chapter 9, "What Stays Behind". Standing: derived. Each count is a count against the old outside world, which at the end of an interior has no moment; the new world re-forms from the ten-dimensional geometry with no past of its own.

The law returns: the structure of the world that this physics derives holds again on the far side of the turn, and it is not carried across. *What Comes After the Dark*, Chapter 9, "What Returns". Standing: derived (the law is no count made against the old outside world, so the fresh start of every count at the turn does not touch it).

The form of the content crosses the turn as one averaged form, with no mark of which black hole it came through. *What Comes After the Dark*, Chapter 9, "What Crosses". Standing: derived from the principle of identity (a difference no comparison can register is no difference) and the absence of any context that draws the differences between interiors. The phrase "averaged and not erased" is quoted there from *The Gravitational Passage*.

Everything of you that ends inside a black hole is kept, as a share of the form of the content from which the next epoch's galaxies grow; nothing of you crosses as you. *What Comes After the Dark*, Chapter 9, "What This Means for You". Standing: derived. Scope, as stated in What Comes After the Dark: in the corpus books I follow the form of the content into the one averaged form, for content that ends inside black holes. For a body carried away alone, I follow the form of the content of that body to the turn, where the content of the body does not cease and a context forms again.

The departures from uniformity of our microwave sky (the first ripples) are the form of the content carried through the turn from the epoch before ours. *What Comes After the Dark*, Chapter 9, "The Faint Pattern"; *What the Beginning Left Behind*, Chapter 11. Standing: an identification, made in the first person (in this book, in Chapter 20).

No body, vessel, readable message or person crosses from one epoch into the next. The form of a message dropped into a black hole arrives "as no message, and as the instructions of no one". Nothing in the next epoch is the same thing as anything in ours, by any finding anyone could make. *What Comes After the Dark*, Chapter 10, "Stepping Off the Step" and "No Message, No Record, No Identity". Standing: derived (no act of comparison spans the turn).

There is no other universe that a journey could reach, on three grounds. First, the turn lies at no moment of our time, so no path joins the epochs. Second, space is the pattern of which events a signal can join, so any region a path reaches belongs to our world, and a region no path

reaches has no position in our pattern. Third, the Incommensuration Theorem excludes a domain that contains every domain. *What Comes After the Dark*, Chapter 10, "No Other Sky Along Any Path". Standing: derived, three independent routes. In words for the third route: a whole holding every domain would have to perfect sameness (one way of belonging shared by every member, which is symmetry) and unbrokenness (every member joined to every other, which is continuity) in one comparison. The theorem, in its exact wording: "Symmetry and continuity cannot both be applied, simultaneously and fundamentally, to any event or comparison; and neither can asymmetry and discontinuity".

Mind uploading is a category error and not an engineering problem; a person is not a very large file; identity, in the sense of a single unitary consciousness, is not something a copy can carry. *What Cannot Be*, Chapter 22, "A Person Is Not a File"; *The Last Turtle*, Chapter 33, Section VII, and Chapter 26, Section IV. Standing: derived from the bound triple (hard randomness, directed time and subjectivity, inseparable) and the Incommensuration Theorem. "Information" in the sentence "a person is not information" is information in the sense of a file or description: a list of separate marks read the same way by every reader (*What Cannot Be*, Chapter 22: persons are "what information, by itself, cannot be"). The no-cloning theorem (Wootters and Zurek 1982; Dieks 1982) is the physical correlate that I name in The Last Turtle. No single operation copies every unknown quantum state, while the outcomes of a measurement can be copied.

A simulated world that contains real subjects is a restricted region of the one world in which it runs. *What Cannot Be*, Chapter 22, "The Program With No One in It" (with Chapter 21). Standing: derived.

No process at any scale is perfectly reversible, and a reversal of evolution does not remove a finding from the order of findings. *The Registered Predictions of Physics from Comparison; A Dated Record* (1 November 2026), Prediction 28, as reproduced in *Side by Side*, Volume One; argued in *The*

Basis of Physics, Essays 9 and 11. Standing: an exclusion the structure of comparison makes; the record lists the measured violations of CP (1964) and of time reversal (CPLEAR 1998; BaBar 2012) as consistent with it.

Real, existent and objective are three distinct claims, told apart by the number of interactions each involves. The real involves exactly one (first person, here and now); existence involves none (a place in a pattern, third person); objectivity involves many (what many comparers would find). Event time is real and does not exist; pi exists and is not real. *The Last Turtle*, Chapter 7, "Real, Existent, Objective", Sections I to IV and XI. Standing: definitions, with the triple assigned its modalities (real immanent, existence omniscient, objectivity transcendent). That measurement establishes existence or objectivity: the same chapter, Section V ("If I can interact with something, if I can measure it ... then I can say that the thing exists, or that it is objective").

The essay on the soul states three resolutions; Chapter 28 uses the second and the third. Resolution 2: "That soul is atemporal (without time). The relation between self and world is temporal". The same resolution states that "the essential nature of substance (particle matter) is also atemporal". The second resolution regards immortality as an isomorph of timelessness, and sets two triples beside each other: no time (atemporality), one time (temporality) and all time (immortality); and self, world and the relation between them. On these corresponding triples, "the religious philosophy of the immortality of the soul finds some basis". Resolution 3: "That the nature of divinity is an isomorph of the innermost nature of soul and is real". The essay's conclusion from the triple of existence, being and objectivity: "the divinity of the soul is real, but it does not exist and it is not objective". *An Immanent Metaphysics*, General Appendix, "The Metaphysics of Science and Religion". Standing: resolutions the metaphysics defines, by isomorphic transformations between triples (the principle of foundational triplication and the principle of type isomorphism, as the essay names them).

Measured values told in the chapter. The temperature of the cosmic microwave background differs from place to place by about one part in a hundred thousand. The root-mean-square sky variation, smoothed to a 10-degree beam, is 30 $\pm$ 5 microkelvin, against a mean temperature of about 2.73 kelvin, a ratio of about 1.1×10^{-5}; the root-mean-square quadrupole is 13 $\pm$ 4 microkelvin. Primary paper: G. F. Smoot and others, "Structure in the COBE differential microwave radiometer first-year maps", *Astrophysical Journal* 396 (1992) L1.

The papers of the scene and of the glow. S. W. Hawking, "Black hole explosions?", *Nature* 248 (1974) 30 (the glow). S. W. Hawking, "Breakdown of predictability in gravitational collapse", *Physical Review D* 14 (1976) 2460 (received 25 August 1975, as *What Comes After the Dark*, Chapter 9, reports). S. W. Hawking, "Information loss in black holes", *Physical Review D* 72 (2005) 084013 (arXiv hep-th/0507171, submitted 18 July 2005).

Chapter 29. How Will the Universe End?

For Chapter 29 of this book I take the content from *What Comes After the Dark*, Chapters 1 to 5 and 8, and from that book's Appendix A, "For the Specialist", for the same chapters. Each claim below gives the corpus book that argues it, its standing as that book states it, and the values the chapter uses.

The outside world of every comparer empties. The accelerating expansion gives every observer a cosmological event horizon (*The Gravitational Passage*, Chapter 18, Section III; told again in *At the Edge of Reality*, Chapter 12): standing, reported. Content beyond an observer's event horizon is no part of that observer's exterior, because it cannot be compared with that observer in principle, and so "every observer's comparable exterior therefore empties" (*The Gravitational Passage*, Chapter 18, Section III): standing, derived from the definition of an observer's exterior as what that observer can ever compare with. Within the horizon, matter clumps into black holes or departs as ejected bodies or radiation, and

what is not bound is carried beyond the horizon (same section; *The View from Inside*, Chapter 16, "Nowhere Else to Be"): standing, reported. *The View from Inside* reaches the same far future twice: in Chapter 2, from the measured energy density of the vacuum, where it calls the far future "a cold, dark, eternally expanding emptiness"; and in Chapter 16, "Nowhere Else to Be", where what is not bound "is carried beyond the horizon by the expansion, driven by the very constant this book explains", the constant whose size that book derives. The span of the emptying beyond the Local Group, a hundred billion to a trillion years (10^{11} to 10^{12} years, read: ten to the eleven to ten to the twelve years), is reported from Krauss and Scherrer (2007) and Adams and Laughlin (1997), as *What Comes After the Dark*, Appendix A, Chapter 1, gives them; of the two papers, Krauss and Scherrer (2007) computes with the measured cosmological constant.

The stars of our own sky stay; other galaxies leave. Every star visible to the eye belongs to our galaxy, which is bound, and the expansion carries away only what is not bound (*What Comes After the Dark*, Chapter 1, "Clumping and Departing", and Chapter 3): standing, derived given the identification of the cosmological constant with the accessible share, with the reported Kottler geometry for a spherical mass.

The floors of the building. The building is a logarithmic scale: floor n stands for 10^n years (read: ten to the n years), and the ground floor, $n = 0$, for one year. The present age, about 13.8×10^9 years, lies at $n \approx 10.1$. The end of normal star formation at the cosmological decade $\eta \approx 14$, the disruption of galaxies over $15 < \eta < 25$ (about 1 to 10 percent of a galaxy's stars falling to the central black hole and the rest evaporated from the galaxy), and the evaporation of black holes over $60 < \eta < 100$ are reported from Adams and Laughlin (1997), where η (read: eta) is the base-ten logarithm of the time in years; *What Comes After the Dark*, Appendix A, Chapters 1, 2 and 5, gives them.

The proton does not decay. The gauge group is a product of three factors, no gauge boson carries both color and electroweak labels, and so every operator that changes baryon number has a zero coefficient (*The*

Branches of the Kinds, Chapter 2, "The Stable Proton", as *What Comes After the Dark*, Appendix A, Chapter 5, gives it): standing, derived by two independent routes, with one measured input (the proton is the lightest whole of baryon number one). Measured: no decay seen, with the lifetime divided by the share of decays into a positron and a neutral pion above 2.4×10^{34} years at 90 percent confidence (Takenaka and others, Super-Kamiokande, 2020).

The glow of a black hole of the Sun's mass. The Hawking temperature is $T_H = \hbar c^3/(8\pi G_N M k_B)$ (read: the temperature equals the reduced Planck constant times the cube of the speed of light, divided by eight pi times Newton's constant times the hole's mass times Boltzmann's constant). For one solar mass it is about 6.2×10^{-8} kelvin (*What the Beginning Left Behind*, Chapter 9, "The Faint Glow"; *The Gravitational Passage*, Chapter 18, Section X, gives about 6×10^{-8} K): standing, established physics (Hawking 1974, with the full paper in 1975). In the accelerating expansion the background temperature falls by a factor e about every seventeen billion years, so the background cools below that temperature in 10^{11} to 10^{12} years (*The Gravitational Passage*, Chapter 18, Section X): standing, computed from established physics. The evaporation then takes about 2.1×10^{67} years (*What the Beginning Left Behind*, Chapter 9, "The Faint Glow", and Chapter 10, "The Emptying, and the Reset", which states that *The Unquantized Arena* computes it from established physics; *The Gravitational Passage*, Chapter 18, Section X, and *The View from Inside*, Chapter 16, give about 10^{67} years). *What the Beginning Left Behind* states the basis of that figure in its own appendix: "emitting photons only, as a black body without greybody factors". The primary paper of the method, which computes the lifetime from the particles a hole emits, is Page (1976). Page's formula for a hole much heavier than 10^{17} grams, $2.16 \times 10^{66}\ (M/M_\odot)^3$ years (read: two point one six times ten to the sixty-six years, times the cube of the hole's mass in solar masses), counts photons, gravitons and neutrinos taken as massless, with graybody factors; *What Comes After the*

Dark, Chapters 1 and 5 and Appendix A, gives Page's figure, about 2×10^{66} years. The largest black holes last to $\eta \approx 100$ (Adams and Laughlin 1997, reported).

Our epoch does not fall back. The Friedmann equation is $H^2 = (8\pi G/3)\rho - kc^2/a^2 + \Lambda c^2/3$ (read: the square of the expansion rate equals eight pi times Newton's constant over three times the energy density, less the curvature term, plus the cosmological constant times the square of the speed of light over three): standing, reported (*The Gravitational Passage*, Chapter 16, Section IV, and Chapter 13, Section VI). The homogeneous model of each epoch is spatially flat, because the curvature is a constant of integration set at the turn, where no length of the old epoch passes (*The Gravitational Passage*, Chapter 18, Section IX; *At the Edge of Reality*, Chapter 19): standing, derived given a stated premise (the new geometry has no prior identity) and an identification (every epoch that leads to a turn makes structure). The cosmological constant is positive, because every factor of $\rho_\Lambda = c_1 \, f \, M_{Pl}{}^4/S$ is positive (read: the energy density of the constant equals the first Chern coefficient $c_1 = 3$, times the trim $f = 1 - 3/(8\pi)$, times the fourth power of the Planck mass, divided by the entropy S of the observer's particle horizon) (*The Gravitational Passage*, Chapter 12, Section IV, with Chapter 13, Section II): standing, derived given the identification of the constant with the accessible share of the vacuum's energy, made in Chapter 3 of this book. With the curvature term zero, the density term not negative and Λ positive, $H^2 \geq \Lambda c^2/3$ at every epoch, so H never reaches zero for any density: standing, derived (*What Comes After the Dark*, Appendix A, Chapter 2, Form A). Within one geometry Λ does not vary, by the contracted Bianchi identity with the conservation of the content's stress-energy; *The Gravitational Passage* states: "So within one geometry Λ does not vary. This is a theorem of the geometry, and it uses no measurement and no value of w" (Chapter 13, Section VI): standing, derived (a theorem of the geometry). The collapse that occurs is the collapse of bound structures into black holes, and the ends of the interiors lie at no moment of the exterior, so the exterior is never contracted as a whole (*What Comes After the Dark*, Appendix A, Chapter 2, Form C): standing,

derived from the reported results of general relativity. Measured: the curvature share $\Omega_K = 0.001 \pm 0.002$ (read: the share of the curvature term is one thousandth, give or take two thousandths), Planck with baryon acoustic oscillations (Planck Collaboration 2020); the flat base model gives $\Omega_m = 0.315 \pm 0.007$ and $H_0 = 67.4 \pm 0.5$ km/s/Mpc, so $\Lambda \approx 1.09 \times 10^{-52}$ per square meter and $H_0\sqrt{\Omega_\Lambda} \approx 55.8$ km/s/Mpc (computed, as *What Comes After the Dark*, Appendix A, Chapter 2, gives them). The corpus's own matter share is 0.311 and its constant share 0.689.

Nothing bound is torn apart. The equation of state of the constant is $w = -1$ exactly (read: the pressure divided by the energy density equals minus one): *The Gravitational Passage*, Chapter 13, Section V, states "$w = -1$ exactly"; standing, derived given the identification of the accessible share. A rip happens for $w < -1$ and only then, and for $w = -1$ a system bound now stays bound (Caldwell, Kamionkowski and Weinberg 2003): standing, reported. The list of kinds holds one scalar field, the Higgs field (*The Story of the Particles*, Level 9, Section IV, as *What Comes After the Dark*, Appendix A, Chapter 3, gives it): standing, derived; its energy is constant after the electroweak crossover (*The Gravitational Companion*, "Comparisons at Single Steps", Section VII): standing, reported; an energy density constant in time has $w = -1$, so the Higgs field supplies no phantom component. The outward share of Λ against the pull that binds a mass M at radius r is $\Lambda c^2 r^3/(3GM)$ (read: the cosmological constant times the square of the speed of light times the cube of the radius, divided by three times Newton's constant times the mass), the same at every later time because Λ is. Values: 0.0069 at the Milky Way's $R_{200} = 217$ kpc with $M_{200} = 1.08 \times 10^{12}$ solar masses (computed from Cautun and others 2020 and Planck 2020, as *What Comes After the Dark*, Appendix A, Chapter 3, gives it); about 8×10^{-23} for the Earth's orbit at one astronomical unit (*What Comes After the Dark*, Chapter 3, "A Steady Wind on the Step", "about eight parts in a hundred thousand billion billion"; from $\Lambda = 1.09 \times 10^{-52}$ m^{-2} and $GM_\odot = 1.327 \times 10^{20}$ m^3 s^{-2} the formula gives 8.3×10^{-23}); 1.9×10^{-69} of the electric force on the electron of hydrogen at the Bohr radius (computed from CODATA 2022, Mohr and others 2025), the share the chapter calls

"smaller still" for an atom. The cosmological constant is the same at every place and time and increases the distance between every pair of distant places, while gravitation acts where content is (*The Weight of Possibility*, Chapter 2, Section II): standing, identification.

Empty space keeps its nature. A vacuum decays by tunneling only if a second held configuration of lower energy exists for a bubble to lead to (Coleman 1977; Coleman and De Luccia 1980): standing, reported. The internal space has one held configuration (*The Compactification*, Chapter 2, Sections III to VII and IX). Each factor of the internal space is homogeneous, so exactly two moduli remain, the volume and the ratio of the radii. Both moduli are fixed at one point, with the radius of the two-sphere one Planck length and the radius of the complex projective plane $\sqrt{6}$ Planck lengths (read: the square root of six). The floor of the size comes from the third axiom with the uncertainty relation. There is no flux, because the action is built from the metric alone. Standing: identification (homogeneity) joined to a theorem (Schur's lemma), with the floor derived and $\sqrt{6}$ a structural value. A first-order computation finds the derived point a stable minimum, the only one in shape between $\sqrt{3}$ and $\sqrt{12}$; it carries the book's standing "computed", and the hold does not rest on it (*The Compactification*, Chapter 2, Section VII). The hold ends where the compactification conditions fail, at the end of an interior or for a body carried away alone, and in the new epoch the product re-forms with the same topology and the same radii in Planck units (*The Compactification*, Chapter 2, Section VII; *What the Beginning Left Behind*, Chapter 5, "Nowhere to Tunnel"): standing, derived given the compactification conditions. For the Higgs field: the potential is $V(\Phi) = -\mu^2|\Phi|^2 + \lambda|\Phi|^4$ (read: minus mu squared times the squared size of the field, plus lambda times the fourth power of its size), with tree-level $\lambda = 1/8$; one scalar doublet only (*Non-Commutative Geometry and the Immanent Metaphysics*, Chapter 19, Proposition 19.10); the set of lowest states one connected three-sphere. The energy of the Higgs field is bounded below, from the principle that every way of varying has a least state (*What Comes After the Dark*, Chapter 4, "The Higgs Field": "This physics also holds the principle that every way of varying has a least state,

so that nothing can fall without limit, and the energy of the Higgs field has a floor"). In the variable $x = |\Phi|^2$ the potential $-\mu^2 x + \lambda x^2$ has one minimum, at $x = \mu^2/(2\lambda)$, the present condensate, with the self-coupling worked out at the electroweak scale (*What Comes After the Dark*, Chapter 4 and Appendix A, Chapter 4): standing, derived given the stated identification for 1/8. The scope, in the corpus's own words: "This chapter makes no claim about the stability of the content's vacuum under such running" (*The Compactification*, Chapter 2, Section VIII); and "This physics gives the field's energy a floor, and, in the two-part curve it derives, that floor is the present state. It does not follow the field's strength out to very high energies" (*What Comes After the Dark*, Chapter 4, "The Higgs Field"). Reported: $\lambda(M_t) = 0.12604$ in the MS-bar scheme at next-to-next-to-leading order; the running self-coupling crosses zero near 10^{10} GeV; the electroweak vacuum is metastable (Buttazzo and others 2013); its lifetime is about 10^{139} years, and more than 10^{58} years at 95 percent confidence (Andreassen, Frost and Schwartz 2018).

The emptying ends in a turn. Ground A: the content does not cease at the end, and the third axiom excludes content without a context, so a context forms again from the ten-dimensional geometry (*At the Edge of Reality*, Chapter 16, "Content Needs a Context"; *The Gravitational Passage*, Chapter 18, Section VII): standing, derived. Ground B: a final featureless emptiness would be perfectly symmetric and perfectly continuous at once, which the Incommensuration Theorem excludes (*The View from Inside*, Chapter 16, "Context Must Be Restored"): standing, derived. Ground C: every entropy is a count made against a context, so no count carries over the turn and each epoch begins its own; a final maximum that holds forever has no context in which to be counted (*What Comes After the Dark*, Chapter 8, "The Third Ground: Every Count Has a Context"; *The Compactification*, Chapter 3, Sections V and VII; *At the Edge of Reality*, Chapter 18; *The Gravitational Passage*, Chapter 18, Section VIII): standing, derived given the stated premise that an entropy is a count relative to a context. The three grounds rest on three independent sources: the third axiom, the Incommensuration Theorem, and what an entropy counts. The ends of all

black-hole interiors are one (*The Gravitational Passage*, Chapter 18, Section II): standing, derived given the principle of comparison and the stated premise that the new context registers no distinction of the old exterior. On the clock of an infalling body the end of a solar-mass hole's interior comes "at most about fifteen microseconds after the crossing" (*The Gravitational Passage*, Chapter 18, Section I): standing, reported (general relativity and the singularity theorems); the end lies at no moment of the exterior's time (same section, as *What Comes After the Dark*, Appendix A, Chapter 2, gives it): standing, reported, with the placement derived. The Hawking flux is taken as real, and "the interior argument proceeds on timescales vastly shorter than the evaporation time" (*The Gravitational Passage*, Chapter 18, Section X); a remnant taken into a black hole is not given back by the hole's glow within the times over which the emptying runs (*What Comes After the Dark*, Chapter 5, "The Last Glow of the Black Holes"): standing, reported. The restoration of context is the Big Bang of the new epoch (*The Gravitational Passage*, Chapter 18, Section VII; *At the Edge of Reality*, Chapter 16): standing, identification, made in Chapter 20 of this book. The cosmological history is a cycle, "and not a single arc from Big Bang to heat death" (*The Gravitational Passage*, Chapter 18, Section XII): standing, derived given the identification. "At the end of an interior the constant acts as nothing at all, because the exterior on which its definition rests has dissolved, so the turn needs no change in the constant" (*What Comes After the Dark*, Appendix A, Chapter 2, Form B; *At the Edge of Reality*, Chapter 20, "The Expansion Does Not Stop It"): standing, derived given the identification of the accessible share.

Measured and reported values told in the chapter, with their primary papers.

Measured or reported value told in the chapter	**Primary paper**
Thomson's three conclusions on the dissipation of mechanical energy, read at the meeting of 19 April 1852	W. Thomson, "On a Universal Tendency in Nature to the Dissipation of Mechanical Energy", *Proceedings of the Royal Society of Edinburgh* 3 (1857) 139, read 19 April 1852; reprinted *Philosophical Magazine* 4 (1852) 304–306
Thomson, born 26 June 1824, professor of natural philosophy at the University of Glasgow from 1846 to 1899, made Baron Kelvin in 1892	University of Glasgow, School of Physics and Astronomy, "Celebrating the life and work of Sir William Thomson, Baron Kelvin of Largs"
The expansion speeds up; the constant is positive	A. G. Riess and others, *Astronomical Journal* 116 (1998) 1009; S. Perlmutter and others, *Astrophysical Journal* 517 (1999) 565
$\Omega_K = 0.001 \pm 0.002$; $\Omega_m = 0.315 \pm 0.007$; $H_0 = 67.4 \pm 0.5$ km/s/Mpc	Planck Collaboration, N. Aghanim and others, "Planck 2018 results. VI. Cosmological parameters", *Astronomy and Astrophysics* 641 (2020) A6
Far-future observers in one merged galaxy lose the evidence of the expansion by about 10^{11} years	L. M. Krauss and R. J. Scherrer, "The return of a static universe and the end of cosmology", *General Relativity and Gravitation* 39 (2007) 1545
Star formation ends near $\eta \approx 14$; galaxies disperse over $15 < \eta < 25$; black holes evaporate over $60 < \eta < 100$	F. C. Adams and G. Laughlin, "A dying universe", *Reviews of Modern Physics* 69 (1997) 337
Proton: $\tau/B(p \to e^+\pi^0) > 2.4 \times 10^{34}$ years at 90 percent confidence	A. Takenaka and others (Super-Kamiokande), *Physical Review D* 102 (2020) 112011

Measured or reported value told in the chapter	Primary paper
Black holes emit thermally	S. W. Hawking, “Black hole explosions?”, *Nature* 248 (1974) 30; full paper: S. W. Hawking, “Particle creation by black holes”, *Communications in Mathematical Physics* 43 (1975) 199
Method of the lifetime from the emitted species	D. N. Page, “Particle emission rates from a black hole”, *Physical Review D* 13 (1976) 198
Rip condition $w < -1$; timetable for $w = -3/2$ and $H_0 = 70$ km/s/Mpc: end 22 billion years ahead, Milky Way about 60 million years before, atoms about 10^{-19} s before	R. R. Caldwell, M. Kamionkowski and N. N. Weinberg, “Phantom Energy: Dark Energy with $w < -1$ Causes a Cosmic Doomsday”, *Physical Review Letters* 91 (2003) 071301; R. R. Caldwell, “A Phantom Menace?”, *Physics Letters B* 545 (2002) 23
Milky Way M_{200} and R_{200}	M. Cautun and others, *Monthly Notices of the Royal Astronomical Society* 494 (2020) 4291
False vacuum decay; gravity and the bubble	S. Coleman, “Fate of the false vacuum: Semiclassical theory”, *Physical Review D* 15 (1977) 2929; S. Coleman and F. De Luccia, “Gravitational effects on and of vacuum decay”, *Physical Review D* 21 (1980) 3305
Higgs self-coupling running; metastability; lifetime	D. Buttazzo and others, “Investigating the near-criticality of the Higgs boson”, *Journal of High Energy Physics* 2013 (12) 089; A. Andreassen, W. Frost and M. D. Schwartz, “Scale Invariant Instantons and the Complete Lifetime of the Standard Model”, *Physical Review D* 97 (2018) 056006

Chapter 30. Will Time Ever Stop?

Below, each claim of Chapter 30 that comes from the corpus stands with the book, chapter and section that carry the claim, and with the standing that book gives the claim. Where mathematics is needed, it is

given in words first and then in symbols, with each symbol read aloud. The measured values the chapter tells follow at the end, with their primary papers.

The answer of the chapter

Claim: time does not stop; no clock comes to a last tick; the end of the sky is the end of what a comparer can compare with, and not the end of time. In What Comes After the Dark I say "observer" where in this chapter I say "comparer"; the two words name the same thing, anything that compares one thing with another and registers what it finds. Where: *What Comes After the Dark*, Chapter 6, "What Happens to Someone Who Is Still There?", sections "The Last Watcher on the Step", "Will Time Ever Stop?" and "No Last Tick"; the same book's appendix "For the Specialist", Chapter 6. Standing: derived given the principle of comparison (a difference that no comparison can register is no difference), with the results of general relativity on the fall reported.

Three times

Claim: physics uses the word "time" for three distinct times: geometric time (the clock's), event time (the order of findings) and evolution time (the parameter of quantum evolution, which belongs to the mathematics of quantum theory); no one time is all three together with each made perfect. Where: *What Cannot Be*, Chapter 14, "Three Kinds of Time", section "Three Times"; *Why Time Travel Is Not a Concept*, Chapter 1, Section II; source *The Unquantized Arena*, Chapter 10, Definitions 10.1 to 10.3 and Propositions 10.1 and 10.2. Standing: derived; "no unified time exists" follows from the Incommensuration Theorem, since a time found both as geometric time (continuous and asymmetric) and as event time (discontinuous and symmetric) would carry at least one of the two pairings the theorem excludes.

The falling clock: finite, with no last tick

Claim: inside the horizon of a black hole that does not rotate, the direction toward the center is the direction of time. The end of the interior comes after a finite proper time, as a limit that every path inside approaches and does not reach. No clock records a last tick; the end of the interior lies at no moment of the outside world. Where: *At the Edge of Reality*, Chapter 9, "The Singularity Is Not Now", sections "Two Clocks, One Structure", "The View from Inside" and "The End Is a Moment"; *The Gravitational Passage*, Chapter 18, Section I; *What Comes After the Dark*, Chapter 6, "No Last Tick". Standing: reported (results of general relativity and the singularity theorems), with the placement of the end relative to the outside world derived.

Value: the longest proper time from the horizon to the end, for a faller starting from rest at the horizon of a black hole that does not rotate, is pi times Newton's constant times the mass of the hole, divided by the cube of the speed of light. In symbols, $\tau_{max} = \pi GM/c^3$, where τ_{max} ("tau max") is that longest proper time, G is Newton's constant, M is the mass of the hole and c is the speed of light. For one solar mass, $\tau_{max} = 1.55 \times 10^{-5}$ s, about fifteen microseconds; for the hole at the center of our Galaxy, about four million solar masses, about a minute. Where: *At the Edge of Reality*, table of values, row "Longest time from the horizon to the end, one solar mass" (citing *The Gravitational Passage*, Chapter 18, Section I); Chapter 9, "The View from Inside". Standing: standard general relativity, reported.

The two scopes of "end of time"

Scope one: for the one who falls in, the end of the interior is the end of time on the faller's own clock ("For the one who falls in, it is the end of time, and it comes soon", *At the Edge of Reality*, Chapter 9); for the outside world it never happens at any time the outside world can name. Scope two: time does not stop, since no clock comes to a last tick, and the turn is no moment of any clock (*What Comes After the Dark*, Chapter 6). Both are held together, each at its scope.

The picture of the halves

The cooling cup is a picture, and the physics it uses is standard. Newton's rule of cooling says that the gap between a body's temperature and its surroundings' shrinks by the same fraction in each equal stretch of time: $\Delta T(t) = \Delta T_0 \, e^{-t/\tau_c}$, read "the gap at time t equals the starting gap times e to the minus t over tau c". In the formula, ΔT_0 is the starting gap and τ_c is a cooling time fixed by the cup and the room. The gap halves every $\tau_c \ln 2$. The drops in temperature, $\Delta T_0/2 + \Delta T_0/4 + \Delta T_0/8 + \ldots$, sum to the finite starting gap ΔT_0, and the sequence has no last term. The corpus uses the same structure in its own picture, "the marks at half the distance to a line, then half of what is left" (*What Comes After the Dark*, Chapter 6, "No Last Tick", reused in Chapter 8, "One End, and the Turn"). Zeno's dichotomy is reported by Aristotle, *Physics*, Book VI, chapter 9 (239b).

The two arrows

Claim: the direction of time is the structural arrow, the one-way order of every comparison (range, act, record), present in one comparison made once and needing no special beginning; the growth of entropy is a second, entropic arrow, statistical and needing a low-entropy beginning; so a maximum of entropy leaves the direction of time in place. Where: *What the Beginning Left Behind*, Chapter 6, "What This Means for the Beginning" ("We now know that the direction of time does not depend on the beginning of the world; only the growth of entropy does"); *Physics Is Not Math*, "Physics Has the Arrow", Section II; *Incommensuration*, Chapter 8, Section X. Standing: derived; the identification of the one-way precedence of the second axiom with the direction of time is an identification, made in Chapter 13 of this book.

Every count has a context

This ground is walked in Chapter 29 of this book; Chapter 30 recalls its result in two sentences and asks only whether time stops wherever entropy reaches its largest value. Claim: an entropy is a count of the states

that the comparisons available from a context cannot tell apart, so an entropy is always a count made against a context. The entropy of a black hole counts the states of the interior of the black hole that no comparison from outside can tell apart. At the end the outside world has emptied and the count has no reference left. Clausius's sentence holds inside every epoch, and a final maximum that holds forever has no context in which to be counted. Where: *What Comes After the Dark*, Chapter 8, "The Third Ground: Every Count Has a Context"; *At the Edge of Reality*, Chapter 18, "Every Count Has a Context"; *What the Beginning Left Behind*, Chapter 7, "A Clean Slate, Counted", section "Every Count Has a Context"; *The Gravitational Passage*, Chapter 18, Section VIII; source *The Compactification*, Chapter 3, Sections V and VII. Standing: derived given the stated premise that an entropy is a count relative to a context; the identification of what a black hole's entropy counts is stated in the first person in *What Comes After the Dark*, Chapter 8. The reset of the count is given by principle; *The Gravitational Passage* states that a count of states across the turn, in numbers, is not given there.

In symbols, with Boltzmann's definition used as stated: $S_C = k_B \ln W_C$, read "S sub C equals k B times the natural logarithm of W sub C", where W_C is the number of states that the comparisons available from the context C cannot tell apart, and k_B is Boltzmann's constant. For a black hole the count is the Bekenstein and Hawking entropy, $S_{BH} = k_B c^3 A / (4G\hbar)$, read "k B times c cubed times A, over four G h-bar", where A is the area of the horizon and ħ is the reduced Planck constant; for one solar mass, $S_{BH}/k_B \approx 1.05 \times 10^{77}$ (*What the Beginning Left Behind*, Chapter 8, "What the Count of an Edge Counts", and Chapter 10; established physics, computed from the measured constants). Clausius's own definition of 1865 is the change $dS = \delta Q_{rev}/T$, read "the change in entropy equals the heat taken in reversibly, divided by the absolute temperature".

What ends at the end of the far future, and what stays

Claim: every observer ends at the end of a black hole's interior or carried away alone. In both places no comparable distribution of mass and energy is left against which a standard of rest could be defined, so the Mach principle fixes no frame. The order of before and after across the exterior, and the order of cause and effect between distant events, rest on the reference of the distant matter. Both orders lose their support. The one-way order inside each act of comparison is not reversed, and at the end the one-way order has no comparable content to order. Where: *The Gravitational Passage*, Chapter 18, Section IV, "The Mach Principle Unpins"; *At the Edge of Reality*, Chapter 13, "The Reference Unpins"; *What the Beginning Left Behind*, Chapter 1, the fourth step; *What Comes After the Dark*, Chapter 6, "Mach and the Bucket", "A Standard That Needs Something There", "Two Ways to Be Left", "The Order Inside Each Comparison" and "The Order Across the Sky". Standing: the two fates derived (from the reported clumping and departing of bound structures); the loss of the standard of rest and of the large-scale direction derived given the principle of comparison; what is at the end of an interior does not cease (*What Comes After the Dark*, Chapter 8, Ground A, derived).

The large-scale direction of time is the one direction of time as the outside world marks it, in three ways at once: *The Gravitational Passage*, Chapter 18, Section IV, names it "the direction of increasing entropy, the direction of expansion, the direction that the Mach reference defines", and *At the Edge of Reality*, Chapter 13, "The Reference Unpins", states that "At the end, time loses that large-scale direction". *What Comes After the Dark*, Chapter 6, "The Order Across the Sky", calls it "The same one direction of time" that the order inside each comparison carries, "also marked on the largest scale". The one-way order inside each comparison is the structural arrow of Chapter 13 of this book; at the end it is not reversed, and at the end of an interior there is no comparable content left for it to order (*The*

Gravitational Passage, Chapter 18, Section IV). In the chapter's words, the order of each comparison "is never reversed", and "no further comparison is left for the one-way order to arrange".

The common reference: "the distant matter serves every observer as a common reference, against which events far apart from each other are placed as before or after one another, and as cause or effect" (*What Comes After the Dark*, Chapter 6, "The Order Across the Sky"). The reference is the content within the comparer's horizon: "Content beyond the horizon is not comparable in principle (Section III), so it fixes no frame for the observer; the reference is the content within the horizon" (*The Gravitational Passage*, Chapter 18, Section IV). The two ships that time their logs by one sky are this book's picture of that reference.

The cosmological event horizon of each comparer, the edge beyond which nothing sent now can ever reach the comparer, is the same edge that *What Comes After the Dark*, Chapter 6, calls the observer's "cosmological horizon". Throughout this book, I use the name that Chapter 23 gives the edge.

The turn is no moment of any clock

Claim: the turn is a limit approached from two sides; no comparison registers it as an event; duration, temperature and rate apply to the approach on each side and to none of the turn. Where: *At the Edge of Reality*, Chapter 16, "One Process, Two Sides", and Chapter 17, "No Comparison Across the Turn"; *The Gravitational Passage*, Chapter 18, Section VIII; *What Comes After the Dark*, Chapter 6, "No Last Tick". Standing: derived given the principle of comparison. The Big Bang as the turn found by our reconstructed history: *At the Edge of Reality*, Chapter 17, "Why the Big Bang Looks Like a Beginning"; the restoration of context as the Big Bang of the new epoch is an identification (*At the Edge of Reality*, Chapter 16, "The Identification").

No meta-time behind the findings

Claim, as I state it in Chapter 30 of this book: findings make the order of event time and do not occur within a time given before the findings. A difference that no comparison can register is no difference. So a stop of a meta-time that no comparison could register is no stop. Where: the first principle, *What Cannot Be*, Chapter 14, "Three Times" ("Time comes with the comparison, not before it", and its quotation of *The Unquantized Arena*: "Findings define the order of event time; they do not occur within a time given before them"), and *Why Time Travel Is Not a Concept*, Chapter 1, Section II; the second principle, *What Comes After the Dark*, Chapter 6, "A Standard That Needs Something There". Standing: the two principles are stated in the books (the first derived, the second a principle of comparison); their application to the authors' meta-time is made in this chapter, in the first person. No book of the corpus discusses a meta-time by that name.

Measured values told in the chapter

Clausius's two closing sentences: R. Clausius, "Ueber verschiedene für die Anwendung bequeme Formen der Hauptgleichungen der mechanischen Wärmetheorie", *Annalen der Physik und Chemie* 125 (1865) 353–400, DOI 10.1002/andp.18652010702; read to the Naturforschende Gesellschaft in Zürich on 24 April 1865. The English of the two sentences follows *What Comes After the Dark*, Chapter 8 (W. F. Magie, *A Source Book in Physics*, McGraw-Hill, 1935, gives "strives toward a maximum").

Clocks flown around the world: J. C. Hafele and R. E. Keating, "Around-the-World Atomic Clocks: Predicted Relativistic Time Gains" and "Observed Relativistic Time Gains", *Science* 177 (1972) 166–168 and 168–170: four cesium beam clocks, October 1971; eastward, a loss of 59 $\pm$ 10 nanoseconds; westward, a gain of 273 $\pm$ 7 nanoseconds, against the time scale of the United States Naval Observatory, in agreement with relativity.

Clocks raised: C. W. Chou, D. B. Hume, T. Rosenband and D. J. Wineland, "Optical Clocks and Relativity", *Science* 329 (2010) 1630–1633: two aluminum-ion optical clocks; one raised by 33 centimeters ran faster by about four parts in ten to the seventeen, the amount general relativity gives.

The rule of rate that these measurements confirm, for motion: a clock moving at speed v runs, against clocks at rest, at the square root of one minus v squared over c squared of their rate. In symbols, $d\tau/dt = \sqrt{(1 - v^2/c^2)}$, read "d tau by d t equals the square root of one minus v squared over c squared", where τ ("tau") is the time the moving clock shows, t is the time of the clocks at rest, v is the speed of the moving clock and c is the speed of light. The rate falls as v grows and reaches zero only at $v = c$, which no body with mass reaches. For a clock at rest at height h above a lower clock, in a field of gravity of strength g, the higher clock runs faster by the fraction $g\ h\ /\ c^2$, read "g times h over c squared"; for $h = 0.33$ m this is about 3.6×10^{-17}, in agreement with the shift of about four parts in ten to the seventeen that Chou and his colleagues measured. Standing: standard special and general relativity, reported.

Ernst Mach, *Die Mechanik in ihrer Entwickelung historisch-kritisch dargestellt* (Leipzig: Brockhaus, 1883), as reported in *What Comes After the Dark*, Chapter 6.

Chapter 31. How Long Will Humanity Survive?

The chapter's answer has a near part and a far part. The near part: the Sun burns steadily for billions of years, held to the rate at which it shines by its own gravity, and the rocks that might strike the Earth are the solar system's first solids, whose paths an early nudge can change. The far part: every thinker, as a physical comparer of one epoch, comes to the end of a black hole's interior or is carried away alone. At either end it has nothing outside to compare against and loses the forms of its own matter, whatever its store of energy, its temperature or its rate. The turn restores a world with the same derived structure, in which comparison happens

again, while no finding, record or count of our epoch is real in the next. The main sources are *What Comes After the Dark*, Chapters 5, 7 and 10 with their sections of Appendix A, and *The Matter We Know*, Volume One, Chapter 6, and Volume Two, Chapter 13. Each standing below is the one the named book gives.

The thinker and thinking

Claim: the smallest comparison needs a reference other than the comparer, a lasting bound structure that keeps the record, and a signal between them. Source: *Why the Quantum Is the Way It Is*, Chapter 2, "Five Particles in an Empty Universe" (two hydrogen atoms and one photon); source *Comparison; The Necessary Basis*, Chapter 4, Section VI. Standing: derived, as a model built by construction and checked by subtraction, with reported atomic physics (*What Comes After the Dark*, Appendix A, Chapter 7).

Claim: energy is the capacity of a system to participate in comparisons, so a store of energy is used only where there is something to compare with. Source: *Comparison; The Necessary Basis*, Chapter 4, Section III. Standing: the need for a target and a record is derived; energy as a compound of the six intrinsics of comparison is an identification (*What Comes After the Dark*, Appendix A, Chapter 7).

Claim: every bound structure, and every observer in it, ends inside a black hole or carried away alone, and there is no third end. Source: *The Gravitational Passage*, Chapter 18, Sections III and IV; told again in *At the Edge of Reality*, Chapter 13, and *What Comes After the Dark*, Chapters 5 and 6. Standing: the clumping and departing are reported; that there are exactly these two ends is derived.

Claim: on the clock of a body that falls into a black hole of mass M, the end of the interior comes after a finite proper time, at most $\pi GM/c^3$. In words: pi times Newton's constant G times the mass M, divided by the cube of the speed of light c. For one solar mass this is 1.55×10^{-5} seconds, about fifteen microseconds after the crossing. Source: *The Gravitational Passage*, Chapter 18, Section I; *At the Edge of Reality*, Chapter 9, and its ap-

pendix table, which gives 1.55×10^{-5} s ($\pi GM/c^3$). Standing: reported (general relativity and the singularity theorems), with the placement of the end at no moment of the exterior derived.

Claim: at the end of an interior and for a body carried away alone, the conditions that hold the six small dimensions compact fail, the forms of matter end with them, and the content does not cease. Source: *The Gravitational Passage*, Chapter 18, Sections VI and VII and Questions; told again in *At the Edge of Reality*, Chapter 13. Standing: derived (the third axiom with the principle of comparison and the modal boundary).

Claim: no thinker makes an unending run of findings, and the conclusion uses neither the size of the store, nor the temperature, nor the rate of thinking. Source: *What Comes After the Dark*, Chapter 7, "What the Emptying Leaves a Thinker"; Appendix A, Chapter 7. Standing: derived, given the premises above. Scope as that appendix states it: the answer covers every thinker that is a physical comparer within one epoch of an accelerating universe; which limit a thinker meets first on its own clock depends on its design, and the answer does not depend on that order.

Claim: the turn restores a large world with the same derived structure (the shape of the internal space, the ratio of its radii and its size at the Planck scale); the new epoch makes stars and black holes; comparison happens there, so comparers are present in the next epoch. Source: *At the Edge of Reality*, Chapter 20, "What Carries Over", and Chapter 21, "The Turn" (the sentence quoted in the chapter); *The Gravitational Passage*, Chapter 18, Section VII. Standing: derived, given the identification of the restoration of context with the Big Bang of the new epoch. Scope as *What Comes After the Dark*, Appendix A, Chapter 7, states it: the collection derives no biology; what it establishes is that the next epoch begins with the same structure and the same clean slate under which minds arose in ours.

Claim: no act of comparison spans the turn, so no finding, record or count of a thinker of our epoch is real in the next. Source: *The Gravitational Companion*, "Two Formal Triples of a Domain", Section III; told again in

What the Beginning Left Behind, Chapter 21, "A Cycle with No First Turn". Standing: derived (the formal triples of a domain), as *What Comes After the Dark*, Appendix A, Chapters 7 and 10, gives it.

Claim: each epoch is a whole physical domain, and the series of epochs is a series of domains of the same structure, not one totality containing them; no domain contains every domain. Source: *The Gravitational Companion*, "Two Formal Triples of a Domain", Section III. Standing: *What Comes After the Dark*, Appendix A, Chapter 10, gives "No domain contains every domain" as derived (the Incommensuration Theorem); *The Gravitational Companion* classes the section's reading of the turn by the two formal triples as an extension of *The Gravitational Passage* that adds no prediction (Section IV). In Chapter 31 of this book I use the claim that no domain contains every domain against the authors' argument from infinity. The collection makes no claim about a completed totality of all epochs (*The Gravitational Companion*, "Two Formal Triples of a Domain", Questions).

Claim: no body, readable record, identity, person or message crosses from our epoch into the next as itself; the form of the content of whatever falls into the black holes crosses as one averaged form; any place a path from here can reach belongs to our own domain. Source: *What Comes After the Dark*, Chapter 10; Appendix A, Chapter 10, whose table names each ground. Standing: derived, at the standings that table gives (several given the identification of the restoration with the Big Bang, of space with the pattern of causal connection, and of the first-person stance as continuity with asymmetry).

Claim: in a universe whose expansion is driven by a positive cosmological constant, no chain of societies passes a message to a society beyond the horizon of the society that sends it; this is the account's answer to Dyson's third question, which Dyson (1979) answered with a tentative "maybe" for a universe with no cosmological constant. Source: *What Comes After the Dark*, Chapter 7, "Dyson's Three Questions", with the horizon of Krauss and Starkman (2000), "Objects more distant than the de Sitter horizon now will forever remain unobservable". Standing: reported

(the de Sitter horizon of general relativity with a positive cosmological constant), with the limit of every comparison at the speed of light as that book states it. Dyson's three questions, as that book gives them: whether an open universe freezes into a permanent quiet as it expands and cools; whether life and intelligence can survive in it forever; and whether societies can keep sending messages to one another across its ever greater distances. Dyson's first question is answered by the turn that ends the emptying (*What Comes After the Dark*, Chapter 8).

Claim: the first of the authors' "two big threats", the collapse of the Higgs field, at the scope the collection states. The collection derives the form of the potential, $V(\Phi) = -\mu^2|\Phi|^2 + \lambda|\Phi|^4$, read as: the potential equals minus mu squared times the squared size of the field, plus lambda times the fourth power of its size; and the tree-level self-coupling $\lambda = 1/8$. The energy is bounded below by the principle that every way of varying has a least state: "This physics also holds the principle that every way of varying has a least state, so that nothing can fall without limit, and the energy of the Higgs field has a floor" (*What Comes After the Dark*, Chapter 4, "The Higgs Field"). In the two-part curve, along the one doublet, that floor is the present vacuum, at the order of the form the spectral action gives and at the weak scale where the collection's self-coupling holds. Source: *What Comes After the Dark*, Chapter 4, "The Higgs Field", and Appendix A, Chapter 4, "The vacuum of the Higgs field"; *The Compactification*, Chapter 2, Section VIII; *The Measures of the Kinds*, Chapter 13. Standing: derived, given the stated identification $\lambda = a^2/2$ for the value 1/8. Scope: the collection does not compute the running of the self-coupling to field values far above the weak scale and makes no claim about the result of that running (*The Compactification*: "This chapter makes no claim about the stability of the content's vacuum under such running"). Reported: run with the Standard Model and measured inputs, $\lambda(M_t) = 0.12604$, the self-coupling crosses zero near 10^{10} GeV and the electroweak vacuum is metastable (Buttazzo and others 2013), with a lifetime of about 10^{139} years, and more than 10^{58} years at 95 percent confidence (Andreassen, Frost and Schwartz 2018).

The rocks

Claim: meteorites are pieces of the solar system's first solids, dated by the two uranium-lead clocks. Source: *The Matter We Know*, Volume One, Chapter 6, "In Use"; the clocks in Chapter 5, "In Use". Standing: reported measurement.

Claim: one click of a Geiger counter that nothing beforehand fixed, followed by ordinary gravity and motion, can change the orbits of asteroids and in time of planets, so the geometry of space and time depends on outcomes not settled until they happen. Source: *The View from Inside*, Chapter 14, "A Geiger Counter and the Orbits of Planets". Standing: an argument of that book by thought experiment, whose one premise beyond ordinary mechanics is hard randomness; *Measurement*, Chapter 14, Section II, derives that no world is purely and completely deterministic (derived, the Incommensuration Theorem, as *What Comes After the Dark*, Appendix A, Chapter 7, lists it); the record of predictions carries the statement as its Prediction 28.

Claim: humanity's next mastery is the mastery of choice, since solving all problems with causation alone has side effects. Source: *The Last Turtle*, Chapter 13, "Choice, Change, and Causation", Section VIII, "Humanity's Three Masteries". Standing: stated in that book as its account of the three masteries; the chapter relates it to the authors' nearest dangers and claims no more of it.

The Sun

Claim: the first reaction of the proton-proton chain, $p + p \rightarrow d + e^{+} + \nu_e$ (read: two protons give a deuteron, the nucleus of heavy hydrogen, one proton and one neutron bound together, with a positron and an electron neutrino), needs the weak force, whose reach is about 2.5×10^{-18} m, so it is rare, and a proton in the core waits billions of years on average. Source: *The Matter We Know*, Volume One, Chapter 1, "In Use" (with Box 1.1), and Chapter 6, Section II. Standing: derived in that book from its stated premises, with measured inputs.

Claim: nuclei in the core meet at the Gamow peak, $E_0 = (E_G(kT)^2/4)^{1/3}$, read: the energy of the peak is the cube root of one quarter of the Gamow energy times the square of the temperature expressed as an energy; for two protons $E_G = 0.493$ MeV, and at 15.7 million kelvin $kT = 1.353$ keV, so $E_0 \approx 6.1$ keV against a barrier of about 1.0 MeV. Source: *The Matter We Know*, Volume One, Chapter 6, Box 6.1. Standing: derived in the box from the Boltzmann factor and the tunneling weight, with the core temperature a reported value.

Claim: a ball of gas in balance under its own gravity has total energy $E = -K$ (read: the total energy equals minus the energy of motion of its particles), so losing energy heats it and gaining energy cools it; the burning returns to the rate at which the star shines, and a spent core contracts and heats until the next fuel burns. Source: *The Matter We Know*, Volume One, Chapter 6, Section II and Box 6.2 (Clausius's virial theorem; Eddington 1926). Standing: derived from standard mechanics, as the box sets it out.

Claim: at about 10^8 kelvin three helium-4 nuclei join into carbon-12 through beryllium-8, at a rate made large by the Hoyle state about 7.65 MeV above carbon-12's ground state (0.38 MeV above three helium-4 nuclei); carbon-12 and helium-4 make oxygen-16; each heavier fuel, by its charge, needs a higher temperature, and only stars many times the Sun's mass burn carbon. Source: *The Matter We Know*, Volume One, Chapter 6, Sections III and IV, and Box 6.1. Standing: derived for the order of the fuels by charge; the Hoyle state's energy is measured. The order by charge, in words: two nuclei of charges Z_1 and Z_2 pass through their electric barrier with a weight that falls as the Gamow energy $E_G = 2\mu c^2(\pi\alpha Z_1 Z_2)^2$ grows (read: twice the reduced mass times the square of the speed of light, times the square of pi times the fine-structure constant times the two charges), so a larger product of charges needs a higher temperature for the same rate. For a proton meeting carbon-12 at the Sun's core temperature, $E_G = 33$ MeV, against 0.493 MeV for two protons (Box 6.1).

Claim: a white dwarf is held up by the degeneracy pressure of its electrons, $P = (3\pi^2)^{2/3}\hbar^2 n^{5/3}/(5m)$ for slow electrons and $P = (3\pi^2)^{1/3}\hbar c n^{4/3}/4$ for electrons near c. Read: for slow electrons the pressure is the two-thirds power of three pi squared, times h-bar squared, times the number density n to the five-thirds, divided by five times the electron mass m; for fast electrons it is the cube root of three pi squared, times h-bar, times the speed of light, times n to the four-thirds, divided by four. Above the Chandrasekhar mass, in outline $M = (\hbar c/G)^{3/2}/(\mu_e m_u)^2$ (read: h-bar times c over G, to the three-halves power, divided by the square of the number of nucleons per electron times the atomic mass unit), and in full 1.46 solar masses for $\mu_e = 2$, no size holds. Source: *The Matter We Know*, Volume Two, Chapter 13, Sections II to IV, Boxes 13.1 and 13.2; exclusion from the principle of identity, Volume One, Chapter 1, Box 1.2. Standing: derived, given the reported physics of a filled sea of fermions; the factor 3.10 between outline and full solution is Chandrasekhar's (1931).

Claim: the Sun, when it has burned its fuel, will leave a white dwarf; the commonest white dwarfs are about 0.6 solar masses and about the size of the Earth. Source: *The Matter We Know*, Volume Two, Chapter 13, Section III. Standing: reported (standard accounts of the evolution of stars and of white dwarfs). The authors give about half the Sun's mass for the Sun's own white dwarf (*Frequently Asked Questions About the Universe*, ch. 19, "Jupiter Goes Bonkers").

Claim: the radius of Sirius B follows from its mass and the stretch of its light, since light climbing from the surface of a star of mass M and radius R loses the share $GM/(Rc^2)$ of its frequency (read: Newton's constant G times the mass, divided by the radius times the square of the speed of light). Source: *The Matter We Know*, Volume Two, Chapter 13, Section I. Standing: reported (standard physics of the gravitational redshift), with the measured shift and mass as inputs.

Claim: since the supporting pressure does not depend on temperature, a cooling remnant keeps its size and becomes a black dwarf of the same size. Source: *What Comes After the Dark*, Chapter 5, "Held Up Without Heat"; Appendix A, Chapter 5. Standing: derived.

Claim: the account parts from the wasting-remnant picture at three places, as *What Comes After the Dark*, Chapter 5, "The Wasting Remnant, and This Account Beside It", names them. First, the dark matter, which acts on ordinary matter only through gravity, gives the remnant no warmth. Second, the proton does not decay, because no gauge carrier joins color to the weak charge. Third, the forms of a remnant's matter end only at the end of its road, inside a black hole or carried away alone, and never by slow wasting. Beside the three places, the same chapter ("Does the Proton Last?") finds that the rest of a remnant's matter lasts too: the electron, the lightest charged particle, does not decay; and neutrons in the carbon and oxygen nuclei of a white dwarf do not decay, because every beta-decay Q-value (the energy a decay would set free) from Z to Z + 1 is negative. Source: *What Comes After the Dark*, Chapter 5, "Does the Proton Last?", "The Wasting Remnant, and This Account Beside It" and "What the Dark Matter Is Here"; Appendix A, Chapter 5, citing *The Branches of the Kinds*, Chapter 2, and *The Weight of Possibility*, Chapter 4, Section II. Standing: proton, derived by two independent routes with one measured input (that the proton is the lightest whole of baryon number one); electron, derived given a measured input; neutrons in nuclei, derived given measured atomic masses; dark matter, derived given the identification of the dark matter as a vibration of context. Beside it: Adams and Laughlin (1997) take proton decay as their working case and describe dark-matter capture in white dwarfs; the collection agrees with them on what holds each remnant up and on the two ends of its path.

Measured and reported values the chapter tells, with their primary papers

Proton-proton neutrinos from the Sun: $6.6 \pm 0.7 \times 10^{10}$ per square centimeter per second, showing about 99 percent of the Sun's power from the proton-proton chain: Bellini and others, Borexino Collaboration, "Neutrinos from the primary proton-proton fusion process in the Sun", *Nature* 512 (2014) 383–386.

Neutrinos of the CNO cycle, the second way of burning hydrogen, in which nuclei of carbon, nitrogen and oxygen help four protons become helium and come out unchanged, about one percent of the Sun's power: Borexino Collaboration, "Experimental evidence of neutrinos produced in the CNO fusion cycle in the Sun", *Nature* 587 (2020) 577–582.

Solar luminosity 3.828×10^{26} W: International Astronomical Union 2015, Resolution B3 (Prša and others 2016); core temperature about 15.7 million kelvin, as *The Matter We Know* cites it (Williams 2024, NASA Sun Fact Sheet, from the standard solar model).

Sirius B: 1.018 ± 0.011 solar masses, orbital period 50.13 years: Bond and others, "The Sirius System and Its Astrophysical Puzzles", *Astrophysical Journal* 840 (2017) 70; radius about 5,600 km, computed from the gravitational redshift 80.65 ± 0.77 km/s: Joyce and others, "The gravitational redshift of Sirius B", *Monthly Notices of the Royal Astronomical Society* 481 (2018) 2361; mean density about 2.8 metric tons per cubic centimeter (computed in *The Matter We Know*, Volume Two, Chapter 13, Section I).

The greatest mass of a white dwarf: Chandrasekhar, "The Maximum Mass of Ideal White Dwarfs", *Astrophysical Journal* 74 (1931) 81–82; the voyage of 1930 from his interview with Spencer Weart, 17 May 1977 (American Institute of Physics oral history 4551-1), as *What Comes After the Dark*, Chapter 5, cites it.

The Hoyle state: Hoyle, *Astrophysical Journal Supplement Series* 1 (1954) 121–146; Cook, Fowler, Lauritsen and Lauritsen, "B^{12}, C^{12}, and the Red Giants", *Physical Review* 107 (1957) 508–515.

No proton decay seen: $\tau/B(p \rightarrow e^{+}\pi^{0}) > 2.4 \times 10^{34}$ years at 90 percent confidence (read: the lifetime divided by the share of decays into a positron and a neutral pion exceeds the value given): Takenaka and others, Super-Kamiokande Collaboration, *Physical Review D* 102 (2020) 112011. No electron decay seen: $\tau \geq 6.6 \times 10^{28}$ years for $e \rightarrow \gamma\nu$: Agostini and others, Borexino Collaboration, "Test of Electric Charge Conservation with Borexino", *Physical Review Letters* 115 (2015) 231802.

The age of the meteorites and the Earth, $4.55 \pm 0.07 \times 10^{9}$ years: Patterson, "Age of meteorites and the earth", *Geochimica et Cosmochimica Acta* 10 (1956) 230–237. The oldest solids, calcium- and aluminum-rich inclusions, 4,567.30 $\pm$ 0.16 million years: Connelly and others, "The Absolute Chronology and Thermal Processing of Solids in the Solar Protoplanetary Disk", *Science* 338 (2012) 651–655.

The Chelyabinsk airburst, 15 February 2013, with its peak brightness at 03:20:32 UTC: Popova and others, "Chelyabinsk Airburst, Damage Assessment, Meteorite Recovery, and Characterization", *Science* 342 (2013) 1069. The published figures: a diameter of 19.8 $\pm$ 4.6 meters, taking the body as a sphere; an entry mass of about 1.3×10^{7} kilograms, within a factor of two; a speed of 19.16 $\pm$ 0.15 kilometers per second at 97 kilometers of height, about sixty-nine thousand kilometers an hour; and 1,210 people injured in the city of Chelyabinsk alone, the greater part of all the injuries. In Chapter 31 of this book I tell the size, speed and injuries in the authors' round figures: twenty meters, sixty thousand kilometers an hour, and about a thousand people hurt (*Frequently Asked Questions About the Universe*, ch. 9).

Dyson's store for indefinite survival of a society as complex as ours, of order 6×10^{37} erg, about eight hours of the Sun's output: Dyson, "Time without end: Physics and biology in an open universe", *Reviews of Modern Physics* 51 (1979) 447.

The finite integrated conscious lifetime in a universe with a positive cosmological constant: Krauss and Starkman, "Life, the Universe, and Nothing: Life and Death in an Ever-expanding Universe", *The Astrophysic-*

al Journal 531 (2000) 22 (submitted 12 February 1999). The temperature of the de Sitter horizon, $T = \hbar H/(2\pi k_B)$ (read: h-bar times the expansion rate, divided by two pi times Boltzmann's constant), about 2.2×10^{-30} kelvin for $H_0\sqrt{\Omega_\Lambda} = 55.8$ km/s/Mpc: Gibbons and Hawking, *Physical Review D* 15 (1977) 2738, computed in *What Comes After the Dark*, Appendix A, Chapter 7, with the Planck values (Planck Collaboration, Aghanim and others, 2020).

The wasting-remnant picture: Adams and Laughlin, "A dying universe: the long-term fate and evolution of astrophysical objects", *Reviews of Modern Physics* 69 (1997) 337.

The chapter also draws on: *The Matter We Know, Volume One*, Chapter 6, Section II; *The Matter We Know, Volume Two*, Chapter 13, Section III.

Chapter 32. Will Science One Day Answer Everything?

The known, the unknown and the unknowable are three classes, distinct, inseparable and non-interchangeable; the soft boundary between the known and the unknown moves with every investigation. Source: *Comparison; The Necessary Basis*, Chapter 11, Section V, "The Known, the Unknown, and the Unknowable" (subsections "Three Classes, Not Two", "The Two Boundaries"). Standing: a claim of the structure of comparison; the third class is introduced in the first person ("I identify a third class that this division misses"). In the impersonal assignment the known is omniscient, the unknown immanent and the unknowable transcendent; from the personal basis the known is immanent and the unknown omniscient (subsection "The Dual Perspective").

The unknown is more fundamental than the known, as the source is more fundamental than the product: every known fact was once unknown. Source: *Comparison*, Chapter 11, Section V, subsection "The Unknown". Standing: a claim of the structure of comparison (Axiom I applied to the triple of known, unknown, unknowable).

The hard boundary between the unknown and the unknowable is fixed by the principle of identity. What cannot be compared even in principle cannot be distinguished from anything, and so cannot be the basis of any assertion. A being of unlimited intelligence, time and resources would still meet the hard boundary. Source: *Comparison*, Chapter 11, Section V, subsections "The Unknowable" and "The Two Boundaries". Standing: a claim of the structure of comparison; its definition depends only on the principle of identity. The unknowable gives the unknown its depth and "ensures that the act of investigation never runs out of territory" (subsection "The Inseparability"); it is reached through knowing (subsection "The Cycle Among the Three", from Axiom II read as many experiences of the known preceding one experience of the unknowable). The chapter's short answer gives the unknowable, and its fixed edge, as the reason the asking never runs out; the deep why is a separate matter, a question that measurement within a world does not reach, because the possibility of a world is inside no world.

The unknowable is a persistent class fixed by the structure of comparison; "The limit the theorem draws is the curvature of the field itself, rather than a wall at the edge of an otherwise open field". Source: *Incommensuration*, Chapter 6, Section XI, "The Two Surviving Modes". Standing: a consequence of the Incommensuration Theorem (the two surviving modes are structurally distinct, neither derivable from nor reducible to the other). The sense of "field" and "curvature" in that sentence is given by *What Cannot Be*, Chapter 12, "Beyond the Farthest Point": "In that phrase the field is a stretch of ground, like the meadow, and its curvature is the bend of that ground, the shape of the domain itself; the curvature of space and time that is gravitation is a different thing". The picture of the traveler's horizon, made by the curve of the earth with no fence at the end of a flat meadow, is from the same section.

The Incommensuration Theorem, in its exact wording: "Symmetry and continuity cannot both be applied, simultaneously and fundamentally, to any event or comparison; and neither can asymmetry and discontinuity". It is a structural fact about the nature of knowing. Source: *Incommensura-*

tion, Chapter 2, Section VI, "The Theorem"; the full statement is aphorism 1.43-2 of *An Immanent Metaphysics*; the form as a prohibition, "Nothing anywhere at all can be both absolutely symmetric and absolutely continuous. Nothing anywhere at all can be both absolutely asymmetric and absolutely discontinuous", is in the Preface of *Incommensuration*, "The Incommensuration Theorem, as a Prohibition"; the proof is in Chapter 6. Standing: a theorem, with no physical premise.

Gödel's first incompleteness theorem is an instance of the Incommensuration Theorem in the domain of formal systems: consistency is a symmetry (sameness of content, the truth value, across difference of context, the path of derivation), and completeness is a continuity (sameness of content, having a truth value, in sameness of context, the language of the system). Source: *Incommensuration*, Chapter 15, Section II, "Instance: Gödel's Incompleteness"; also *The Basis of Physics*, "What Physics Cannot Reach", Section VI; *Physics Is Not Math*, Chapter 21, "The Map Is Not the Territory", Section V (a system both perfectly consistent and perfectly complete would perfect the first forbidden pairing). Standing: a derivation of a domain-specific result from the theorem, which *Incommensuration* states as "a claim of exact correspondence", whose mapping can be checked term by term against the standard statement, and expressly not an analogy. The picture of statements as points and derivations as paths, with consistency as agreement of two paths at one point and completeness as "no islands", is the one *Incommensuration* gives in the same section. The scope condition of Gödel's theorem (a system rich enough for arithmetic, with axioms listed by an effective procedure) is the theorem's own scope condition: the system is capable of self-comparison. Presburger arithmetic and the theory of dense linear orders, which lack that capacity, are consistent and complete. The two survivors in this domain are the consistent but incomplete system (symmetric and discontinuous, the mode mathematicians work in) and the complete but inconsistent one (trivial). Gödel's paper: K. Gödel, "Über formal unentscheidbare Sätze der Principia Mathematica und verwandter Systeme I", *Monatshefte für Mathematik und Physik* 38 (1931) 173–198.

Physics answers what, where, how and when, and the shallow why (the why that asks for the law of which a case is an instance, answered by a more general what); it does not answer the deep why (the why that asks for the possibility from which a world is chosen), because that possibility is inside no world and every measurement is an interaction within one. Source: *The Basis of Physics*, essay "The Deep Why", Sections III and IV ("The deep why is not a question physics has failed to answer", Section IV); *What Cannot Be*, Chapter 20, "What Physics Cannot Reach", sections "What Physics Answers" and "The Deep Why" ("It is no question that physics has failed to answer and might yet answer with better instruments"). The two books carry the same text in two registers. Standing: as both books state it, the match of the six questions (who, what, how, why, where, when) with the six measures (mass, space, force, time, probability, possibility) is a claim of the metaphysics itself (*An Immanent Metaphysics*, aphorisms 1.92-3 to 1.92-8), and "That physics answers what, where, how and when, and the shallow why, and not the deep why, is a reading of what physics does, with the correspondence as its structural reason" (*The Basis of Physics*, "The Deep Why", Section VI). In the grid of the six measures, what and where are mass in space (omniscient), how and when are force in time (immanent), who and why are probability in possibility (transcendent). The deep why is well formed (possibility is one of the six measures every measurement presupposes); accounts of a world arising from a vacuum or from a law (Hawking and Mlodinow, *The Grand Design*, 2010; Krauss, *A Universe from Nothing*, 2012) answer a how and a what and presuppose the state and the laws. The three usual replies at the level of the laws each step outside measurement into a claim about the range of possible laws or worlds. One reply says that the laws simply hold and there is no further why; that says nothing false, and it declines the question. A second says that the laws could not have been otherwise, because consistency picks them out; that is a claim about the range of possible laws, and measurement is not how it is made. A third says that only some of the worlds that might have been have anyone in them to ask; that too is a claim about worlds that might have been, and again it is not made by

measurement. Each reply steps outside the world in order to answer (*What Cannot Be*, Chapter 20, "The Deep Why"). Metaphysics is the study of the relations between domains, and physics the study of the interactions within one (*What Cannot Be*, Chapter 20, "The Deep Why" and "Physics as Instance, Metaphysics as Basis"). The essay "locates the deep why, and says what kind of answer it would take"; it does not claim that metaphysics answers what physics cannot.

Falsifiability is the criterion proper to explanation and prediction (why and how), which forbid observations; a description (what) forbids nothing and is judged by significance, completeness and relevance; demanding falsifiability of a description is a category error. Falsifiability holds by levels: in the conventional sense the axioms, being no law of any one domain, are not falsifiable; in the sense of consequences, the structural results reach into physics, where experiment can contradict them. The account accepts the standard of experiment in full wherever a claim says what will be found, and its own claims of that kind are gathered in the appendix "What the Coming Measurements Will Find". Source: *The Basis of Physics*, "What Physics Cannot Reach", Section V; *What Cannot Be*, Chapter 20, "The Right Test for Each Kind of Claim"; *Comparison*, Chapter 14, Section V, "Two Senses of Falsifiability"; *Two Theories, One World*, Chapter 26, "'This Is Only Philosophy'" ("a structural result first, then predictions that can fail"). Standing: a claim of the metaphysics about kinds of claim; *What Cannot Be*, "Before We Begin", "Three Kinds of Claim", and *Comparison*, Chapter 2, Section IV, keep three kinds apart (claims of the structure of comparison; claims or readings of established physics; identifications or structural exclusions).

Every theory is a triple: an object domain (the world, transcendent), a model domain (the formalism, omniscient) and a correspondence domain (the links made by measurement, immanent); by Axiom I the correspondence is more fundamental, and object and model are conjugate, so the world always exceeds the formalism and the formalism carries structure with no referent (gauge freedom, global phase, coordinate artifacts). The world exceeds every model because the transcendent is the mode of what

goes beyond specification and the omniscient the mode of what is specified; a complete model would be a specification of what goes beyond specification. Theories are replaced when the object is found, from the side of the correspondence, to exceed the model; the replacement "is not usually a refutation of the old theory within its domain of correspondence", and "Newtonian mechanics is as good as it ever was where its correspondences hold". Source: *The Basis of Physics*, "What Physics Cannot Reach", Sections I to III; *What Cannot Be*, Chapter 20, "Three Parts of Every Theory", "The World Exceeds the Model", "The Model Exceeds the World". Standing: a claim of the metaphysics (the triple of theory and Axioms I and III); the reading of gauge and coordinate freedom as structure with no referent is a reading of a known feature of physical theories, as *What Cannot Be* names it.

The edge of comparison marked by the speed of light rests on comparison alone (interaction is comparison; comparison has structural limits; the speed of light marks the outer one), and "the edge of the domain would remain if quantum theory were modified or replaced". Source: *What Cannot Be*, Chapter 12, "The Shape of What Can Reach What", section "The Edge Rests on Comparison Alone". Standing: a structural exclusion (no signal crosses the edge), independent of the no-communication theorem of Ghirardi, Rimini and Weber (1980), which is a result within the quantum formalism.

The two present theories, quantum theory and general relativity, stand exactly as experiment has confirmed them, and the account changes no prediction of quantum theory; the change it makes is in how the two are related (joined side by side, through the act of measurement, with the arena unquantized, as Chapter 8 found). Source: *Two Theories, One World*, Chapter 3, "What Remains When the Error Is Removed"; Chapter 19, "The Pattern" ("The account adds nothing to the mathematics and changes no prediction of quantum theory"). Standing: a structural exclusion (no single theory finds both survivors perfected), with the two theories taken as experiment has confirmed them.

The ether question was dissolved, not answered: in 1887 Michelson and Morley found no motion of the Earth through it; in 1905 Einstein showed that the electromagnetic field needs no medium; Maxwell's equations stood unchanged. Source: *Two Theories, One World*, Chapter 3, "Ordinary Examples", which gives four marks of every category error (the question sounds sensible; the effort can be sincere and clever; every answer of the kind asked for fails; when the categories are seen the question is dissolved and nothing real is lost). Standing: reported history, given as a case of category error.

The framework is a theory, so the framework falls under what I say about theories in the framework. The framework cannot describe the particular values and events of a world, and the framework cannot enter the unknowable. The framework also cannot convey the living process of discovering, working through and using the framework, which "can be pointed toward, shown by example and suggested by story" and cannot be handed over as structure. The framework predicts and locates all three things that the framework cannot do. Source: *The Basis of Physics*, "What Physics Cannot Reach", Sections VI to IX; *What Cannot Be*, Chapter 20, "Three Things the Framework Cannot Do" and Summary; *Comparison*, Chapter 14, Section VI ("A metaphysics is not a theory of everything so much as it is a comprehensive description of the foundations of domains"). Standing: a consequence of the triple of theory and the Incommensuration Theorem applied to the framework itself (a description is symmetric with what it describes and so cannot be perfectly continuous with it).

Measured values and records told in the chapter, with their primary sources.

Item	Value or record	Primary source
Bell's bound for any account in which hidden local causes fix every outcome	score at most 2; quantum theory allows up to $2\sqrt{2} \approx 2.83$ (read: two times the square root of two)	J. S. Bell, "On the Einstein Podolsky Rosen paradox", *Physics* 1 (1964) 195–200
Loophole-free test at Delft, electron spins 1.3 kilometers apart	$S = 2.42 \pm 0.20$ (as *Why the Quantum Is the Way It Is* reports it)	B. Hensen and others, "Loophole-free Bell inequality violation using electron spins separated by 1.3 kilometres", *Nature* 526 (2015) 682–686
The other two loophole-free tests of 2015 (Vienna; Boulder)	inequality violated	M. Giustina and others, *Physical Review Letters* 115 (2015) 250401, doi: 10.1103/PhysRevLett.115.250401; L. K. Shalm and others, *Physical Review Letters* 115 (2015) 250402, doi: 10.1103/PhysRevLett.115.250402
Michelson and Morley, motion of the Earth through the ether	no motion found; relative velocity "probably less than one sixth the earth's orbital velocity, and certainly less than one-fourth"	A. A. Michelson and E. W. Morley, "On the Relative Motion of the Earth and the Luminiferous Ether", *American Journal of Science*, series 3, 34 (1887) 333–345, doi:10.2475/ajs.s3-34.203.333
Maxwell's equations, light as a wave of the electromagnetic field	the laws of electricity, magnetism and light	J. C. Maxwell, "A Dynamical Theory of the Electromagnetic Field", *Philosophical Transactions of the Royal Society of London* 155 (1865) 459–512

Item	Value or record	Primary source
Hilbert's address, Königsberg, 8 September 1930	"Wir müssen wissen. Wir werden wissen".	D. Hilbert, "Naturerkennen und Logik", *Die Naturwissenschaften* 18 (1930) 959–963; English translation in W. Ewald, *From Kant to Hilbert* (1996), vol. 2, 1157–1165
Gödel's announcement, Königsberg, 7 September 1930	first incompleteness theorem, mentioned in the general discussion	"Diskussion zur Grundlegung der Mathematik", *Erkenntnis* 2 (1931), in the proceedings of the conference, pp. 87–190; the theorem: Gödel, *Monatshefte für Mathematik und Physik* 38 (1931) 173–198

Chapter 33. What Does That Even Mean?

Chapter 33 gathers the short answers of Chapters 1 to 32 and adds the corpus's account of questions, of the unknowable and of meaning. Each short answer it gathers is entered under its own chapter in this appendix, with its corpus book, its standing and its exact values; the table below names, for each Part, the chapters it gathers and the corpus books that carry them. The claims that Chapter 33 states on its own account follow the table.

Part	What the chapter gathers	Chapters of this book	Principal corpus books of those chapters
One	Two of the three bends make up the ninety-five percent; gravitation holds no share of the budget; the closed list of kinds; forced charges and the counted ladder of masses; mass as one relation	1 to 6	*The Weight of the Unseen* (answer 2.7); *The Weight of Possibility* (Ch. 2, Secs. II and VII; Ch. 3, Sec. V); *The View from Inside*; *The Gravitational Passage* (Ch. 13, Sec. III); *The Story of the Particles*; *Why These Numbers*

Part	What the chapter gathers	Chapters of this book	Principal corpus books of those chapters
Two	Gravity as the arena; three forces and the arena; one geometry for each alternative; one account, joined side by side; space as the pattern of what can affect what; ten dimensions	7 to 11	*The Unquantized Arena*; *Two Theories, One World*; *The Compactification*
Three	Three times; the one-way order of comparison; travel to an earlier time names nothing; the speed of light as the edge of comparison	12 to 15	*What Cannot Be* (Chs. 12 to 16); *Incommensuration* (Ch. 8); *Why Time Travel Is Not a Concept*
Four	The messengers from space; light of every energy arriving together; travel within the reach of light; the same materials in every star	16 to 18	*The Matter We Know*; *Two Theories, One World*; *What Cannot Be* (Ch. 21)
Five	The mirror of every state and the residue of matter; the turn and one origin; one end of every interior; the epoch before; flat, with no short loop, and the same as a space without end for every measurement made from inside; every comparer at the center of its own horizon	19 to 23	*What the Beginning Left Behind*; *At the Edge of Reality*; *The Weight of Possibility* (Ch. 3, Sec. II)

Part	What the chapter gathers	Chapters of this book	Principal corpus books of those chapters
Six	A copy is a second person; a person is not information; chance and choice; the world is not a program; the form is kept, and nothing crosses as itself	24 to 28	*At the Edge of Reality* (Ch. 11); *What Cannot Be* (Chs. 7, 21, 22); *What Comes After the Dark*
Seven	The emptying that never turns back and ends in a turn; no last tick; thinking begins again in each epoch; three kinds of question, and the unknowable beside them	29 to 32	*What Comes After the Dark* (Chs. 2, 6, 7); *The Basis of Physics*; *Comparison* (Ch. 11, Sec. V)

The shares of the budget that the chapter recalls are those of *The Weight of Possibility*. The share of the cosmological constant, Omega sub Lambda, the cosmological constant's fraction of the critical density, is 0.689, from the identity of *The Gravitational Passage*, Chapter 13, Section III, in which I squared times Omega sub Lambda equals eight less three over pi, where I is the comoving distance light has traveled over the whole expansion in units of the Hubble distance: $I^2\Omega_\Lambda = 8 - 3/\pi$, with $I = 3.20$. The matter fraction is then 0.311. The ratio of dark to ordinary matter, Omega sub c over Omega sub b, is six less two over pi: $\Omega_c/\Omega_b = 6 - 2/\pi = 5.3634$ (*The Weight of Possibility*, Chapter 3, Section V), and the two densities are $\Omega_b = 0.0486$ and $\Omega_c = 0.2608$. Standing: derived given the identification of the cosmological constant with the share of the vacuum's energy open to a measurement made from inside (*The View from Inside*, Ch. 11; *The Gravitational Passage*, Ch. 13), as Chapter 3 states.

Gravitation holds no share of the budget: *The Weight of the Unseen*, answer 2.7, states that gravitation "is not an item in the budget of the universe at all", and *The Weight of Possibility*, Chapter 2, Section VII, states that in a flat epoch "the distortion of space is all local: gravitation is struc-

ture, and has no share of its own in the budget". The large-scale term of the distortion of space, the spatial curvature, is zero in a flat epoch, and the measured spatial curvature is consistent with zero (Aghanim and others 2020, as that section cites). So the ninety-five percent of the authors' pie is two of the three bends: the cosmological constant, the bend of time, and the dark matter, the bend of possibility. Standing: derived (the three distortions from the Incommensuration Theorem and the three clauses of the third axiom, *The Weight of Possibility*, Ch. 2, Secs. I to V), with the dark matter's identification as stated in that book, Chapter 1, Section IV.

The light of distant bursts and the grain of space. Claim: the arena has no least step, and the arrival together of light of every energy agrees with that derivation and places any grain of space that would slow light below the Planck scale. Source: *What Cannot Be*, Chapter 21, section "The Arena Has No Least Step" ("the gamma-ray burst measurement of 2009 places any grain of space that would slow light below the Planck scale"); *Two Theories, One World*, as Chapter 16 cites it, for the exclusion of the simplest pictures of a grainy space and time. Standing: the absence of a least step is derived; the measurements (Vasileiou and others for the burst of 2009; Cao and others, *Physical Review Letters*, 2024, placing any first-order dependence on energy above about ten times the Planck energy) agree with it, and Chapter 16 gives their values.

What the exclusions of the book mean. Claim: when the corpus says that something cannot be, it means that the request names nothing, and what is excluded in principle is excluded, for that reason, in all future practice. Source: *What Cannot Be*, "Before We Begin", section "What 'Cannot Be' Means Here". Standing: a definition of the book's use of "cannot be"; the exclusions themselves are the book's third kind of claim, structural exclusions (same preface, section "Three Kinds of Claim").

The deep why. Claim: physics answers the why that asks for a law (a more general what). Physics does not answer the why that asks for the possibility of there being a world, because every measurement is an interaction inside one world. The second why, the deep why, is a well formed question. Source: *The Basis of Physics*, essay "The Deep Why", Sections III

and IV ("The deep why is not a question physics has failed to answer"; "for the same reason that a ruler does not measure temperature"; "Nothing is missing from the ruler"). Standing: a structural claim, resting on the correspondence of the six questions with the six measures (same essay, Section I, citing *An Immanent Metaphysics* and *Comparison*, Ch. 6).

The known, the unknown and the unknowable. Claim: the soft boundary between the known and the unknown moves with every investigation; the hard boundary between the unknown and the unknowable is fixed by the principle of identity; the unknowable gives the unknown its depth and "ensures that the act of investigation never runs out of territory"; the unknowable is reached through knowing. Source: *Comparison*, Chapter 11, Section V, "The Known, the Unknown, and the Unknowable" (subsections "The Two Boundaries", "The Inseparability", "The Cycle Among the Three"). Standing: the third class is an identification stated in the first person ("I identify a third class that this division misses"); the fixity of the hard boundary is argued from the principle of identity. Chapters 32 and 33 keep the deep why and the unknowable apart: the deep why is one question, about the possibility of a world; the unknowable is what no comparison could reach, and it stands beside all three kinds of question.

A question opens; a grade closes. Claim: a grade is a label recording how sure a checker is of a step; a question names what is needed to settle the matter and so carries the instruction for the next step; a label such as "coincidence" is a grade and carries none. Source: *Physics Is Not Math*, Chapter 13, "A Value That Lands", Section V, "A Grade Closes; a Question Opens" ("The grade closes the inquiry, and the question opens it"), with the grade as Chapter 12 of that book names it. Standing: argued from two historical cases (the agreement of inertial and gravitational mass; Balmer's rule).

The meaning of a choice. Claim: one undetermined outcome is randomness described from outside and choice described from inside (a modal rotation: the event stays the same and the position of description changes); the meaning of a choice "cannot be extracted, passed on in its particulars, or reproduced by any process other than the one that is the

choice". Source: *What Cannot Be*, Chapter 7, "Choice, Change and Cause", section "From Outside, Chance; From Inside, Choice". Standing: derived from the residual that the Incommensuration Theorem guarantees in every description, with the two descriptions conjugate.

Meaning cannot be removed. Claim: meaning is present wherever comparison occurs, and it cannot be removed; nihilism would need a fixed point of meaninglessness, and there is none. Source: *What Cannot Be*, Chapter 7, section "Meaning Cannot Be Removed" ("Meaning belongs to the structure of the residual, and nothing can remove it"; "Meaningful, here, means significant to the process an outcome came from"). Standing: argued in three steps (no edge of meaning can be drawn from outside meaning; the idea that choice is meaningful is a fixed point; every definition of meaninglessness is meaningful). Scope, as the book states it: the claim is that the residual has a character of value that no description can strip from it, and it is not the claim that every event has a significance someone could write down.

The blind spot of a theory. Claim: the formalism of physics cannot contain the doing of physics (which measurement to make, the recognition that a model has been exceeded, which anomaly to pursue). Source: *The Basis of Physics*, essay "What Physics Cannot Reach", Section VIII, "What the Framework Can Do from Its Own Blind Spot" ("The blind spot of a theory is where its practice lives"). Standing: derived from the conjugacy of the first axiom, applied to a theory and its practice.

Comparison begins again in each epoch. Claim: the structure is the same in every epoch, comparers are present in the next epoch as in ours, and no thinking of the next epoch continues any thinker of this one; the cycle of epochs has no first turn. Source: *What Comes After the Dark*, Chapter 7, "Can a Mind Keep Thinking for Ever?", section "Where Thinking Begins Again"; and Chapter 6, section "No Last Tick", for the statement that no clock records a last tick and that the turn is not a moment of any clock. Standing: as that book states it, held by "this physics" from the derived sameness of the six small dimensions in every epoch (shape, and size counted in Planck lengths).

Measured value told in the chapter. The age of our epoch, about 13.8 billion years (the "fourteen billion" of the listener's letter that the authors quote), is the measured age to three figures: Planck Collaboration (N. Aghanim and others), "Planck 2018 results. VI. Cosmological parameters", *Astronomy and Astrophysics* 641 (2020) A6, as cited for this figure in *The Quantum Bridge* and used in *The View from Inside*, Chapter 12.

What the Coming Measurements Will Find: The Measurements to Date

This part gives, for the predictions of the appendix "What the Coming Measurements Will Find", the measurements made so far, grouped as the appendix groups them. Each value is given as *The Registered Predictions of Physics from Comparison; A Dated Record* (1 November 2026, https://doi.org/10.67291/RQQS3025) states it, in *Side by Side*, Volume One, Appendix B, unless another source is named. "Standard deviations" means the distance between a prediction and a measurement in units of the measurement's stated uncertainty. Each distance is computed by the method of the corpus book that the record names. The record cites each measurement by author and year; the full entry given after it is the one the named corpus book carries in its bibliography. The rule of decision of the record applies to every line: a result counts when it is established at five standard deviations by at least two independent kinds of measurement.

Chapter 1. What Is the Universe Made Of?

Prediction 7 (matter fraction $\Omega_m = 0.311 \pm 0.001$, read "omega m"). The microwave background gives 0.315 ± 0.007, 0.6 standard deviations away: Aghanim, N. and others (Planck Collaboration) (2020), "Planck 2018 results. VI. Cosmological parameters", Astronomy and Astrophysics 641, A6. The baryon acoustic oscillations of DESI alone give 0.2975 ± 0.0086, 1.6 standard deviations away on the other side: DESI 2025, the second data release, Abdul-Karim, M. and others (DESI Collaboration)

(2025), "DESI DR2 Results II: Measurements of Baryon Acoustic Oscillations and Cosmological Constraints", Physical Review D 112, 083515. The microwave background's fit of the Hubble constant, 67.4 $\pm$ 0.5 kilometers per second per megaparsec, lies 0.8 standard deviations from the predicted 67.8 $\pm$ 0.3. The distance ladder of Cepheid variables gives 73.04 $\pm$ 1.04: Riess, A. G. and others (2022), "A Comprehensive Measurement of the Local Value of the Hubble Constant with 1 km s^{-1} Mpc^{-1} Uncertainty from the Hubble Space Telescope and the SH0ES Team", Astrophysical Journal Letters 934, L7. The record states its distance from 67.8 as 4.9 standard deviations, citing *The Registered Predictions of The Gravitational Passage*, Section III; *Side by Side*, Volume One ("Figures in the sealed text"), states it as 5.0 standard deviations in units of the measurement's own uncertainty and 4.8 with the prediction's uncertainty added in quadrature. The record adds that a value near 73 would need a matter fraction near 0.268.

Prediction 16 ($\Omega_c/\Omega_b = 6 - 2/\pi = 5.3634$, the density of the dark matter over the density of the ordinary matter). The South Pole Telescope, Planck and the Atacama Cosmology Telescope together give 5.370 $\pm$ 0.048, 0.14 standard deviations away: Camphuis, E. and others (SPT-3G Collaboration) (2026), "SPT-3G D1: CMB temperature and polarization power spectra and cosmology from 2019 and 2020 observations of the SPT-3G Main field", Physical Review D 113, 083504. Planck alone gives 5.364 $\pm$ 0.065, 0.01 standard deviations away (Aghanim and others 2020, above). Analyses that add the baryon acoustic oscillations of DESI give 5.199 $\pm$ 0.035, 4.7 standard deviations away (about 4.0 with a correlation of -0.4 between the two densities), from one kind of measurement: Louis, T. and others (2025), "The Atacama Cosmology Telescope: DR6 Power Spectra, Likelihoods and ΛCDM Parameters", arXiv:2503.14452. Routes that do not use the microwave background give the share of the ordinary matter in all the matter as 0.1587 $\pm$ 0.0066 and 0.1542 $\pm$ 0.0063 (primordial nucleosynthesis with the oscillations and with the full-shape analysis of DESI) and 0.156 $\pm$ 0.034 (the gas of galaxy clusters), against the predicted 0.15644; *The Weight of Possibility*, Chapter 5, Section II, gives the sources of the three

values: Schöneberg 2024 with DESI Collaboration 2025; Forero-Sánchez and others 2026; Mantz, A. B. and others (2022), "Cosmological constraints from gas mass fractions of massive, relaxed galaxy clusters", Monthly Notices of the Royal Astronomical Society 510, 131 to 145.

Prediction 17 (the shared coefficient $k = 1$, the curvature of the internal dimensions in Planck units, entering $I^2\Omega_\Lambda = 8 - 3k/\pi$ and $\Omega_c/\Omega_b = 6 - 2k/\pi$). The measured ratio gives $k = 0.99 \pm 0.08$ (*The Weight of Possibility*, Chapter 5, Section III). *The Registered Predictions of The Weight of Possibility*, Section IV, gives 0.989 ± 0.075 from the ratio and 1.13 ± 0.21 from the matter fraction (Planck 2018), and, within the analyses that add DESI, 1.26 ± 0.06 and 0.68 ± 0.11. The record's Section XI states that the two DESI values differ by 4.7 standard deviations; *Side by Side*, Volume One ("Figures in the sealed text"), states the difference as 4.6. If the rule holds, the measured ratio gives a ratio of the radius of $\mathbb{C}P^2$ to the radius of S^2 of 2.49 ± 0.28, against the 2.45 ($\sqrt{6}$) of *The Gravitational Passage*.

Chapter 2. What Is Dark Matter?

Prediction 18 ($S_8 = 0.823 \pm 0.006$). The lensing of the microwave background, the complete Kilo-Degree Survey and the growth rate from the motions of galaxies agree within one standard deviation; the final clustering and lensing of the Dark Energy Survey lies 2.5 standard deviations below, and the clusters counted by eROSITA 3.2 above; those two differ from each other by 4.5. *The Weight of Possibility*, Chapter 5, Section VI, gives the sources: Qu and others 2026 and Omori and others 2026 (lensing of the microwave background); Wright, A. H. and others (2025), "KiDS-Legacy: Cosmological constraints from cosmic shear with the complete Kilo-Degree Survey", Astronomy and Astrophysics, arXiv:2503.19441; Alam and others 2021 (growth rate); Abbott, T. M. C. and others (DES Collaboration) (2026), "Dark Energy Survey Year 6 Results: Cosmological Constraints from Galaxy Clustering and Weak Lensing", arXiv:2601.14559; Ghirardini, V. and others (2024), "The SRG/eROSITA all-sky survey: Cosmology constraints from cluster abundances in the western Galactic hemisphere", Astronomy and Astrophysics 689, A298.

Prediction 19 (gravity only). Every such search has found nothing. The LUX-ZEPLIN experiment (LZ), a detector of liquid xenon deep underground, excludes interaction rates down to about 2×10^{-48} cm^2 at 40 GeV (2024), as *The Alphabet of Particles*, entry N3, reports: LZ Collaboration (Aalbers, J. and others) (2025), "Dark Matter Search Results from 4.2 Tonne-Years of Exposure of the LUX-ZEPLIN (LZ) Experiment", Physical Review Letters 135, 011802.

Prediction 20 (no decay). *What Comes After the Dark*, Appendix B, reports that the microwave background and the history of the expansion bound a decay of all of the dark matter into particles that no detector sees to lifetimes beyond about a hundred and sixty billion years: Poulin, V., Serpico, P. D. and Lesgourgues, J. (2016), "A fresh look at linear cosmological constraints on a decaying dark matter component", Journal of Cosmology and Astroparticle Physics 08 (2016) 036. The same appendix gives Penrose's lifetime for his erebons (his name for the particles of the dark matter) as perhaps about a hundred billion years: Penrose, R. (2018), "The Big Bang and its Dark-Matter Content: Whence, Whither, and Wherefore", Foundations of Physics 48, 1177.

Prediction 21 (perfectly cold). The faintest satellite galaxies and the substructure seen by strong lensing place the half-mode mass of any cutoff below about ten million solar masses at 95 percent confidence: Nadler, E. O., Birrer, S., Gilman, D., Wechsler, R. H., Du, X., Benson, A., Nierenberg, A. M. and Treu, T. (2021), "Dark Matter Constraints from a Unified Analysis of Strong Gravitational Lenses and Milky Way Satellite Galaxies", The Astrophysical Journal 917, 7.

Prediction 22 (gyrations of about the Planck mass). The record reports no measurement that reaches this mass ("Untested at this date").

Prediction 24 (the tide only). The record reports no measurement. *Side by Side*, Volume Two, in the register beside Lee Smolin, reports wide binary stars that prefer Newtonian dynamics over the modified dynamics at 19 standard deviations: Banik, I., Pittordis, C., Sutherland, W., Famaey, B.,

Ibata, R., Mieske, S. and Zhao, H. (2024), “Strong constraints on the gravitational law from Gaia DR3 wide binaries”, Monthly Notices of the Royal Astronomical Society 527, 4573–4615.

Chapter 3. What Is Dark Energy?

Prediction 8 ($w = -1$, $w_0 = -1$ and $w_a = 0$; read “w nought” for the present value and “w a” for its rate of change with the scale of the universe). The microwave background with baryon acoustic oscillations and type Ia supernovae gives $w = -1.03 \pm 0.03$ (Aghanim and others 2020, above). The final analysis of the Dark Energy Survey, combined with DESI and the microwave background, gives $w_0 = -0.82 \pm 0.05$ and $w_a = -0.63$ ($+0.21/-0.18$), about three standard deviations from a cosmological constant, and 2.6 without its supernovae: Abbott, T. M. C. and others (Dark Energy Survey Collaboration) (2026), “Constraints on Dynamical Dark Energy from Multiple Probes in the Full Dark Energy Survey”, arXiv: 2605.27221. The record states that this departure rests on one family of combined analyses. *What Comes After the Dark*, Appendix B, adds that the second data release of DESI reports a preference for a present value above -1, at 3.1 standard deviations with the microwave background and 2.8 to 4.2 when supernovae are added (DESI Collaboration 2025, above).

Chapter 4. What Is the Most Basic Element of Matter?

Prediction 26 (color, charge and spin). The record states that most of what *The Quantum Passage* states here has been measured already, and that each measurement found what the book states. *Side by Side*, Volume One, in the register beside Anton Zeilinger, reports the reversal of a spinor’s sign at 360° and its restoration at 720°: Rauch, H., Zeilinger, A., Badurek, G., Wilfing, A., Bauspiess, W. and Bonse, U. (1975), “Verification of coherent spinor rotation of fermions”, Physics Letters A 54, 425–427; Werner, S. A., Colella, R., Overhauser, A. W. and Eagen, C. F. (1975), “Observation of the phase shift of a neutron due to precession in a magnetic field”, Physical Review Letters 35, 1053–1056.

Prediction 30 (the closed list). None has been found. The Large Hadron Collider excludes gluinos below about 2300 GeV, a W′ with the couplings of the W below about 6000 GeV and a Z′ with those of the Z below about 5150 GeV, and leptoquarks below about 1500 to 1800 GeV (*The Alphabet of Particles*, entries N4 to N9). The Micro Booster Neutrino Experiment (MicroBooNE) excluded the single light sterile neutrino proposed to account for the excesses seen by the Liquid Scintillator Neutrino Detector (LSND) and the Mini Booster Neutrino Experiment (MiniBooNE): MicroBooNE Collaboration (2025), "Search for Light Sterile Neutrinos with Two Neutrino Beams at MicroBooNE", Nature 648, 64–69.

Prediction 31 (three generations). The invisible width of the Z counts $N_\nu = 2.9963 \pm 0.0074$ light neutrino species, 0.5 standard deviations from three: Janot, P. and Jadach, S. (2020), "Improved Bhabha Cross Section at LEP and the Number of Light Neutrino Species", Physics Letters B 803, 135319. The rates at which the Large Hadron Collider makes the Higgs boson exclude a fourth generation of the Standard Model kind.

Prediction 35 (no new loop). The measured magnetic moment of the muon less the Standard Model's value of 2025 is $(38 \pm 63) \times 10^{-11}$, against which the zero stands at -0.60 standard deviations: Muon g−2 Collaboration, Aguillard, D. P. and others (2025), "Measurement of the Positive Muon Anomalous Magnetic Moment to 127 ppb", Physical Review Letters 135, 101802; Aliberti, R. and others (Muon g−2 Theory Initiative) (2025), "The anomalous magnetic moment of the muon in the Standard Model: an update", Physics Reports 1143, 1–158. The limit on $\mu \to e\gamma$ is 1.5×10^{-13}, forty-two orders of magnitude above the prediction: MEG II Collaboration (2025), European Physical Journal C 85, 1177.

Chapter 5. Are the Particles' Numbers Just Arbitrary?

Prediction 37 (ceilings and relations). The top quark, 172.60 ± 0.27 GeV, stands near the ceiling of 174.1036 GeV; the charged leptons give 0.66666 for Koide's ratio; global fits prefer the normal order at less than three standard deviations. The record cites no paper for these three values. The top mass is the Particle Data Group's value of 2026 (Takahashi

and others 2026), and the tau mass behind Koide's ratio is its value of 2024 (Navas and others 2024); the preference for the normal order is that of the global fit NuFIT 6.0, at a difference in chi-squared of 6.1 (Esteban and others 2024).

Prediction 38 (neutrino masses). The splittings are $\Delta m^2_{21} = (7.60 \pm 0.17) \times 10^{-5}$ eV^2 and $\Delta m^2_{31} = (2.521 \pm 0.023) \times 10^{-3}$ eV^2, against which the count route stands at -0.94 and -0.36 standard deviations. DESI, in flat ΛCDM (the standard model of cosmology, with a cosmological constant Λ and cold dark matter) with the prior that the sum is positive, bounds the sum below 64.2 meV at 95 percent confidence, a bound that lies between the two routes; with the prior of the normal order, or with an equation of state that varies, both routes lie below the bound (DESI Collaboration 2025, above). The Karlsruhe Tritium Neutrino experiment (KATRIN) bounds the beta decay mass below about 0.45 eV: Aker, M. and others (KATRIN Collaboration) (2025), "Direct neutrino-mass measurement based on 259 days of KATRIN data", Science 388, 180–185.

Prediction 39 (lepton mixing). The lepton phase is measured at $\delta_\ell = 217.8°$ ($+34.2°/-30.6°$). The square of the sine of θ_{23} is 0.533 ± 0.018, against which the segment family's 43.34° stands at -3.44 standard deviations, and at $+0.04$ against the NuFIT 6.0 analysis with the Super-Kamiokande atmospheric data: Esteban, I., Gonzalez-Garcia, M. C., Maltoni, M., Martinez-Soler, I., Pinheiro, J. P. and Schwetz, T. (2024), "NuFit-6.0: updated global analysis of three-flavor neutrino oscillations", Journal of High Energy Physics 12 (2024) 216. The square of the sine of θ_{13} is 0.0217 ± 0.0007. JUNO's first result for the square of the sine of θ_{12} is 0.3092 ± 0.0087: JUNO Collaboration, Abusleme, A. and others (2026), "Measurement of Reactor Neutrino Oscillation with the First JUNO Data", Nature 654, 343–348. The record states that at its six-year precision JUNO would place the carry family's 0.3185 at 6.0 standard deviations if its central value stays at 0.3092.

Prediction 40 (tau mass). The tau mass is measured at 1776.93 ± 0.09 MeV, against which Koide's relation (the record's "balance") stands at +0.43 standard deviations and the ladder at +2.4. The record cites no paper for this value. The value is the Particle Data Group's of 2024 (Navas and others 2024).

Prediction 41 (the quark triangle). The measured values are δ_q = 66.12° ± 1.43° (+0.65 standard deviations from 67.15°), β = 22.62° ± 0.45°, γ = 66.4° (+2.7°/−2.8°) and α = 84.1° (+3.7°/−3.0°). The record states that with the central value of α kept at 84.1°, the right angle lies outside two standard deviations once the upper uncertainty of α falls below 2.95°, and outside three below 1.97°. The record cites no paper for these values. The four values are those of the Particle Data Group's review of the quark-mixing matrix (Takahashi and others 2026), which gives β through the measured sin 2β = 0.710 ± 0.011, and δ_q as 1.154 ± 0.025 radians.

Prediction 42 (strength of color, W and Z, Higgs, top). The measured values are $\alpha_s(M_Z)$ = 0.1180 ± 0.0009 (+0.97 standard deviations), M_W = 80.3625 ± 0.0077 GeV, M_H = 125.13 ± 0.11 GeV (against which the four forms stand at +0.38 to +0.86) and m_t = 172.60 ± 0.27 GeV (all six readings within 0.7 standard deviations). The coefficient of the span (the second-order coefficient of the count of halvings from the electron's mass to the reduced Planck mass) is 3.7120 ± 0.0835 from Newton's constant and the electron, given ε = $11/(80\pi^2)$ (+0.05). The record cites no paper for these values. The strength of color is the world average in the Particle Data Group's edition of 2024 (Navas and others 2024); the W, Higgs and top masses are its values of 2026 (Takahashi and others 2026), the W mass being the combination of the LHC and Tevatron W-mass working group of May 2026, which that edition takes as the world average; the coefficient of the span is computed, in *The Strengths of the Kinds*, Chapter 5, Box IV-1, from Newton's constant and the electron's mass as the recommended values of 2022 give them (Mohr and others 2025). The record makes four further statements of Prediction 42. The strength of color comes from the second closure with the value 21/4 of the gap count at the span's end, which *The Strengths of the Kinds* carries beside the value 5, and with the

level 169/4 of the couplings. The W and Z masses and the weak angle come from the carriers' law joined to the relation of light, with the SMDR form of the matching (SMDR: Standard Model in Dimensional Regularization, the program of Martin and Robertson). These values carry the law's own agreement with the measured masses and add no independent evidence. The level 169/4 holds if and only if the W mass lies within about 5 MeV of 80.3488 GeV. The measured excess of the Higgs self-coupling over 1/8 agrees with $1/(24\pi^2)$.

Chapter 7. Why Is Gravity So Different from the Other Forces?

Prediction 4 (universal free fall; no shield). MICROSCOPE, titanium and platinum, gives an Eötvös parameter of $[-1.5 \pm 2.3\ \text{(statistical)} \pm 1.5\ \text{(systematic)}] \times 10^{-15}$: Touboul, P. and others (MICROSCOPE Collaboration) (2022), "MICROSCOPE Mission: Final Results of the Test of the Equivalence Principle", Physical Review Letters 129, 121102. Antihydrogen falls toward the Earth at $(0.75 \pm 0.13 \pm 0.16)$ g, where g is the acceleration with which matter falls at the Earth's surface: Anderson, E. K. and others (ALPHA-g Collaboration) (2023), "Observation of the effect of gravity on the motion of antimatter", Nature 621, 716–722. No shielding is found, with an absorption coefficient of $(3 \pm 5) \times 10^{-23}$ cm^2 g^{-1}: Williams, J. G., Turyshev, S. G. and Boggs, D. H. (2009), "Lunar laser ranging tests of the equivalence principle with the Earth and Moon", International Journal of Modern Physics D 18, 1129–1175.

The chapter also draws on: *The Matter We Know, Volume One*, Chapter 11, Section I.

Chapter 8. How Does Gravity Meet the Quantum?

Prediction 1 (entanglement through gravitation). No experiment has yet reported entanglement through gravitation alone, or its absence at a sensitivity that reaches the predicted phase. The proposal: Bose, S. and others (2017), "Spin Entanglement Witness for Quantum Gravity", Phys-

ical Review Letters 119, 240401; the witness: Chevalier, H., Paige, A. J. and Kim, M. S. (2020), "Witnessing the nonclassical nature of gravity in the presence of unknown interactions", Physical Review A 102, 022428.

Prediction 2 (no collapse from gravitation alone). An underground search for the radiation that collapse noise would make has ruled out the version of the Diósi and Penrose model with no free parameter; versions with a larger effective size remain under test: Donadi, S., Piscicchia, K., Curceanu, C., Diósi, L., Laubenstein, M. and Bassi, A. (2021), "Underground test of gravity-related wave function collapse", Nature Physics 17, 74–78.

Prediction 3 (no quantum of the arena). The first gravitational wave detected matched the classical waveform of general relativity, and no graviton has been detected: Abbott, B. P. and others (LIGO Scientific Collaboration and Virgo Collaboration) (2016), "Observation of gravitational waves from a binary black hole merger", Physical Review Letters 116, 061102.

Prediction 6 (two polarizations; speed of light). The three-detector event GW170814 favors purely tensor polarization: Abbott, B. P. and others (2017), "GW170814: A Three-Detector Observation of Gravitational Waves from a Binary Black Hole Coalescence", Physical Review Letters 119, 141101. GW170817 with its gamma-ray burst bounds the difference between the speed of gravitational waves and the speed of light to between -3×10^{-15} and $+7 \times 10^{-16}$ of the speed of light: Abbott, B. P. and others (2017), "Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A", Astrophysical Journal Letters 848, L13.

Chapter 9. Is There a Theory of Everything?

Prediction 33 (no proton decay). The lifetime for decay into a positron and a neutral pion exceeds 2.4×10^{34} years, and (*What Comes After the Dark*, Appendix B) for decay into a muon and a neutral pion it exceeds sixteen million billion billion billion years (1.6×10^{34} years), each at 90 percent confidence: Takenaka, A. and others (Super-Kamiokande Collab-

oration) (2020), "Search for proton decay via $p \to e^+\pi^0$ and $p \to \mu^+\pi^0$ with an enlarged fiducial volume in Super-Kamiokande I–IV", Physical Review D 102, 112011. The reaches of the coming searches are from Hyper-Kamiokande Proto-Collaboration (2018), "Hyper-Kamiokande Design Report", arXiv:1805.04163, and DUNE Collaboration, Abi, B. and others (2020), "Deep Underground Neutrino Experiment (DUNE), Far Detector Technical Design Report, Volume II: DUNE Physics", arXiv:2002.03005, as *What Comes After the Dark*, Appendix B, cites them.

Prediction 36 (running only at known masses). The running of the strength of light from zero momentum to the Z mass, and of the strength of color from the tau mass to the TeV scale (a TeV is a trillion electron volts), follows the rates of the closed list; no measured running differs from them. The record cites no paper for this statement. The measured strength of light at zero momentum is the recommended value of 2022 (Mohr and others 2025), and at the Z mass the value of the Particle Data Group's review of the electroweak model (Navas and others 2024); the measured strength of color, from the tau mass to beyond two TeV, is summarized in its review of quantum chromodynamics (Navas and others 2024, Figure 9.5), against the running computed from its world average.

Chapter 10. What Is Space?

Prediction 5 (no least length). The arrival of high-energy photons from gamma-ray bursts places any energy dependence of the first order above about ten times the Planck energy: Cao, Z. and others (LHAASO Collaboration) (2024), "Stringent tests of Lorentz invariance violation from LHAASO observations of GRB 221009A", Physical Review Letters 133, 071501. *Side by Side*, Volume Two, in the register beside Lee Smolin, adds the earlier bound above 1.2 Planck energies: Abdo, A. A. and others (Fermi LAT and Fermi GBM Collaborations) (2009), "A limit on the variation of the speed of light arising from quantum gravity effects", Nature 462, 331–334.

Chapter 13. Why Does Time Only Go Forward?

Prediction 28 (no perfect determinism or reversibility). The violations of CP (1964) and of time reversal (the CPLEAR experiment at CERN, 1998; the BaBar experiment at SLAC, 2012) are consistent with the required asymmetry: Angelopoulos, A. and others (CPLEAR Collaboration) (1998), "First direct observation of time-reversal non-invariance in the neutral-kaon system", Physics Letters B 444, 43–51; Lees, J. P. and others (BaBar Collaboration) (2012), "Observation of time-reversal violation in the B^0 meson system", Physical Review Letters 109, 211801. The violation of CP of 1964 is that of Christenson, Cronin, Fitch and Turlay, as the corpus books cite it.

Prediction 34 (strong CP; no axion). The neutron's electric dipole moment is below 1.8×10^{-26} e cm (e cm is the charge of the electron times a centimeter), so $\bar{\theta}$ (read "theta bar") is below 1.8×10^{-10}: Abel, C. and others (2020), "Measurement of the permanent electric dipole moment of the neutron", Physical Review Letters 124, 081803. The photon mass is below 10^{-18} eV; the record cites no paper for this bound. The bound is the Particle Data Group's (Takahashi and others 2026).

Chapter 15. Can We Travel Faster Than Light?

Prediction 27 (no signal faster than light). The record reports no measurement under Prediction 27. *Side by Side*, Volume One, in the register beside Nicolas Gisin, reports that his group in 2008 bounded the speed of any influence between entangled findings from below at ten thousand times the speed of light, under the frame condition that register states: Salart, D., Baas, A., Branciard, C., Gisin, N. and Zbinden, H. (2008), "Testing the speed of 'spooky action at a distance'", Nature 454, 861–864.

Chapter 19. Why Are We Made of Matter, Not Antimatter?

Prediction 15 (one sign everywhere). The record reports no measurement under Prediction 15.

Prediction 32 (Dirac neutrinos; no neutrinoless double beta decay). No experiment has observed the decay: the complete KamLAND-Zen 800 data give a half-life above 3.8×10^{26} years in xenon-136 (Abe, S. and others (KamLAND-Zen Collaboration) (2025), "Search for Majorana Neutrinos with the Complete KamLAND-Zen Dataset", Physical Review Letters 135, 262501), and LEGEND-200, the Germanium Detector Array (GERDA) and the MAJORANA DEMONSTRATOR, three experiments with germanium detectors, together give above 1.9×10^{26} years in germanium-76 (LEGEND Collaboration, Acharya, H. and others (2026), "First results on the search for lepton number violating neutrinoless double-β decay with the LEGEND-200 experiment", Physical Review Letters 136, 022701), each at 90 percent confidence.

Chapter 20. What Happened During the Big Bang?

Prediction 9 (flat to the size of the departures). The microwave background with baryon acoustic oscillations gives $\Omega_K = 0.001 \pm 0.002$ (Aghanim and others 2020, above). *Side by Side*, Volume Two, Appendix O, reports that the second data release of DESI with the microwave background gives 0.0023 ± 0.0011, on the open side, at about two standard deviations from zero (Abdul-Karim and others 2025, above, as discussed by Chen, S.-F. and Zaldarriaga, M. (2025), "It's All Ok: Curvature in Light of BAO from DESI DR2", arXiv:2505.00659).

Prediction 10 (no primordial gravitational waves). The ratio of tensor to scalar power is bounded at $r < 0.032$, and no primordial tensor signal has been detected: Tristram, M. and others (2022), "Improved Limits on the Tensor-to-Scalar Ratio Using BICEP and Planck Data", Physical Review D 105, 083524. *What Comes After the Dark*, Appendix B, gives the bound of the BICEP and Keck telescopes with Planck and WMAP as below about three parts in a hundred at 95 percent confidence: Ade, P. A. R. and others (BICEP/Keck Collaboration) (2021), "Improved Constraints on Primordial Gravitational Waves Using Planck, WMAP, and BICEP/Keck Observations through the 2018 Observing Season", Physical Review Letters 127, 151301. The record states the reach of the coming instruments

as about one part in a thousand for the Simons Observatory and below two parts in a thousand for LiteBIRD. *Side by Side*, Volume One ("Figures in the sealed text"), gives the published targets as about three parts in a thousand for the Simons Observatory and about one part in a thousand for LiteBIRD. *What Comes After the Dark*, Appendix B, gives them as a targeted uncertainty of three parts in a thousand for the Simons Observatory (Ade and others 2019) and a required uncertainty below one part in a thousand for LiteBIRD (LiteBIRD Collaboration, Allys, E. and others (2023), "Probing Cosmic Inflation with the LiteBIRD Cosmic Microwave Background Polarization Survey", Progress of Theoretical and Experimental Physics 2023, 042F01).

Prediction 11 (adiabatic). The microwave background bounds an isocurvature mode at a few percent of the power: Akrami, Y. and others (Planck Collaboration) (2020), "Planck 2018 results. X. Constraints on inflation", Astronomy and Astrophysics 641, A10.

Prediction 12 (one pattern). The record states the excluded white noise of independent pieces as "an index of four in the curvature". The spectral index is 0.965 ± 0.004 (Aghanim and others 2020, above).

Prediction 14 (gravitational waves of an epoch). The record's Section XI reports the background seen by the pulsar-timing arrays; the record cites no paper for the background. The background is the one the NANOGrav Collaboration reported from fifteen years of timing 67 pulsars (Agazie and others 2023).

Chapter 23. How Big Is the Universe?

Prediction 23 (no short loop). Searches of the microwave background find every such path through our location longer than 98.5 percent of the diameter of the last scattering surface: Petersen, P. and others (2023), "Cosmic topology. Part I. Limits on orientable Euclidean manifolds from circle searches", Journal of Cosmology and Astroparticle Physics 2023 (01), 030.

Prediction 25 (the statistics of quantum theory). Three-slit experiments find the third term consistent with zero: Sinha, U., Couteau, C., Jennewein, T., Laflamme, R. and Weihs, G. (2010), "Ruling out multi-order interference in quantum mechanics", Science 329, 418–421. Network experiments in 2022 found the complex composition: Chen, M.-C. and others (2022), "Ruling out real-valued standard formalism of quantum theory", Physical Review Letters 128, 040403; Li, Z.-D. and others (2022), "Testing real quantum theory in an optical quantum network", Physical Review Letters 128, 040402.

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Abbott, B. P., and others (LIGO Scientific Collaboration and Virgo Collaboration), "GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral", *Physical Review Letters* 119 (2017) 161101.

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People in the Scenes

Jorge Cham, cartoonist and creator of the online comic *PHD Comics*: *We Have No Idea* (2017) and *Frequently Asked Questions About the Universe* (2021), the two books as the reader opens them; Preface, "A Frequently Asked Preface".

Daniel Whiteson, professor of experimental particle physics at the University of California, Irvine: *We Have No Idea* (2017) and *Frequently Asked Questions About the Universe* (2021), the two books as the reader opens them; Preface, "A Frequently Asked Preface".

Jean-Jacques Dordain, Director General of the European Space Agency: the media briefing on the first Planck cosmology results, ESA Headquarters, Paris, 21 March 2013; Chapter 1, "What Is the Universe Made Of?".

George Efstathiou, Director of the Kavli Institute for Cosmology, University of Cambridge: the same briefing, ESA Headquarters, Paris, 21 March 2013; Chapter 1, "What Is the Universe Made Of?".

Vera Rubin, Department of Terrestrial Magnetism, Carnegie Institution of Washington: observations of the Andromeda galaxy at Lowell Observatory and Kitt Peak in the late 1960s, published February 1970; Chapter 2, "What Is Dark Matter?".

Kent Ford, Department of Terrestrial Magnetism, Carnegie Institution of Washington: the same observations, Lowell Observatory and Kitt Peak, late 1960s, published February 1970; Chapter 2, "What Is Dark Matter?".

Albert Einstein: his paper on the static universe read to the Prussian Academy of Sciences, Berlin, 8 February 1917, and his letter of 4 February 1917; Chapter 3, "What Is Dark Energy?".

Paul Ehrenfest: recipient in Leiden of Einstein's letter of 4 February 1917; Chapter 3, "What Is Dark Energy?".

Joseph John Thomson, professor of experimental physics at Cambridge: his talk on cathode rays at the weekly evening meeting of the Royal Institution, London, Friday 30 April 1897; Chapter 4, "What Is the Most Basic Element of Matter?".

Johann Jakob Balmer, teacher at a girls' school, then about sixty years old: his rule for the lines of hydrogen, Basel, 1885; Chapter 5, "Are the Particles' Numbers Just Arbitrary?".

Anders Ångström, Swedish physicist: named in the scene of Basel, 1885, as the measurer of the four wavelengths of hydrogen that Balmer used; Chapter 5, "Are the Particles' Numbers Just Arbitrary?".

Eduard Hagenbach-Bischoff, physicist and Balmer's friend: told Balmer of the observed fifth line and further lines of hydrogen, Basel, 1885; Chapter 5, "Are the Particles' Numbers Just Arbitrary?".

Niels Bohr, Danish physicist: gave the reason for Balmer's rule in 1913; Chapter 5, "Are the Particles' Numbers Just Arbitrary?".

Fabiola Gianotti, spokesperson of the ATLAS experiment: the seminar at which ATLAS and CMS reported the new particle, CERN, near Geneva, 4 July 2012; Chapter 6, "What Is Mass?".

Joe Incandela, spokesperson of the CMS experiment: the same seminar, CERN, near Geneva, 4 July 2012; Chapter 6, "What Is Mass?".

Peter Higgs, theorist: invited to the same seminar and present at it, CERN, near Geneva, 4 July 2012; Chapter 6, "What Is Mass?".

François Englert, theorist: invited to the same seminar and present at it, CERN, near Geneva, 4 July 2012; Chapter 6, "What Is Mass?".

David Scott, Apollo 15 astronaut: the hammer and the feather, during the crew's third walk on the lunar surface, Hadley landing site, the Moon, 2 August 1971; Chapter 7, "Why Is Gravity So Different from the Other Forces?".

Joe Allen, astronaut, speaking to the crew from the ground: his answer to the fall of the hammer and the feather, Houston, 2 August 1971; Chapter 7, "Why Is Gravity So Different from the Other Forces?".

Marco Drago, physicist: the automated e-mail of 11:53 in the morning, local time, with the two plots of the gravitational-wave signal, Max Planck Institute for Gravitational Physics, Hannover, Germany, 14 September 2015; Chapter 8, "How Does Gravity Meet the Quantum?".

Andrew Lundgren, Drago's colleague: asked by Drago, in Lundgren's office, whether he knew of a planted signal, the same institute, Hannover, 14 September 2015; Chapter 8, "How Does Gravity Meet the Quantum?".

Howard Georgi, physicist at Harvard University: the unified scheme of the three forces, worked out at home in one evening, Cambridge, Massachusetts, January 1974; Chapter 9, "Is There a Theory of Everything?".

Sheldon Glashow: Georgi's partner in the attempt, to the end of 1973, to join the weak and the electromagnetic forces; Chapter 9, "Is There a Theory of Everything?". He was Georgi's coauthor of "Unity of All Elementary-Particle Forces", published in *Physical Review Letters* in February 1974.

Gottfried Wilhelm Leibniz: his third paper to Clarke, dated at Hanover on 25 February 1716, in the exchange begun in 1715; Chapter 10, "What Is Space?".

Caroline, Princess of Wales, who had gone to London with the court of Hanover: received every paper of the exchange and passed it to the other side, 1715 to 1716; Chapter 10, "What Is Space?".

Samuel Clarke: answered Leibniz's papers and printed the exchange, London, 1717; Chapter 10, "What Is Space?".

Theodor Kaluza, a young mathematician who lectured at the university in Königsberg: sent his five-dimensional theory to Einstein early in 1919; Chapter 11, "How Many Dimensions Are There?".

Albert Einstein: replied to Kaluza on 21 April 1919, and submitted Kaluza's paper to the Prussian Academy of Sciences, Berlin, on 8 December 1921; Chapter 11, "How Many Dimensions Are There?".

Oskar Klein: proposed in 1926 that the fifth dimension is curled into a small circle; Chapter 11, "How Many Dimensions Are There?".

Joseph C. Hafele, assistant professor of physics, Washington University in St. Louis: four cesium beam clocks flown twice around the world on ordinary scheduled airliners, first two weeks of October 1971; Chapter 12, "What Is Time?".

Richard E. Keating, astronomer of the United States Naval Observatory, Washington: the same flights, first two weeks of October 1971; Chapter 12, "What Is Time?".

Arthur Stanley Eddington: the Gifford Lectures, University of Edinburgh, January to March 1927, published in 1928 as *The Nature of the Physical World*; Chapter 13, "Why Does Time Only Go Forward?".

Kurt Gödel, logician: his rotating world and his essay for Einstein's seventieth birthday, Institute for Advanced Study, Princeton, 1949; Chapter 14, "Why Can't I Travel Back in Time?".

Albert Einstein: his reply to Gödel in the same volume, Institute for Advanced Study, Princeton, 1949; Chapter 14, "Why Can't I Travel Back in Time?".

Ole Rømer, astronomer of the Royal Academy of Sciences: the emersion of Io seen ten minutes late on 9 November 1676, Paris; Chapter 15, "Can We Travel Faster Than Light?". He had predicted at the beginning of September 1676 that this emersion would come late, and his account appeared in the *Journal des Sçavans* on 7 December 1676.

Victor Hess, observer of the electricity of the air: the flight of the hydrogen balloon *Böhmen*, 7 August 1912; Chapter 16, "Who Is Shooting Superfast Particles at the Earth?". The balloon rose from Aussig on the Elbe at twelve minutes past six in the morning and came down at Pieskow, fifty kilometers east of Berlin.

Captain W. Hoffory, who flew the balloon *Böhmen*: the same flight, 7 August 1912; Chapter 16, "Who Is Shooting Superfast Particles at the Earth?".

E. Wolf, who kept the weather observations: the same flight, 7 August 1912; Chapter 16, "Who Is Shooting Superfast Particles at the Earth?".

Enrico Fermi: the walk to lunch at Fuller Lodge and his question at the lunch table, Los Alamos, New Mexico, summer 1950; Chapter 17, "What's Stopping Anyone from Traveling Between the Stars?".

Edward Teller: the same walk and lunch, Los Alamos, New Mexico, summer 1950; Chapter 17, "What's Stopping Anyone from Traveling Between the Stars?".

Emil Konopinski: the same walk and lunch, at which he brought up a cartoon from *The New Yorker*, Los Alamos, New Mexico, summer 1950; Chapter 17, "What's Stopping Anyone from Traveling Between the Stars?".

Herbert York: the same walk and lunch, Los Alamos, New Mexico, summer 1950; Chapter 17, "What's Stopping Anyone from Traveling Between the Stars?".

Frank Drake: the first day of Project Ozma, with the Howard Tatel telescope of the National Radio Astronomy Observatory, Green Bank, West Virginia, 8 April 1960; Chapter 18, "Are We Alone?".

Carl Anderson: the cloud-chamber photograph of the positron, California Institute of Technology, Pasadena, California, 2 August 1932; Chapter 19, "Why Are We Made of Matter, Not Antimatter?".

Arno Penzias, radio astronomer of Bell Laboratories: measurements with the twenty-foot horn-reflector, Crawford Hill Laboratory, Holmdel, New Jersey, July 1964 to April 1965 (the antenna turned to the sky from 1963); Chapter 20, "What Happened During the Big Bang?".

Robert Wilson, radio astronomer of Bell Laboratories: the same measurements, Crawford Hill Laboratory, Holmdel, New Jersey, July 1964 to April 1965; Chapter 20, "What Happened During the Big Bang?".

Bernard Burke, of the Massachusetts Institute of Technology: named in the same scene as the colleague to whom Penzias mentioned the unexplained noise; Chapter 20, "What Happened During the Big Bang?".

Robert Dicke, of Princeton: named in the same scene as the physicist whom Penzias then called, and as an author of the companion letter of 1965; Chapter 20, "What Happened During the Big Bang?".

James Peebles, of Princeton: named in the same scene as the author of the paper, then unpublished, that Dicke sent to Penzias, and as an author of the companion letter of 1965; Chapter 20, “What Happened During the Big Bang?”.

P. G. Roll, of Princeton: named in the same scene by surname, as an author of the companion letter of 1965; Chapter 20, “What Happened During the Big Bang?”.

D. T. Wilkinson, of Princeton: named in the same scene by surname, as an author of the companion letter of 1965; Chapter 20, “What Happened During the Big Bang?”.

J. Robert Oppenheimer: the paper on continued gravitational contraction, University of California, Berkeley, received by *Physical Review* on 10 July 1939; Chapter 21, “What Happens If I Fall into a Black Hole?”.

Hartland Snyder: the same paper, University of California, Berkeley, received on 10 July 1939; Chapter 21, “What Happens If I Fall into a Black Hole?”.

Stephen Hawking: his paper “The Boundary Conditions of the Universe” at the study week on cosmology and fundamental physics, Pontifical Academy of Sciences, Vatican City, 28 September to 2 October 1981; Chapter 22, “What Came Before the Big Bang?”.

Edwin Hubble: plate H335H of the Andromeda Nebula, taken with the Hooker telescope, Mount Wilson Observatory, California, night of 5 to 6 October 1923; Chapter 23, “How Big Is the Universe?”.

Harlow Shapley, of Mount Wilson: the debate “The Scale of the Universe”, meeting of the National Academy of Sciences, Washington, 26 April 1920; Chapter 23, “How Big Is the Universe?”.

Heber Curtis, of the Lick Observatory: the same debate, Washington, 26 April 1920; Chapter 23, “How Big Is the Universe?”.

Hugh Everett III, graduate student in physics: his doctoral thesis, Princeton University, submitted 1 March 1957, and his paper of July 1957; Chapter 24, “Is There Another You?”.

John Wheeler: named in the same scene as Everett's adviser, Princeton, 1957; Chapter 24, "Is There Another You?".

Dik Bouwmeester: the teleportation of the polarization of a photon, Institute for Experimental Physics, University of Innsbruck, Austria, reported in *Nature* on 11 December 1997; Chapter 25, "Why Can't We Teleport?".

Jian-Wei Pan: the same experiment, Innsbruck, reported on 11 December 1997; Chapter 25, "Why Can't We Teleport?".

Klaus Mattle: the same experiment, Innsbruck, reported on 11 December 1997; Chapter 25, "Why Can't We Teleport?".

Manfred Eibl: the same experiment, Innsbruck, reported on 11 December 1997; Chapter 25, "Why Can't We Teleport?".

Harald Weinfurter: the same experiment, Innsbruck, reported on 11 December 1997; Chapter 25, "Why Can't We Teleport?".

Anton Zeilinger: the same experiment, Innsbruck, reported on 11 December 1997; Chapter 25, "Why Can't We Teleport?".

Edward Lorenz, meteorologist: the rerun of his weather model, Massachusetts Institute of Technology, around 1960; Chapter 26, "Are Humans Predictable?".

Nick Bostrom, Faculty of Philosophy, Oxford University: his paper "Are You Living in a Computer Simulation?", published in *Philosophical Quarterly*, 2003; Chapter 27, "Do We Live in a Computer Simulation?".

Stephen Hawking: his talk and concession at the 17th International Conference on General Relativity and Gravitation, Dublin, Wednesday 21 July 2004; Chapter 28, "Is an Afterlife Possible?".

John Preskill, physicist at the California Institute of Technology: on the stage during the same talk, and the one who accepted the baseball encyclopedia that Hawking offered in conceding the bet, Dublin, 21 July 2004; Chapter 28, "Is an Afterlife Possible?".

Kip Thorne, Hawking's partner in the bet: on the stage during the same talk, Dublin, 21 July 2004; Chapter 28, "Is an Afterlife Possible?".

William Thomson, later Lord Kelvin: his paper "On a Universal Tendency in Nature to the Dissipation of Mechanical Energy", meeting of the Royal Society of Edinburgh, Edinburgh, 19 April 1852; Chapter 29, "How Will the Universe End?". He was then twenty-seven years old and professor of natural philosophy at the University of Glasgow.

Rudolf Clausius, professor of physics at the Swiss Federal Technical Institute: read his paper naming entropy to the Natural Science Society of Zürich, Zürich, 24 April 1865; Chapter 30, "Will Time Ever Stop?".

Freeman Dyson, of the Institute for Advanced Study, Princeton: the four James Arthur Lectures on Time and its Mysteries, New York University, autumn 1978; Chapter 31, "How Long Will Humanity Survive?".

Kurt Gödel: announced his first incompleteness theorem in the general discussion of the Second Conference on the Epistemology of the Exact Sciences, Königsberg, 7 September 1930; Chapter 32, "Will Science One Day Answer Everything?".

David Hilbert: his address "Naturerkennen und Logik" to the congress of the Society of German Scientists and Physicians, of which a four-minute part was broadcast by radio, Königsberg, 8 September 1930; Chapter 32, "Will Science One Day Answer Everything?".

Emil du Bois-Reymond: his address to the Society of German Scientists and Physicians, 1872; Chapter 32, "Will Science One Day Answer Everything?".

Jorge Cham: *Frequently Asked Questions About the Universe* (2021), and the listeners' letters as its last chapter reports them; Chapter 33, "What Does That Even Mean?". The book was made from the questions that listeners sent to the twice-weekly podcast *Daniel and Jorge Explain the Universe*.

Daniel Whiteson: the same book of 2021 and the same listeners' letters; Chapter 33, "What Does That Even Mean?".

Terms

Each term below is explained in plain words in the Preface or in the chapter named on the last line of the term's entry, and that part of this book is the first part to explain the term. The entries are reminders of the plain explanations in the Preface and the chapters, collected in one place. In the entries, "the authors" are Jorge Cham and Daniel Whiteson, and a headword followed by "the authors' word" in parentheses gives the word or phrase that Cham and Whiteson use for the subject this book treats under the headword.

Absolute zero. The coldest cold there is. Chapter 20.

Act of comparing. The first of the three positions of every comparison: the relating, the bringing of two things into relation. Chapter 4.

Ancestor-simulation. The philosopher Nick Bostrom's name for a run of the whole mental history of humankind on a computer of a civilization far ahead of ours. Chapter 27.

Annihilation. The making of a pair of particles run the other way: a particle and its antiparticle meet, both disappear, and their energy leaves, most often as two photons. Chapter 19.

Anomaly cancellation. The requirement that certain sums over the particles of one generation come to zero. The physicists' description of the forces is consistent exactly when the sums over the particles of one generation come to zero, and physicists call a failure of the sums an anomaly. Chapter 5.

Antihydrogen. The antimatter counterpart of a hydrogen atom: a particle with the proton's mass and the opposite charge, bound to a particle with the electron's mass and the opposite charge. Chapter 7.

Antimatter. Matter whose particles have the same masses as the particles of ordinary matter and the opposite charges. Chapter 4.

Antineutrino. The antimatter partner of a neutrino. Chapter 18.

Antiparticle. A particle that has the same mass as a second particle and carries every label of the second particle reversed. Chapter 19.

Antipode. The point directly opposite you on the far side of a globe. Chapter 15.

Antiquark. The mirror partner of a quark, with the opposite charges. Chapter 9.

Arena (the authors' word: gravity, one of four forces). Space and time together: two of the three settings, the space and the time in which every finding of physics is made. Gravity is the arena, the stage of space and time on which the three forces (electromagnetism, the strong force and the weak force) act, and so gravity stands beside the three forces and is not a fourth force. Chapter 7.

Asymmetric. Said of a thing that is different everywhere, as the height along a ramp is. Chapter 1.

Asymptotic safety. A research program in which physicists treat the geometry of space and time as one more field whose strength changes with scale. Chapter 9.

Atemporal. Without time. Chapter 28.

Axioms. The basic statements on which an account is built. The third axiom of my account has three clauses, the three facts about the settings set out in Chapter 1: the settings are inseparable, not interchangeable and distinct; the third axiom holds of every comparison, and this book uses it for the three settings (Chapter 1) and for content and context (Chapters 22, 28 and 29). Chapter 1.

B minus L. The baryon count less the lepton count. Chapter 19.

Balance. The settled state of a crowd of particles in which every reaction runs as often forward as backward. Chapter 19.

Baryon. A whole made of three quarks, such as the proton and the neutron. Chapter 19.

Baryon count. The number of baryons less the number of antibaryons. Chapter 19.

Beam splitter. A half-silvered mirror that lets part of the light through and turns the rest aside. Chapter 25.

Bend (the authors' word: the 95 percent we have no idea about). When a setting is out of its plain shape, the setting is bent. A setting's plain shape is the same throughout, and a bent setting is uneven: one part of the setting differs from another part. Gravitation bends space, the cosmological constant bends time, and the dark matter bends possibility. Preface.

Billion. A thousand million. Chapter 1.

Black dwarf. The dark body that a white dwarf becomes when the white dwarf has cooled. Chapter 31.

Black hole. A region in which matter is packed so densely that nothing that falls in, not even light, comes back out. Chapter 2.

Bound. Held to something by gravity, as the Earth is held to the Sun. Chapter 29.

Bound triple. The arrow of time, hard randomness and the subjective, taken together. Chapter 27.

Boundary condition. The state that a set of equations is given at an edge, from which the equations then run, such as the starting position of a thrown ball, or the temperature of a rod at its two ends. Chapter 22.

C P. Swapping every particle for its charge-reversed twin and mirroring space, the two together. The letters stand for charge and parity, and parity is the physicists' name for the mirroring of space. Chapter 13.

Carriers. The photon, the electron and the proton: the three positions of comparison (the act of comparing, the thing compared and the thing compared against), present in the world as particles. Chapter 4.

Category error. Applying a concept where the concept does not belong, so that a request that uses the concept there cannot be met because the request is badly formed, which is a different thing from being hard to meet. Chapter 8.

Cathode rays. The glow that streams from the negative metal plate of a glass tube from which nearly all the air has been pumped. Chapter 4.

Causality. In the authors' use, the rule that effects follow their causes. Chapter 15.

Causation. A one-way relation between findings, in which the first finding makes a difference to the second finding. In Chapter 15, causation is the cone of what can reach what at each event. Chapter 26.

Ceiling. The limit of about a hundred seventy-four GeV above which no particle of matter can be heavier. The structure of comparison sets the ceiling. Chapter 5.

Cepheid. A star that brightens and fades in a steady rhythm: the length of the rhythm shows how bright the star truly is. Chapter 23.

CERN. The European laboratory for particle physics near Geneva. Preface.

Cesium beam clock. A clock that keeps time by counting the waves of a radio signal held in tune by atoms of cesium. Chapter 12.

Channel. One way in which a thing can be found, as a cup is found by sight, by its warmth and by its weight. Chapter 2.

Chaotic. In the physicists' sense, which the authors use, said of a system so sensitive to small changes that a tiny error in a forecast of the system grows until the forecast is worthless. Chapter 26.

Charge. The property that a force takes hold of, as electric force takes hold of electric charge. Chapter 2.

Classical. In the sense of my book *The Last Turtle*, said of a thing that can be virtualized: someone can build a model of the thing that behaves as the original does for every purpose that matters. Chapter 25.

Closed system. A system that nothing enters and nothing leaves. Chapter 27.

Closed timelike curve. A path in space and time that a clock could follow and that returns to where and when it started. Chapter 14.

Closed universe. In the physicist Freeman Dyson's use, a universe whose expansion stops and turns into a collapse. In Dyson's use, an open universe is a universe that expands forever. Chapter 31.

Closure account. The second account in my book *Why These Numbers* (the first is the working account), with one further stated step in the way the step of the ladder of masses is written. The closure account needs one measured input, the electron's mass. Chapter 5.

Cloud chamber. A closed vessel of damp gas in which a fast charged particle leaves a line of tiny droplets behind the particle, as a high jet leaves a white trail across a cold sky. Chapter 19.

Cold. Said of dark matter, in the astronomers' sense: moving so slowly that the dark matter clumps on every scale, down to the smallest. Chapter 2.

Collective passage. A shift of the whole field of the weak force at once. Each collective passage turns up nine quarks and three leptons together. Chapter 19.

Collider. A machine in which particles are smashed together so that physicists can see what comes out. The Large Hadron Collider at CERN is a collider in the shape of a great ring. Preface.

Color. The physicists' name for the charge that the strong force acts on. Color comes in three kinds, and the word is only a name: nothing about a quark is colored. Chapter 5.

Color field. The field of the strong force. Chapter 6.

Column. In the words of my book *The Weight of Possibility*, one setting together with the content found in that setting. Chapter 1.

Common source (the authors' word: Theory of Everything). When two descriptions arise from the same act of comparison and apply to the same world, and each is perfected in one of the two characters a comparison allows, the two descriptions have a common source. One character is separate, countable steps, each step the same wherever it is found, and the other character is smoothness that differs from place to place. Chapter 9.

Compact. Said of a dimension with a finite extent. The compact dimensions of this book also have no edge, as the surface of a ball has a finite area and no edge. Chapter 11.

Comparer (the authors' word: observer). Whatever makes a comparison: a person, an instrument, a detector, an atom, anything that registers one thing against another, whether or not the comparer has a mind. Chapter 1.

Comparison. The act of finding whether two things are the same or different in some respect. Every measurement is a comparison. Chapter 1.

Complete. Said of a system in which every true statement in its language can be proved. Chapter 32.

Computation. A passage from one list of separate marks to the next by one rule applied the same way at every step. Chapter 25.

Condensate. The one steady value into which the Higgs field settles everywhere in space. Chapter 5.

Confinement mass. The mass of a whole whose parts cannot get out, which is the proton's kind of mass. Chapter 6.

Conjugate. When neither of two things comes before the other, and each can be made perfect only at the expense of the other, the two things are conjugate. Chapter 8.

Consistent. Said of a system that never proves a statement both true and false. Chapter 32.

Content (the authors' word: normal matter, the 5 percent). What a finding finds: in your finding that your coffee is warm, the warmth of the coffee. Chapter 1.

Context. Where the content of a finding is found. The context has three sides, the three settings of space, time and possibility. Chapter 1.

Continuous. Said of a thing in which nothing is sudden: a small move in a setting brings only a small change of what is found, as a small step along a ramp brings only a small rise. Chapter 1.

Continuum. The smooth whole of every possible value, with no gaps anywhere, in which between any two values there is always another. Chapter 27.

Correlation. An agreement between two lists. A correlation is no connection, and no one can send a message with a correlation. Chapter 15.

Cosmic ray. A particle that arrives at the Earth from space. Chapter 16.

Cosmological constant (the authors' word: dark energy). The one constant term in Einstein's equations of gravity, the same at every place and every time. Chapter 3 shows that the cosmological constant is the share of the energy of empty space that a measurement made from inside takes in. Chapter 1.

Cosmological event horizon. The edge beyond which nothing sent now can ever reach a given comparer. Chapter 23.

Count. Information in the second of two senses: a count of the states that look alike from outside, made relative to one way of looking. Information in the first sense is the form of the content. Chapter 28.

Coupling (the authors' word: the Higgs field gives mass). A number that says how much of a particle the condensate takes hold of. Chapter 5.

CPT theorem. The theorem that swapping every particle for its charge-reversed twin, mirroring space and reversing time, all three together, is an exact symmetry of every theory of the kind physicists use for particles and forces. Chapter 13.

Criticality. A state in which small disturbances can cascade to large scales. Chapter 26.

Curvature. The amount by which space and time are bent. Chapter 20.

Cycle of epochs (the authors' word: what came before the Big Bang). The succession in which stars, galaxies and black holes form in one epoch, the interiors of that epoch's black holes share one end, the turn restores a large world, and the restored world is the next epoch. Chapter 22.

Dark energy. The authors' name, and the physicists' name, for what physicists think is causing the universe to expand. In this book, the name for dark energy is the cosmological constant. Preface.

Dark matter. What physicists take to be a kind of matter, known only by its pull on the matter we can see. In this book's account, the dark matter is made of gyrations. Preface.

Decay. To turn into lighter things and give them one's energy. Chapter 2.

Deep why. The why that asks for the possibility from which a whole world is chosen. Chapter 32.

Deeper. When a second field of knowledge cannot be carried out, stated or checked without a first field, while the first field can be carried out without the second, the first field is deeper than the second. Chapter 9.

Degeneracy pressure. The pressure a crowd of electrons exerts because no two electrons can share the same state (the rule called exclusion), so the electrons cannot all settle into the lowest states. Degeneracy pressure needs no heat at all. Chapter 31.

Degree of freedom. One independent way in which something can hold energy or vary, as each string of a piano can ring on its own. Chapter 3.

Degree of interaction. How much contact a comparer has with the comparer's world. The degree of interaction can come as near to zero as you like. Chapter 22.

Delta. The proton's excited partner: the same light quarks of the first generation, with their three spins aligned. Chapter 16.

Determinism. The claim that a complete description of everything at one moment fixes everything at every other moment. Chapter 26.

Deterministic. Said of a computation whose next state is fixed by its present state and its rule, so that, run twice from the same start, the computation gives the same sequence. Chapter 27.

Dimension. One independent direction in which a thing can be placed. Chapter 2.

Discontinuous. Said of a thing with something sudden in it, as at the edge of a step. Chapter 1.

Dissipate. To spread energy out as heat, in a form from which no more work can be drawn. Chapter 29.

Distortion. In the words of my book *The Weight of Possibility*, a bend. Chapter 1.

Domain of comparison. The range within which comparisons can be made. Each kind of comparison has its own domain, and every domain has two edges, a farthest reach and a finest grain (Chapter 23). Chapter 8.

Doublet. A pair of particles alike in kind and different in one respect, such as the up quark and the down quark, or the electron and its neutrino. Chapter 7.

Drake equation. The question of life elsewhere, broken into factors, in a form named after the radio astronomer Frank Drake. Chapter 18.

e. The number mathematicians call e, about two and three quarters, the natural measure of steady growth. Chapter 3.

Earliest horizon. The greatest distance a signal could have crossed since the turn, in the first moments of our history. Chapter 20.

Edge of comparison (the authors' word: the speed limit of the universe). The outer edge of what any comparison can connect. Chapter 15.

Effective theory. A description that holds within a stated range and states its own range. Chapter 8.

Einstein's equations of gravity. The equations that say how energy shapes space and time. Chapter 1.

Electromagnetism. The force between electric charges, which also makes light. Chapter 2.

Electron volt. The energy one electron gains in crossing one volt, about the push of a single small battery. Chapter 5.

Emersion. The moment a moon comes out of the shadow of its planet, as Io comes out of the shadow of Jupiter. Chapter 15.

Energy levels. The particular energies an atom's electrons can have. Chapter 18.

Entangled. Said of two particles linked so that their measured results agree in a pattern that no instructions carried by the particles could give the results. Chapter 15.

Entropic arrow (the authors' word: entropy). The growth of entropy in things of very many parts, the arrow of the cream in your coffee. Chapter 13.

Entropy. A count of the arrangements of a thing's small parts that look the same from outside. The count is always made relative to some way of looking at the thing. Chapter 13.

Epistemology. The study of knowing: how anything comes to be known, checked and held. Chapter 32.

Epoch. One era of the world, in which stars, galaxies and black holes form. Chapter 2.

Equation of state. The pressure of a kind of stuff that fills the universe divided by the density of that stuff. Chapter 29.

Equivalence of weight and inertia. A body's gravitational mass equals the body's inertial mass. Chapter 7.

Equivalence principle. Einstein's statement that gravity and a steady speeding up cannot be told apart in a small closed room. Chapter 7.

Equivalent density. The density at which a black hole's mass would fill a sphere of a given radius. Chapter 21.

Error of method. A mistake built into one way of measuring, which that way's own stated margin of error does not show. Chapter 1.

Ether. The material of which physicists once thought light was a motion. Chapter 32.

Evaporation. Shedding mass a little at a time, as a puddle dries, until a lower level of the same kind is reached. Chapter 2.

Event. Anything that happens. Chapter 10 uses the word in a narrower sense: one happening at a single place and a single moment. Chapter 1.

Event time. The time of findings: the order of findings for one comparer. Chapter 12.

Evolution time. The number on the single dial in quantum theory's rule for how a quantum state changes. Chapter 12.

Exchange mass. The mass that carried energy shows, which is the photon's kind of mass. Chapter 6.

Exclusion. The rule that no two electrons can share the same state. Chapter 31.

Exist (the authors' word: soul). To stand as structure: a thing that exists is the same however anyone consults the thing, as a law is. Chapter 14.

Experimental particle physics. The study, by experiment, of the smallest pieces of matter. Preface.

Faithful reversal. A reversed process that passes back through exactly the states the original passed through, and arrives at exactly the condition the original started from. Chapter 13.

False vacuum. A settled state of empty space that is not the lowest settled state, as a valley can hold a ball and not be the lowest valley in the country. Chapter 29.

Fenced region (the authors' word: simulation). What a simulated world with real people in it is: a part of this world, fenced off by a computation, inside this world. Chapter 27.

Fermi paradox. The puzzle that the galaxy is very large and very old, and we have heard from no one else in the galaxy. The puzzle is named after the question the physicist Enrico Fermi asked at lunch at Fuller Lodge, in Los Alamos, New Mexico, about where the beings from other worlds were. Chapter 17.

Field. In physics, something spread through all of space whose smallest ripples are the particles. Light, for example, is the ripple of one field. Chapter 3.

File (the authors' word: you are information). A list of separate marks, each of a few fixed kinds, read the same way by every reader. Chapter 25.

Finding (the authors' word: measurement). The outcome of one comparison, laid down as a record. Chapter 1.

First ripples. The faint departures from evenness with which an epoch begins. Chapter 20.

First-person stance. Your stance as the one who looks. Chapter 25.

Flat. Said of space on the largest scale when lines that start out parallel stay parallel. Chapter 3.

Flatness problem. The question why space was so flat at the beginning of our epoch. Chapter 20.

Form of the content (the authors' word: quantum information is never destroyed). Which alternatives the matter has taken. Chapter 20.

Formalism. The written equations and rules of physics. Chapter 33.

Free will theorem. The theorem of the mathematicians John Conway and Simon Kochen: if the experimenters' choices of direction are not fixed by prior information, then the particles' responses are not fixed by prior information either. Chapter 26.

Fusion. The joining of light nuclei into heavier ones, the burning that keeps a star shining. Chapter 18.

Gamma rays. Light of the highest energies. Chapter 8.

Gamma-ray burst. A brief, enormous flash of the most energetic light, from a galaxy far away. Chapter 10.

Geiger counter. An instrument that clicks once for each particle a radioactive source gives off. Chapter 8.

General relativity. Einstein's theory of gravity, also called the general theory of relativity, which describes the shape of the arena. Chapter 7.

Generation. One of the three instances of a position of comparison: every kind of matter occurs three times, alike in charge and in every force, and differing in mass. Chapter 4.

Geometric time. The time that belongs to the shape of the arena. Chapter 12.

Geometry (the authors' word: quantum gravity). One shape of space and time, such as our epoch has. Chapter 8 shows that each alternative of the matter has its own smooth geometry. Chapter 3.

GeV. A billion electron volts, a little more than the mass of one proton. An MeV is a million electron volts, a thousandth of a GeV. Chapter 5.

Gluon. A carrier of the strong force. Chapter 6.

Goldilocks zone. The authors' name for the band of orbits neither too close to a star nor too far from it, so that a planet is neither too hot nor too cold. Chapter 18.

Grade. In my book *Physics Is Not Math*, a label that records how sure a checker is of a step. A grade contains no instruction for the next step. Chapter 33.

Grain. A least step of length or of duration, a smallest piece below which there is nothing smaller, as a printed photograph has a smallest dot. Chapter 8.

Gravitational lensing. The bending of light by unseen mass: the unseen mass bends the light as a glass lens does. Chapter 2.

Gravitational mass. How strongly gravity pulls on a body. Chapter 7.

Gravitational size. A length that measures how strongly a body curves the arena: the body's mass times Newton's constant, divided by the speed of light squared. The gravitational size is half the radius of a black hole of the same mass. Chapter 8.

Graviton. A particle that would carry gravity, as the photon carries light. Chapter 8 shows that the word "graviton" names at most a step in the description of small waves of the arena: one packet of energy in that description, counted as packets of light are counted. Chapter 7.

Gyration (the authors' word: dark matter). A lasting vibration of the six small dimensions of possibility, and the unit of which the dark matter is made. Chapter 2.

Half-life. The time in which half of a batch of radioactive atoms will have broken apart. Chapter 26.

Halo. The great cloud of dark matter in which each galaxy sits. Chapter 1.

Halving. A factor of two in mass. Chapter 5.

Handedness. The sense in which a fast particle's spin turns about its direction of motion, as a right-handed or a left-handed screw turns. Chapter 6.

Hard boundary. In my book *Comparison*, the edge of the unknowable: the edge of what can be compared even in principle. The structure of the act of knowing sets the hard boundary, and the hard boundary is fixed. Chapter 32.

Hard randomness (the authors' word: randomness). An outcome that no description of what came before fixes, however complete that description is, for any comparer whatsoever. Chapter 26.

Heat death. A final state in which everything has one temperature and nothing ever happens again. Chapter 29.

Heavy hydrogen. A nucleus of one proton and one neutron. Chapter 19.

Held structure. A structure whose parts are held in place by bonds, as a crystal is. Chapter 8.

Higgs boson. The particle of the Higgs field. Chapter 4.

Higgs field. The one field in the full list of the kinds of particle that fills all of space with a settled value. The Higgs field gives the particles their masses. Chapter 3.

History. In my book *The Matter We Know*, what events set: how many of each whole there are, place by place. Chapter 18.

Horizon. The surface around a black hole from inside which no signal can reach the outside. The authors call the horizon the event horizon. Chapter 21.

Horizon problem. The question how regions of the sky that never traded a signal came to agree so closely. Chapter 20.

Hoyle state. The state of carbon at just the energy that lets three helium nuclei join into one nucleus of carbon. Chapter 18.

Hydrogen line. The radio wavelength of twenty-one centimeters that hydrogen gives off, the same everywhere. Chapter 18.

Hyperspace. A second space beside ours that a ship could slip into. Chapter 17.

Identity, the. When the share of the energy of empty space that a measurement from inside takes in is set equal to the slice that empty space holds of the total energy (the total that the rate of expansion fixes), one relation in pure numbers (numbers with no units) is left: the identity. In the identity, the strength of gravity and the rate of expansion cancel. Chapter 3.

Image tube. A tube that strengthens faint light before it reaches a photographic plate. Chapter 2.

Immanent Metaphysics. The account from which I answer in this book. Immanent means within. In the Immanent Metaphysics I reason from inside the act of knowing, here and now, as the act happens, and from no place outside the world. Preface.

Incommensurable. Said of two things that no common measure fits. Chapter 1.

Incommensuration Theorem. In its exact wording: "Symmetry and continuity cannot both be applied, simultaneously and fundamentally, to any event or comparison; and neither can asymmetry and discontinuity". In plain words, at the foundation of any event or comparison, symmetry and continuity cannot both be perfect together, and neither can asymmetry and discontinuity. The Incommensuration Theorem is a structural fact about the nature of knowing. Chapter 1.

Indexing. In my book *Physics Is Not Math*, an order of states that reads the same both ways: a numbering of states in which nothing happens, like the page numbers of a finished book. Chapter 27.

Inertia. A body's resistance to being moved. Chapter 6.

Inertial mass. The mass measured by a body's inertia. Chapter 6.

Inflation. The authors' answer to the sameness and the flatness of the sky: a brief phase, early in the history of the universe, in which space itself grew enormously faster than light could travel across the growing space. In this book's account, no long inflation happened: no inflation long enough to stretch the lengths we observe today from inside the earliest horizon to beyond the earliest horizon. Chapter 20.

Inseparable, not interchangeable, distinct. The three facts about the settings that are the three clauses of the third axiom: every finding has all three settings; no setting can stand in for another; and each setting is a different setting. Chapter 1.

Instance. One particle that fills one position of comparison, with one respect facing the act of comparing. A respect is one of the three ways in which a comparison can read (find) a particle of matter, and each respect belongs to one position of comparison. Chapter 4.

Interference. The joining of waves that arrive by two paths, which shows as a pattern of high and flat. Chapter 27.

Interior. Everything inside a black hole's horizon. Everything outside the horizon is the hole's outside world, the world of the hole's epoch. Chapter 21.

Internal space. The six small dimensions taken together as one shape, which holds the possibilities that content can take. Chapter 11.

Invariant. Said of a quantity that every comparer finds the same. Chapter 15.

Inverse strength. One divided by the strength of a force, so that a large inverse strength means a feeble force. Chapter 9.

Ion. An atom with an electric charge, because the atom has lost or gained an electron. Chapter 12.

Isomorph. A concept with the same structure as another. Chapter 28.

Isotropic. The same in every direction. Chapter 20.

Kind (the authors' word: particle (a point with a label)). A sort of particle whose every member is found exactly like every other: the same mass, the same charge, the same behavior, wherever and whenever the member is found. Chapter 4.

Known. What earlier comparisons have laid down as structure: patterns found, values measured, results anyone can state, repeat and share. Chapter 32.

Koide's relation. The Japanese physicist Yoshio Koide's relation among the masses of the electron, the muon and the tau, pictured as an arrow that leans exactly forty-five degrees away from the diagonal. In numbers, the relation says that the sum of the three masses, divided by the square of the sum of their square roots, is exactly two thirds. Chapter 5.

Labels. The marks by which each of the three forces (electromagnetism, the strong force and the weak force) acts on a particle. Chapter 4.

Landscape. String theorists' name for the whole collection of states in string theory for empty space to settle into, pictured as a many-valleyed country with one valley for each state. Chapter 9.

Large Hadron Collider. The great ring at CERN in which particles are smashed together so that physicists can see what comes out. Preface.

Last-scattering surface. The far sphere from which the oldest light set out when the young universe first became clear. Chapter 23.

Lawful reversal. The claim that if a process obeys the laws, the same process run backward obeys the laws too. Chapter 13.

League. An old measure of distance, about four kilometers. Chapter 15.

Lepton. A particle of matter that does not feel the strong force, as the electron does not. Chapter 4.

Lepton count. The number of leptons less the number of antileptons. Chapter 19.

Lifetime. The average time a thing lasts before it decays. Chapter 2.

Light cone. The set of all the events that can be causally joined to a given event. Chapter 15.

Light-year. The distance light travels in a year. Chapter 2.

Limit. A value that something approaches more and more closely and never reaches. Chapter 20.

Limit of comparison. The scale that bounds how sharply any comparison made from a place can locate anything, the same at every place. Chapter 2.

Liquid xenon. A heavy gas cooled until the gas is liquid. Chapter 2.

Listed. Said of a collection that can be set out in order, first, second, third, without leaving anything out. Chapter 27.

Local Group. The small family of galaxies held together by their own gravity: our galaxy, Andromeda, and some dozens of smaller galaxies. Chapter 29.

Loop quantum gravity. A research program in which space itself is built of tiny loops, each the size of the Planck length. Chapter 9.

Many worlds. The account in which every outcome of every quantum event happens, each in its own branch of the world, with a copy of every observer in each branch. Chapter 24.

Mass (the authors' word: mass (a label)). The measure of one relation of a thing to the thing's context, found three times: as the thing's pattern, as its inertia and as its weight. Chapter 6.

Maxwell's equations. The laws of electricity, magnetism and light that James Clerk Maxwell wrote down in 1865, in which light is a wave. Chapter 32.

Meaningful. In my book *What Cannot Be*, said of an outcome that is significant to the process from which the outcome came, that carries the character of that process, and that has a share in value. Chapter 26.

Mechanical energy. Energy that can do work, as the energy of a turning wheel, or of a weight raised on a rope. Chapter 29.

Merger. One description in which the directions of space and time themselves carry both characters at the foundation: smooth and different from place to place, and also coming in exact, repeating steps. Chapter 9.

Meson. A particle made of a quark bound to an antiquark. Chapter 13.

Metaphysics. The study of what must be so for anything at all to be known. Preface.

Metastable. Said of a state that is held, able in principle to pass by tunneling to a lower state, and lasting far beyond the age of the universe. Chapter 29.

Metauniverse. The authors' word for a larger whole filled with quantum bits, connected or not, of which our universe would be one connected blob. Chapter 22.

Meteorites. The rocks from space that reach the ground. Chapter 31.

Minimality principle. Of the numbers that comparison supplies, each setting has the least number that meets every requirement that comparison places on the setting. Chapter 11.

Mini-Neptune. The authors' word for a planet smaller than Neptune and larger than the Earth. Chapter 18.

Multiverse (the authors' word: the multiverse; pocket universes). A collection of many universes, each a whole world of its own, cut off from ours. Chapter 24.

Muon. The electron's heavier copy in the second generation, the same in charge, spin and every force, about two hundred times the electron's mass. Chapter 4.

My account. The Immanent Metaphysics together with the physics I work out from it in my books. The appendices call it this account. Preface.

Names nothing (the authors' word: possible (no known law forbids it)). Said of a request that puts a word where the word's meaning does not reach, as a request for the color of the number seven. Chapter 14.

Nebula. In the astronomy of the 1920s, any faint cloudy patch of light in the night sky. Chapter 23.

Negative energy. Less energy than empty space has. Chapter 17.

Neutral kaon. An unstable particle with no net charge, made of a quark bound to an antiquark. Chapter 13.

Neutrino. The very light particle that passes through almost everything. Chapter 2.

Neutron star. The collapsed core of a burned-out star, as dense as the nucleus of an atom. Chapter 8.

Newton's constant. The measured number that sets how strongly gravity acts. Chapter 7.

Nihilism. The view that nothing means anything. Chapter 33.

No-boundary proposal. The physicist Stephen Hawking's proposal that the universe has no boundary at all, so that there is no edge at which a condition has to be supplied from outside. Hawking set the proposal out in full with the physicist James Hartle. Chapter 22.

No-cloning theorem. The theorem that no process can make an exact copy of an arbitrary quantum state, a state that the copier does not already know. Chapter 25.

No-hair theorem. The theorem that once a black hole has settled, everything about the hole that can be registered from outside is fixed by three numbers, the hole's mass, spin and electric charge, whatever fell into the hole. Chapter 21.

Nova. A star that flares up once. Chapter 23.

Nucleon. A proton or a neutron. Chapter 6.

Objective (the authors' word: soul). Holding across many acts of comparison, as what many comparers would find alike. Chapter 28.

Observable universe. In the authors' words and in the words of astronomers, everything whose light has reached us. Preface.

Oldest light. The light set free when the universe was about three hundred and eighty thousand years old, stretched since into a faint glow of microwaves. Chapter 1.

One origin. The source of the whole new world at the turn: no comparer inside that world can find separate beginnings for any two parts of the world. Chapter 20.

Ordinary interior. In my book *At the Edge of Reality*, the stretching and squeezing inside a black hole, written out for all ten dimensions with each of the six small dimensions kept at its size. Chapter 22.

Orrery. A working brass model of the solar system, with planets carried round the Sun by gears at their proper paces. Chapter 27.

Particle horizon. The edge of everything whose light has reached us. Chapter 3.

Pattern. In my book *The Gravitational Companion*, how much of a thing there is to be found: every arrangement, motion and relation of the thing's parts that could be found in a comparison. Chapter 6.

Pattern of verdicts. The verdicts, same or different, of every possible comparison of a thing with every other thing. Chapter 24.

Peak. The strength with which each favored size of the spots of the oldest light shows. Chapter 2.

Phantom energy. The physicist Robert Caldwell's name for stuff that fills the universe and grows denser as space grows. Chapter 29.

Phase. A position on a circle, like the position of the hand of a clock. Chapter 4.

Phonon. One small unit of definite energy in the vibrations of a held lattice, such as a crystal: a vibration of the crystal itself, with no extra thing added to the crystal. Chapter 2.

Photon. The particle of light. Chapter 4.

Pion. The lightest of the particles made of quarks. Chapter 6.

Planck curvature. The amount of bending of space at which the quantum corrections to the description of small waves of space grow as large as the effects that the corrections correct. Chapter 8.

Planck density. The density at which the smooth description of space and time reaches the Planck scale. Chapter 21.

Planck energy. The energy held in the Planck mass. Chapter 16.

Planck length (the authors' word: Planck length (smallest distance)). The one length at which a body's gravitational size and the body's quantum size meet, about a hundred billion billion times smaller than a proton. The Planck length limits how sharply a comparison made from inside the world can place a body. Chapter 8.

Planck mass. The mass at which gravity's strength on a body reaches one: about twenty-two millionths of a gram, about the mass of a grain of quartz sand a quarter of a millimeter across. Chapter 7.

Planck scale. The scale at which a body's gravitational size equals its quantum size. Chapter 8.

Planck time. The time light takes to cross a Planck length. Chapter 20.

Planck's constant. The smallest package of action, of happening, that nature deals in. Planck's constant marks the inner edge of comparison: for a given energy, Planck's constant sets a floor under how fine a single comparison can be. Chapter 15.

Plasma. A gas so hot that its atoms are broken into charged pieces. Chapter 2.

Point of view. The two sides of a comparison together: where the comparison is made from, and what it is aimed at. Chapter 11.

Polarization. The direction in which the waves of light vibrate. Chapter 20.

Positron. The antimatter partner of the electron. Chapter 4.

Possibility. The setting that is the range of what could have been found instead. Preface.

Powers of ten. A count of factors of ten: forty-five powers of ten is a factor of a one followed by forty-five zeros. Chapter 2.

Principle of existence. Existence without any interaction whatsoever is indistinguishable from non-existence, and therefore is non-existence. Chapter 24.

Principle of identity (the authors' word: a copy of you). What no comparison can distinguish, in any way at all, is one thing and not two. Chapter 24.

Product. In geometry, a shape made by setting the whole of one shape at every point of another shape. Each of the two shapes is called a factor of the product. Chapter 11.

Program. The written set of rules by which a computation goes from one state to the next. Chapter 27.

Proper time. The time a clock shows as the clock is carried along the clock's own path through space and time. Chapter 12.

Proton. The particle that forms, alone, the nucleus (the core) of the simplest atom, hydrogen. Chapter 2.

Pseudo-random. Said of a fixed rule whose output looks random and is set entirely by the number the rule starts from. Chapter 27.

Pure randomness. An outcome found different whatever its setting, with nothing joining the outcome to anything. Chapter 26.

Pure ratio. A number with no unit. Chapter 15.

Quantize. To give a field the character of what is found: the waves of the field are then found in countable packets, and the exact symmetries of the field fix which packets can be found. Chapter 8.

Quantum bits. The authors' term for smaller units of which space itself may be made, each standing for one location and linked to the others. Chapter 22.

Quantum fields. Fields such as light, described by quantum theory. Chapter 8.

Quantum gravity. The search for a quantum theory of gravity. Chapter 8.

Quantum size. The length within which, by quantum theory, a body cannot be pinned down. The quantum size shrinks as the body's mass grows. Chapter 8.

Quantum state. A smooth mathematical wave that sets the odds of each possible finding. Chapter 12.

Quantum teleportation. The moving of an unknown quantum state from one place to another, which leaves no copy behind. Chapter 25.

Quantum theory. Quantum mechanics, the physics of the very small: of atoms, of light, and of the particles that matter is made of. Chapter 3.

Quark. A particle of matter; quarks, bound together, build the tiny core at the center of every atom. A quark also feels the strong force, the force that binds the inside of a proton (Chapter 4). Chapter 1.

Radius of curvature. The length that sets a bend of space as a whole. Chapter 20.

Real (the authors' word: soul). Given in an actual act of comparison, which happens when it happens, as a measurement does. Chapter 14.

Recollapse (the authors' word: Big Crunch). The expansion of the universe as a whole stopping, turning around, and contracting all of space together. Chapter 29.

Reconstructed history. In my book *At the Edge of Reality*, the history built from what arrives now. The reconstructed history exists as a map or a record exists. Chapter 20.

Record. What a finding leaves behind for later comparisons to read: a stain on the table, or your memory of the spill. Chapter 14.

Redshift. The stretching of light into longer, redder waves on its way to us. Chapter 23.

Residual. In my book *What Cannot Be*, the part of each event that no law fixes: the part that is choice when seen from inside. Chapter 33.

Residue. What remains when nearly everything else has gone one way. Chapter 19.

Resonance. A reaction that goes far faster because the energy brought in matches a state of the thing produced, as a swing rises high when it is pushed in time with its own swing. Chapter 16.

Rest mass. The fixed characteristic a lasting thing keeps when it sits still, which is the electron's kind of mass. Chapter 6.

Restoration of context. The re-forming of a large outside world: three directions of space open out, and the six small dimensions close back to their small size. Chapter 22.

Right-handed. Said of the part of a neutrino that spins in one sense about the neutrino's direction of travel, as a screw turns one way. The other part of the neutrino spins in the opposite sense. Chapter 2.

Ripples of space. Waves in the shape of space itself, which physicists call gravitational waves. Chapter 2.

Rotation of the content. In my book *The Story of the Particles*, turning a particle so that another of the particle's respects faces the act of comparing, while the position of comparison that the particle fills stays where it is. Chapter 4.

Second law of thermodynamics. The law that the entropy of a thing of many parts, left to itself, does not decrease. Chapter 13.

Self-consistency principle. In a world with loops in time, the principle that the only possible histories are the histories in which the state of things at each event is one state and not two. Chapter 14.

Setting. One of the three sides of every finding in which anything is measured: space, time or possibility. Preface.

Shadow. The black circle that anyone looking at a black hole sees, larger than the hole itself, because the hole also pulls in light that passes close by. Chapter 21.

Shallow why. The why that asks for the law of which a thing is a case, and is answered by naming the law. Chapter 32.

Short loop. A closed path around space, one that cannot be shrunk to a point, that is shorter than the width of all we can see, the diameter of our horizon. Chapter 23.

Signal. Anything that passes from one event to another and lets a record at the second depend on an act at the first: a shout, a letter, a radio pulse. Chapter 15.

Simulation. A computation built to copy the behavior of some physical thing. Chapter 27.

Single change. One particle turning into others under one force, as when a neutron turns into a proton, an electron and an antineutrino. Chapter 19.

Singularity (the authors' word: inside a black hole (unknown)). In the authors' terms, the single point of zero volume and endless density into which everything draws together when the expansion is run backward in Einstein's theory of gravity. In this book, the singularity is where the smooth description of space and time reaches the edge of its domain. Chapter 20.

Six aspects of comparison. The six aspects every comparison has, in three pairs: sameness and difference, the side the comparison is made about and the side the comparison is made from, and content and context. Chapter 5.

Six small dimensions of possibility (the authors' word: extra dimensions (hidden, curled up)). The six further dimensions of the world, beyond the three of space and the one of time, held far too small to see. Chapter 11 shows that the six small dimensions are the range of what a finding could be, present at every place and never a place themselves. Chapter 2.

Soft boundary. The line between the known and the unknown, which moves with every investigation. Chapter 32.

Soft randomness. Unpredictability that comes from a limit of what we know. Chapter 26.

Space (the authors' word: space is a thing ("space goo")). The setting that is the place of a finding. Chapter 10 shows that space is the pattern of which events can affect which. Preface.

Spacelike separated. Said of two events so far apart in space, and so close in time, that nothing traveling at the speed of light could pass between them. Chapter 15.

Special theory of relativity. Einstein's theory of how lengths and durations compare for comparers moving steadily relative to one another. Chapter 15.

Spectral index. The number by which astronomers measure how the strength of the first ripples changes with length. The spectral index is exactly one for a pattern that is the same at every length. Chapter 20.

Spectral line. A color at which the atoms of one element take in or give off light. Chapter 18.

Spectrograph. A device that spreads the light of a source into its colors, the way a prism spreads sunlight into a rainbow. Chapter 2.

Spin. A built-in amount of turning, like a top that never runs down. Chapter 4.

Spin echo. The signal that returns when a second pulse brings the drifting spins of a liquid's nuclei back into step. Chapter 14.

Standard candle. A lamp of known brightness, whose faintness as seen from Earth shows how far away the lamp is. For astronomers, the lamp is a star whose true brightness is known. Chapter 3.

Standard Model. The established theory of the kinds of particle and of the three forces among the particles (the strong force, the weak force, and the electric and magnetic force). Chapter 5.

Standard picture of cosmology. The account of the universe that most astronomers use. Chapter 1.

Standing. In my book *Why These Numbers*, each number has a standing, and the standing says where the number's value comes from. Chapter 5.

Starting place, step and widening. The three numbers that set the ladder of masses of one family of particles, such as the up quarks (up, charm and top). The ladder of masses is the masses set out one below another in halvings. The masses of a family are pictured as three houses on a road that runs downhill from the top quark's mass, one house for each member. The starting place is how far down the road the family's heaviest member stands. The step is a number of halvings taken once for each generation down. The widening is a number of halvings taken as many times as the square of the generation number (the heaviest member is generation zero, the next generation one, and the lightest generation two). Chapter 5.

State. Where a particle is, how the particle moves and which way the particle's spin points, taken together. Chapter 4.

String theory. A proposed theory in which each particle is one way a tiny string can vibrate, in a space and time of ten or eleven dimensions. Chapter 9.

Strong computationalism. The thesis that the right program, running on any machinery, would thereby be conscious. Chapter 27.

Strong force. The strong nuclear force, which holds together the core of every atom. The strong force also binds the inside of a proton (Chapter 4). Chapter 2.

Structural arrow (the authors' word: the arrow of time). The one-way order of every comparison, from the range of what could be found, to the act, to the record, together with the impossibility of running any process backward faithfully. Chapter 13.

Structure. In my book *The Matter We Know*, whatever follows from the form of comparison (what every act of comparing must contain) and from the kinds of particle and their forces, with no measured number. Chapter 18.

Structure of comparison. What every comparison must contain. Chapter 1.

Subjective. The side from which experience occurs, the stance of the one to whom things happen. Chapter 27.

Subjectivity. In my book *What Cannot Be*, the first-person stance: being the one who looks, from inside. Chapter 25.

Superdeterminism. The claim that the experimenters' choices of direction and the particles' states were fixed together, from one shared past, so that the choices only seem free. Chapter 26.

Superposition. A combination of alternatives held together with a definite relation, in quantum theory's description. Chapter 8.

Surface of simultaneity. A single "now" stretched across the whole universe. Chapter 12.

Symmetric. Said of a thing when what is found stays the same across a change of setting, as each step of a staircase is like every other. Chapter 1.

Synchrocyclotron. A machine that whirls particles outward in a spiral. Chapter 16.

Tau. The electron's heavier copy in the third generation, about three thousand four hundred and seventy-seven times the electron's mass. Chapter 4.

Test in principle. A test whose logic is valid whether or not any instrument can carry the test out. Chapter 27.

Thing compared. The second position of every comparison: what is known, the thing the instrument reports. Chapter 4.

Thing compared against. The third position of every comparison: what the act of comparing reaches toward and never contains in one act, the beyond. Chapter 4.

Third-order term. An extra piece of an interference pattern that would belong to three paths together. Chapter 27.

Three settings. The three settings in which anything is measured: space, the place of a finding; time, the moment of a finding; and possibility, the range of what could have been found instead. Preface.

Three times (the authors' word: time). Geometric time, event time and evolution time: the time on your clock, the order of your findings, and the time of quantum change. Chapter 12.

Throat. The narrowest part of the tunnel of a wormhole. Chapter 17.

Time. The setting that is the moment of a finding. Chapter 12 shows that the one word "time" names three times: geometric time, event time and evolution time. Preface.

Torus. The shape of the authors' donut: the shape a video-game screen takes when the screen's opposite edges are joined. A torus can be flat and finite at once. Chapter 23.

Trace. In my book *The Matter We Know*, a mark that a motion leaves in one particle, such as the angle by which one nucleus has drifted. Chapter 14.

Trillion. A million million. Chapter 2.

True choice. In my book *Home in the World*, a selection made with nothing before the selecting fixing it. Chapter 18.

Tunneling. The passing of a ball held in a valley through the ridge into a lower valley without climbing over the top, as quantum physics allows. Chapter 29.

Turn, the (the authors' word: the Big Bang (singularity)). The limit at which an epoch begins: our history, traced back, approaches the limit and shows the limit as a first moment. Chapter 20.

Two bits. Two answers of yes or no, which are enough to name four outcomes. Chapter 25.

Uncertainty principle. In the authors' words, the rule that nobody can know everything about a particle at once: the particle's position and the particle's velocity do not both exist as exact information at the same time. Chapter 25.

Unifying group (the authors' word: unification of the forces). One larger family of changes, containing the changes of all three forces (electromagnetism, the strong force and the weak force), under which the laws stay the same, so that at some very high energy the three forces would act as one force with one strength. Chapter 9.

Unitary. Said of a consciousness that is one undivided point of view, the one who looks. Chapter 25.

Unknowable (the authors' word: we have no idea). What could not be found by any comparison, even in principle, for a reason in what knowing is, which no effort and no instrument changes. Chapter 32.

Unknown (the authors' word: we have no idea). What can be found by further comparisons and has not been found yet. Chapter 32.

Uranium-lead clocks. The two chains of radioactive decay by which uranium turns into lead at rates known from the laboratory, which tell how long ago a grain of rock locked its uranium in. Chapter 31.

Vacuum (the authors' word: the energy of empty space (predicted far too large)). Empty space at its lowest energy: every field at its quietest, with no particles present. Chapter 3.

Value that lands (the authors' word: coincidence (the charges)). A value that agrees with what is measured. Chapter 5.

Virgo. The European detector of ripples of space near Pisa, in Italy, a partner of the same kind as the two detectors of LIGO, the American observatory built to catch ripples of space. Chapter 8.

W boson. One of the two charged carriers of the weak force. Chapter 19.

Warp drive. A ship that would shrink the space ahead of it and stretch the space behind it. Chapter 17.

Wavelength. The length of the wave of a color of light, which sets the color. Chapter 5.

Weak force. The weak nuclear force, a feeble force behind one kind of radioactivity. The weak force also turns one kind of quark or lepton into another (Chapter 4). Chapter 2.

Well. A place a little denser than its surroundings, whose extra pull draws more matter in, as water runs into a dip in the ground. Chapter 2.

White dwarf. The cooling remnant of a star like the Sun: in the authors' figures, about half the Sun's mass in a ball about the size of the Earth. Chapter 31.

White hole. A region that would throw out what a black hole takes in. Chapter 17.

Whole. In my book *The Matter We Know*, a thing bound together out of smaller parts, such as a proton, a nucleus, an atom or a molecule. Chapter 18.

Within the reach of light. Said of every event in the upper cone of a given event (the upper cone contains every event that the given event can affect): light sent out from the given event, or anything slower than light, can get to each event in the upper cone. Chapter 17.

Working account. In my book *Why These Numbers*, the account used in the book's chapters, in which measurement supplies six numbers. Chapter 5.

Wormhole. A tunnel that joins two different places and times. Chapter 14.

Z boson. The heavy, uncharged force particle of the weak force. Chapter 4.

Zoo. The physicists' name for the whole collection of the kinds of particle. Chapter 4.

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