

Where Every Road Arrives

The Immanent Metaphysics
for Readers of Michio Kaku

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Kaku's Promise

The Carp in the Tea Garden

What would a fish make of the world above its pond? As a small boy, Michio Kaku asked himself that question about the carp in a garden pond. Kaku is now a physicist who writes books for general readers, and he tells the story near the start of his book *Hyperspace* (1994). His parents would sometimes take him to the Japanese Tea Garden in San Francisco. He writes that one of his happiest memories is of crouching beside the garden's pond, "mesmerized by the brilliantly colored carp swimming slowly beneath the water lilies" (*Hyperspace*, ch. 1, "The Education of a Physicist").

He wondered how the world must look to the carp. The carp spend their whole lives in the shallow water. So the carp would believe, as he puts it, that their "universe" is the murky water and the lilies. The boy could sit a few inches from the carp. "The carp and I spent our lives in two distinct universes, never entering each other's world", he writes, "yet were separated by only the thinnest barrier, the water's surface" (*Hyperspace*, ch. 1, "The Education of a Physicist"). He imagined carp "scientists" who would scoff at any fish who proposed "that a parallel world could exist just above the lilies" (same section). One day a rainstorm struck the pond, and waves on the pond's surface pushed the lilies in every direction. The carp cannot see the surface they live under, so to the carp the lilies would seem to move with nothing touching them, and so, Kaku thought, the carp scientists would explain the movement of the lilies with a mysterious, invisible "force" acting between the lilies. A *force*, in physics, is a push or a pull by which one thing acts on another. He also imagined lifting one of the carp scientists out of the water for a moment and throw-

ing the fish back. To the other carp, the lifted scientist would vanish without a trace and then reappear out of nowhere, and afterward the lifted scientist would tell a story "of a journey beyond the universe", as Kaku puts it, that most of the carp would dismiss (same section).

Kaku writes, "I often think that we are like the carp swimming contentedly in that pond" (*Hyperspace*, ch. 1, "The Education of a Physicist"). He means that we, too, take our own pond, the part of the world we can see, for everything there is. Yet other dimensions, and even other universes, may lie just beyond our grasp. By other dimensions Kaku means directions beyond the length, width and height we know.

Kaku sets a second childhood memory beside the memory of the carp pond. In the spring of 1955, when he was eight years old, his teachers told his class that a great scientist had just died, and that the scientist had died with his unfinished papers still sitting on his desk. The scientist was Albert Einstein. Einstein called the unfinished work the *unified field theory*, which Kaku describes as "a theory that could explain all the laws of nature, from the tiniest atom to the largest galaxy" (*Hyperspace*, ch. 1, "The Education of a Physicist"). A *law of nature* is a rule that nature has been found to follow wherever the rule has been tested. The boy read every book about Einstein that he could find, and he decided that he would try to solve the mystery of the unfinished theory on Einstein's desk, "even if I had to become a theoretical physicist to do it". A *theoretical physicist* is a physicist whose work is to find the laws of nature by reasoning and mathematics. Kaku became a theoretical physicist. As a grown man, he sees what the child could not see. He sees that there was perhaps a link between the carp in the Tea Garden and the papers on Einstein's desk. Kaku came to think that higher *dimensions* might be the way to complete the theory Einstein left unfinished. In the sense Kaku means here, a dimension is a direction in which things can be laid out and measured. Length, width and height are three dimensions.

The carp pond and Einstein's unfinished papers are the two childhood memories behind a promise that Kaku makes his readers in his books. The promise has three parts. First, the world is larger and stranger than

the pond we live in. Second, the laws of the world may be simpler than the laws look from inside our pond. Third, any reader can come to understand the world, if the reader is willing to follow the reasoning, step by step. Kaku makes the promise to his readers in five books, published from 1994 to 2023. The five books are *Hyperspace*, *Physics of the Impossible*, *Parallel Worlds*, *The God Equation* and *Quantum Supremacy*. If you are holding this book, you have probably read and enjoyed at least one of the five books.

What Kaku Tells Us

In *Physics of the Impossible* (2008), Kaku examines the word "impossible" itself. "As a physicist", he writes, "I have learned that the 'impossible' is often a relative term" (Preface, "The 'Impossible' Is Relative"). When Kaku was a schoolboy, his teacher called the idea that two continents could drift apart silly, and in those years a meteor that killed the dinosaurs sounded like science fiction. He writes that today we know that the continents do move, and that a giant meteor most likely did wipe out the dinosaurs. Because the impossible is often relative, Kaku sorts impossible things into three classes (Preface, "Predicting the Future"). A *Class I* impossibility is a thing that breaks no known law of physics, and so, Kaku writes, a thing of Class I might be possible in this century or perhaps the next, in modified form. A *Class II* impossibility is a thing at the very edge of what physics understands. Kaku leaves unsettled whether a thing of Class II is possible at all. "If they are possible at all", he writes, things of Class II might be realized thousands to millions of years from now. A *Class III* impossibility is a thing that breaks the laws of physics as we know them. Kaku finds very few Class III impossibilities, but if any Class III impossibility does turn out to be possible, he adds, the discovery would mean a fundamental shift in our understanding of physics. Kaku also gives a rule of thumb that many physicists share: "Unless there is a law of physics explicitly preventing a new phenomenon, we eventually find that it exists" (Preface, "Studying the Impossible"). In the Epilogue of *Physics of the Impossible*, Kaku turns

to questions that some scientists now call forever unanswerable. His example is the question of what happened before the *Big Bang*, the hot, dense beginning from which our universe has been expanding. He writes that the questions some scientists call unanswerable may perhaps better be seen as challenges for the next generation of scientists: "These limits are like piecrusts, made to be broken" (Epilogue, "The Future of the Impossible").

Kaku places time machines and travel through wormholes in Class II. In the Preface of *Hyperspace*, Kaku describes a *wormhole* as a tunnel linking distant parts of space and time. In the Preface of *Hyperspace* he also reports that physicists are studying wormholes seriously, and he stresses that the work is still highly speculative. He reports, too, that "Time machines have now left the realm of speculation and fantasy and have become legitimate fields of scientific research".

In *The God Equation* (2021), Kaku tells the story of Einstein's dream of one theory for all the laws of nature, the dream that the boy took up when Einstein died. The goal of Einstein's dream is a *final theory*: "a single formula from which, in principle, one could derive all other equations" (*The God Equation*, Introduction to the Final Theory). An *equation* is a statement, written in mathematics, that two quantities are equal, and physicists write the laws of physics as equations. Kaku tells us that Einstein wanted an equation "perhaps no more than one inch long" (*The God Equation*, Introduction, "Einstein's Dream"). Kaku's own candidate for the final theory is *string theory*, and to his mind string theory is the only candidate. String theory says that the smallest pieces of matter are tiny vibrating strings, loops like minute rubber bands. Each way a string can vibrate is a different kind of *particle*, one of the tiny pieces of which all matter is made, so each kind of particle is like one note that a string can play. In string theory, all the laws of physics can be reduced to the harmonies of the strings, the ways the strings vibrate together. He writes, "The universe is a symphony" (*The God Equation*, Introduction, "Einstein's Dream"). Kaku himself has worked on string theory since 1968.

Kaku looks for the final theory beyond the four dimensions we know, three of space and one of time. He gives his reason in the Preface of *Hyperspace*. Kaku names four themes for *Hyperspace*: in his words, the first of the four themes is "that the laws of nature become simpler and more elegant when expressed in higher dimensions". He writes that when one more dimension is added to the four, the equations of gravity and of light appear to merge together like two pieces of a jigsaw puzzle: "Light, in fact, can be explained as vibrations in the fifth dimension". Kaku's picture of light is the carp pond again: the carp's "force" is waves on a surface that the carp cannot see, and light, in the same way, would be vibrations in a fifth dimension that we cannot see. He reports that string theory "even predicts the precise number of dimensions: ten": the four dimensions we know, and six more dimensions of space.

In *Parallel Worlds* (2005), Kaku turns from our one universe to many universes. He writes that our universe may be one bubble among countless others. In his picture, new bubbles form all the time, like bubbles in boiling water, and each bubble is a universe. He writes that, as scientists speculate, perhaps "Genesis occurs repeatedly in a timeless ocean of Nirvana" (*Parallel Worlds*, ch. 1, opening). Kaku's image means that universes are born again and again, in an ocean that has no beginning and no end. Physicists call the whole set of universes the *multiverse*. Kaku is candid that string theory, too, allows many universes. In *The God Equation* he writes that perhaps the most important criticism of string theory is that string theory predicts many universes: the theory "by itself is unique, but it probably has an infinite number of solutions" (Introduction, "An Army of Critics"). A *solution*, in string theory, is one possible universe that the equations of string theory allow. So our universe would be one solution among a great many.

Kaku cares about the many universes for a reason close to the heart. He explains that our universe is expanding faster and faster. In the end all the stars will go out, in what physicists call the *big freeze*: the long cooling in which the universe goes dark and cold, and life can no longer go on. Kaku asks whether intelligent life could escape the big freeze,

and in answer he sets out in *Parallel Worlds* eleven steps by which an advanced civilization, billions of years from now, might try to escape. He calls the eleventh and last step the last hope. He writes that if the only wormholes that stay open are far too small for a traveler, a civilization would have one option left. The civilization could write enough information to re-create itself at the scale of atoms, and then send the information through a wormhole too small for a traveler, into a new universe. In the new universe, the information would be used to build the civilization up again (*Parallel Worlds*, ch. 11, "Step Eleven: The Last Hope"). In *Physics of the Impossible* he puts the hope of escape in one sentence: "the theory of the multiverse may be the salvation for all intelligent life in our universe" (ch. 13, "Contact Between Universes?"). Kaku tells his reader plainly how far beyond us the last hope lies: he writes that every step of the last hope "is so far beyond today's capability that it must read like science fiction" (*Parallel Worlds*, ch. 11, "Step Eleven: The Last Hope"). He adds that nothing in the laws of physics or biology prevents a civilization from carrying out the last hope.

In *Quantum Supremacy* (2023), Kaku turns to a machine that is being built now. A *quantum computer* is a computer built from parts that follow the rules of *quantum* physics, the physics of the very small, where energy and matter come in tiny indivisible amounts. Kaku defines *quantum supremacy* as the point at which a quantum computer "could decisively outperform an ordinary digital supercomputer on specific tasks" (*Quantum Supremacy*, ch. 1, opening). A *supercomputer* is one of the largest and fastest ordinary computers. He writes that perhaps the greatest benefit of the quantum computer will be to work out how *molecules* behave: molecules are the small clusters of atoms that make up every substance and every living thing (ch. 1, "Simulation"). Of the chemistry of aging he writes, "only a quantum system can fully explain another quantum system" (ch. 13, "Digital Immortality"). He even hopes that a quantum computer will sort through the many solutions of string theory and show which solution is our universe: "So quantum computers may be the final step in finding the Theory of Everything"

(ch. 16, "Quantum Computers May Hold the Key"). The *theory of everything* is another name for the final theory that Kaku describes in *The God Equation*: one theory of all the forces and all the particles.

Kaku closes *Parallel Worlds* on one more hope, the warmest hope of all. Kaku believes that the people alive now may be living through the greatest transition in human history. The transition is the change to what he calls a *type I civilization*: a civilization that can use all the energy of the sunlight that falls on the civilization's home planet. "Perhaps the purpose and meaning of the current generation", he writes, "are to make sure that the transition to a type I civilization is a smooth one". Kaku's book ends with three sentences (*Parallel Worlds*, ch. 12, "Transition to Type I Civilization"):

> The choice is ours. This is the legacy of the generation now alive. This is our destiny.

Kaku's message comes to eight claims, gathered from his five books: *Hyperspace*, *Physics of the Impossible*, *Parallel Worlds*, *The God Equation* and *Quantum Supremacy*. The "impossible" is often relative. Time machines and travel through wormholes lie at the very edge of what physics understands, if they are possible at all. One equation may contain every law of nature. The laws of nature become simpler when physicists write the laws in higher dimensions. Ours may be one universe among many. A civilization might one day escape a dying universe. Quantum computers can decisively outperform ordinary computers on particular tasks. And the choice of our future is ours.

Who This Book Is For, and What It Does

This book is for you if you have read Kaku and have no training in physics or mathematics. You need no other preparation.

The *Immanent Metaphysics* is my own work: I first set it out in my book *An Immanent Metaphysics* (2001), and I have worked out its physics in a series of later books, which the appendix For the Specialist names wherever a chapter draws on them. I teach the physics of the Immanent Metaphysics in this book, and from here on I call that account of physics 'this account'; I teach this account through Kaku's own message. *Metaphysics*, in this book, 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, while the act of knowing takes place, and never from a place outside the world. I begin the Immanent Metaphysics from one act, *comparison*, which is setting one thing beside another and telling the two apart. Comparison is the act by which anything is known. When a carpenter sets a ruler beside a board and reads where the board ends, the carpenter is making a comparison. Every measurement is an act of comparison, and every result of physics depends on comparisons. In the Immanent Metaphysics I ask what every comparison must contain. I work out the physics of this account from what every comparison must contain. The starting point of the Immanent Metaphysics uses nothing from physics: no measurement, no law and no result of any experiment.

In his books Kaku reasons from the experiments and the equations of physics. In this account I reason from the act of comparison. Kaku and I start from different places. So wherever Kaku and I reach the same result, the two lines of reasoning support the result independently, and so the result is better supported than the result would be by either line of reasoning alone. In many places I reach the same result as Kaku by reasoning from comparison, and in the chapters I show the steps from comparison to each result that Kaku and I share. In other places I reach a different result from Kaku's, and in the chapters I give the reason for the difference, in plain words. In every chapter I state Kaku's part of the message first, fairly and with his own words quoted. After I have stated Kaku's part, I set this account beside Kaku's part.

Kaku has spent decades inviting readers to the deepest questions in physics. I accept Kaku's invitation.

How to Read This Book

This book has nine chapters. I open each chapter on a question of the kind that a reader of Kaku carries away from his books. In the rest of the chapter I answer the question. The table gives the nine questions, each beside the chapter in which I answer the question.

Chapter	Title	The question it answers
1	Two Kinds of Impossible	When a scientist tells you that something is impossible, isn't that just another prediction waiting to be broken?
2	Faster Than Light, and Back in Time	If nothing in the laws of physics forbids a wormhole or a time machine, will someone one day send a message faster than light, or go back and change the past?
3	Ten Dimensions	If there really are six more dimensions too small to see, how could anyone know, and why ten?
4	One Equation?	Is there a single equation, perhaps an inch long, that unites every force of nature, and if there is none, what holds the world together?
5	The Numbers of Nature	If a theory derived all the constants of nature, would that prove it right?
6	One Bubble Among Many?	Is our universe one bubble among countless others, and is that why the laws of nature are just right for us?
7	The Quantum Machine	If a quantum computer can do what no ordinary computer can, is there anything a quantum computer cannot do?
8	When the Stars Go Out	If every star goes out and the universe freezes, is there any way out for us, and does anything we are or do last?

Chapter	Title	The question it answers
9	Where Every Road Arrives	What do I hold now, after the walk, and what is mine to do?

In the question of Chapter Five, the *constants of nature* are the fixed numbers in the laws of physics, such as the speed of light. The question of each chapter follows from the answer of the chapter before, so the chapters are meant to be read in order, and each chapter builds on the chapters before it. So I teach each word and each result once, where the reader first needs it, and at the head of each later chapter a short box, "What this chapter uses", lists the words and results that the chapter takes from the chapters before it, with the chapter that teaches each one. A reader who goes in order can pass the box by, and a reader who opens the book in the middle has, in the box, what the chapter needs. Each chapter also sets off with a rule at the left the passages in which I state what Kaku showed, in his own words; if you know Kaku's books well, you can pass those passages by, and if you do not, they give you what each chapter answers.

I make you three promises in this book, and I keep all three promises in every chapter. The first promise is that I explain every technical word in plain words where the word first appears, and set the word in italics there, as I have set the words explained in this Preface. The second promise is that the chapters contain no equations: I say in words each relation that the chapters need. The third promise is that you may skip the book's two *appendices*, the sections at the back of the book that follow the chapters, and still follow the argument of every chapter. The appendix "For the Specialist" contains the mathematics. For every claim of the chapters that depends on my other books, a small raised number in the text leads to the Notes at the back of the book, which name the book, and the appendix "For the Specialist" gives the book, chapter and section where the claim is made, with the mathematics. The appendix "What the Coming Measurements Will Find" lists every measurement still to come

that bears on the chapters, and for each measurement the appendix states what this account says the measurement will find. The glossary at the back of the book has two parts. In the first part, I set each of Kaku's words beside the word this book uses in place of Kaku's word. The second part lists the other words that carry a meaning of their own in this book. The glossary is a reminder: I explain each word of the glossary in full in the text, where the word first appears.

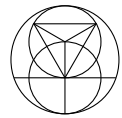
I use one picture all through the book. Picture a country where the only way to travel is by road, and call the country the road country. For a traveler in the road country, a place is somewhere a road could bring you, whether or not the road has been built yet. The road country appears again and again, from Chapter One to the last sentence of Chapter Nine. In the picture, the roads stand for paths. Wherever the road country appears, the road country stands for one thing: the one world, which is everything any path can reach. Every road that arrives anywhere arrives at a town of the one country, and a request for a "town" that no road could ever reach names nothing; that is what I show in each chapter, for one of Kaku's roads at a time.

Here, in brief, is what this book holds that Kaku's books do not. The word "impossible" says two different things, and one of the two, a request that names nothing, no length of time can change (Chapter One). A message sent faster than light, and a return to one's own past as it was, are requests of that kind (Chapter Two). The ten dimensions are of three kinds, one of time, three of space and six of possibility, and the six are never traveled through (Chapter Three). Gravity and the quantum are two descriptions of one world, joined side by side, and there is no single equation of the kind Kaku hopes for (Chapter Four). Every number of nature has a standing, and a number that lands is a question (Chapter Five). There is one world, with one vacuum and no ocean of bubbles, and the sky needs no inflation (Chapter Six). A quantum computer is a faster car on the same roads (Chapter Seven), and the long dark ends in a turn to a new epoch (Chapter Eight).

If you have read another of my books written for the readers of another author, you know the ground I lay in Chapter One already: comparison and the Incommensuration Theorem, told here in the picture of the road country. What is new for you starts with the two kinds of impossible in the same chapter, and runs through every chapter after it.

Kaku promises his readers that the world is larger than our pond, and that we can come to understand the world. I take Kaku at his word, with "the world" in this book's sense: the one world, everything any path can reach, is larger than our pond, and we can come to understand the one world. Kaku opens *Physics of the Impossible* on the word "impossible" itself, and a reader of Kaku might well ask first about the word "impossible".

When a scientist tells you that something is impossible, isn't that just another prediction waiting to be broken?



Chapter One

Two Kinds of Impossible

When a scientist says something is impossible, is that just another prediction waiting to be broken?

If you have read Michio Kaku's *Physics of the Impossible* (2008), you have good reason to ask whether a scientist's "impossible" is just another prediction waiting to be broken, because Kaku's book is full of learned people who said "impossible" and were wrong: about flying machines, about rockets in empty space, about the energy locked in the atom. And yet learned people called some things impossible two and a half centuries ago, and those things are still impossible today. Some of the things they called impossible always will be.

A Vote in Paris

On 3 May 1775, the Royal Academy of Sciences met in Paris. The Academy was the body of France's leading men of science. The members had before them one more paper claiming to have squared the circle. To square a circle is to draw a square with exactly the area of a given circle. The minutes call the man who sent the paper M. de la Frainaye. The question was put to the members: should the Academy go on examining papers that claim to square the circle at all? The members voted. The Academy resolved to examine no more papers that claimed to square the circle.

The Academy printed the resolution in its own yearly record for 1775. The resolution named four kinds of proposal the Academy would no longer examine: duplicating the cube, trisecting the angle, squaring the circle, and perpetual motion. Three of the four came from *geometry*, the mathematics of shapes, and from one of the oldest games of geometry: drawing with only a pair of compasses and an unmarked ruler. The first geometry proposal was *duplicating the cube*: drawing the edge of a cube with exactly twice the volume of a given cube. The second geometry proposal was *trisecting the angle*: cutting any angle into three equal parts. The third geometry proposal was *squaring the circle*: drawing a square with exactly the area of a given circle. The three geometry proposals were drawings, but the fourth proposal was a machine. The resolution named any machine announced as a *perpetual motion*. A perpetual motion is a machine that, once started, would go on running and doing work forever, with nothing fed to it from outside: no fuel, no falling water, no wind. Kaku tells of the Academy's resolution on perpetual motion in his chapter on perpetual motion. He writes that by 1775 inventors were proposing so many designs that the Academy stated that it would "no longer accept or deal with proposals concerning perpetual motion" (*Physics of the Impossible*, ch. 14, "Perpetual Motion Machines Through History").

Since 1775, mathematicians have proved three of the four items on the Academy's list impossible, and no one has proved the fourth impossible. In 1837 the French mathematician Pierre Wantzel proved that the cube cannot be duplicated, and the angle cannot in general be trisected, with compasses and ruler alone, and in 1882 the German mathematician Ferdinand von Lindemann proved that the circle cannot be squared with compasses and ruler alone. Since the proofs of Wantzel and Lindemann, no geometer anywhere is waiting for a cleverer construction. No one will ever find a cleverer construction, because the rules of compasses and ruler have no place for one. The perpetual motion machine is different. No one has given a proof like Wantzel's or Lindemann's for the machine. More than two centuries after the vote, Kaku still keeps one door ajar: he leaves open whether the machine is impossible for good.

So the Academy put two different kinds of thing on one page, and treated the two kinds alike. Three requests asked for something the rules of geometry have no place for. The fourth asked for a machine that nature, as far as anyone had ever found, does not allow. Today we call all four impossible, but the word "impossible" does not mean the same thing each time.

What Kaku Showed

Kaku sets out his view of the impossible in one sentence near the start of his Preface: "As a physicist, I have learned that the 'impossible' is often a relative term" (*Physics of the Impossible*, Preface, "The 'Impossible' Is Relative"). He tells how a teacher of his once dismissed two ideas that both turned out to be true: that continents could drift apart, and that a meteor from space had ended the dinosaurs. Kaku names one of the central questions running through his book: "just because something is 'impossible' today, will it remain impossible centuries or millions of years into the future?" (same section). He tells how Lord Kelvin, perhaps the most prominent physicist of Victorian Britain, declared flying machines impossible. He tells too how the editors of the *New York Times*, in an editorial of January 1920, mocked the American rocket pioneer Robert Goddard for thinking a rocket could push itself through empty space.

Kaku writes that physics can now give rough estimates of when, if ever, a technology such as a spaceship to the stars may be realized (Preface, "The 'Impossible' Is Relative"), and he sorts the impossible into three classes (Preface, "Predicting the Future"). Class I impossibilities "are technologies that are impossible today but that do not violate the known laws of physics". and physicists write each law down so that others can check the law again. Kaku's Class I things include invisibility and *teleportation*. Teleportation is sending a thing from one place to another without the thing's crossing the space between. Kaku writes that Class I things might be possible in this century or perhaps the next, in

modified form. Class II things "sit at the very edge of our understanding of the physical world". Kaku writes that, "if they are possible at all", Class II things might be realized thousands to millions of years from now. His examples of Class II include time machines and travel through *wormholes*. Wormholes are shortcuts through space that appear among the solutions of Einstein's theory of gravity. Class III is the last class: "These are technologies that violate the known laws of physics". Kaku says there are very few Class III things.

Kaku adds a rule of thumb to Classes I, II and III. Many physicists share the rule. He quotes the novelist T. H. White, "Anything that is not forbidden, is mandatory!", and then he puts White's saying in a physicist's words: Kaku's example of the rule is the time machine. The physicist Stephen Hawking looked for a law that would forbid time travel, and Hawking could not prove that any such law exists. So, Kaku says, physicists have had to take time machines seriously.

When Kaku looks back in his Epilogue over every technology his book has examined, he finds only two in Class III: perpetual motion and *precognition*, the seeing of the future. Kaku places even perpetual motion and precognition with care. He places perpetual motion machines in Class III in a particular sense: "either they are truly impossible, or we would need to fundamentally change our understanding of fundamental physics on a cosmological scale" (ch. 14). He writes that precognition "seems to be ruled out, at least for the foreseeable future" (ch. 15). In his Epilogue Kaku sets the physical sciences beside mathematics. Mathematicians have proved that some things cannot be done, and Kaku names the trisected angle as one of those things. But he writes that in the physical sciences "it is always dangerous to declare that something is absolutely impossible" (Epilogue, "The Future of the Impossible"). Then Kaku gives his reason: "things that are impossible today violate the known laws of physics, but the laws of physics, as we know them, can change" (same section). Kaku reports that some scientists now set limits to what we can ever know. One limit is that we will never know what happened before the Big Bang, the hot, dense begin-

> ning of our universe. Another limit is that we will never find a theory of everything, the one theory of all the forces and all the particles. Kaku writes that limits to what we can ever know may perhaps better be seen as challenges, and his image for the limits is a kitchen one: "These limits are like piecrusts, made to be broken".
>
> Kaku's view is a generous view of science, and a careful one. Kaku never lets a scientist's confidence take the place of a finding, and he leaves open every possibility that the known laws leave open. Kaku's readers come away from his book with courage, and with the right to doubt anyone who says "never" too quickly.

Where We Agree

I agree with Kaku that the laws of physics, as we know them, can change, and I reach the agreement by a route of my own, which starts from what a law is. Every finding of physics is made by *comparison*. Comparison is the act by which anything is known: setting one thing beside another and telling them apart. I sort descriptions into three levels by how widely each level holds, that is, how widely each level is true. I measure how widely a level holds by the domains in which the level holds. A *domain* is the whole range of places, or of things, that can be joined to one another: our own universe is a domain, and the surface of the Earth is a domain for a walker.

Laws hold within one domain: our own universe, with its particular *constants* (the fixed numbers, such as the strength of gravity, that the laws of our universe contain) and its particular particles. *Principles* hold across many domains: a principle would hold in any domain that allows *objective findings* (findings that come out alike for everyone who checks them), whatever the particular physics of the domain. *Axioms*, the third level, hold between all domains: in my words, the level of the axioms would hold "in any universe with any physics". My examples of laws are the conservation of energy, the *Standard Model* (the theory of the particles of matter and of the forces among them), and Einstein's theory of gravity.

Energy is the capacity to make things move, warm up or change, and the *conservation of energy* is the finding that the total amount of energy is never made and never lost, only passed from one form to another. Physicists write laws down, communicate them and test them. Laws are falsifiable: if an experiment contradicts a law, the law must be revised. Every Class III verdict rests on a law of physics, so the verdict can be revised together with the law. On whether the laws can change, Kaku and I hold the same view.

Kaku and I agree, too, about what the limits of our present knowledge are good for. Kaku says that the limits some scientists set to our knowledge may perhaps better be seen as "the challenges awaiting the next generation of scientists" (Epilogue). I say something parallel about any argument about the world that is still missing a step, and I call the missing step a gap: "In inquiry, a gap is the place where the next question is asked". A gap in an argument about the world is the limit of what we know, where the next work is done.

Kaku and I agree, too, about the machine on the Academy's list. I use the perpetual motion machine as my own picture of a sure judgment made in advance: an engineer who knows that energy is conserved can judge a design for a perpetual motion machine from its drawings. She does not need to wait for the machine to be built. The engineer can even point to where the design goes wrong: "at the part of the drawing where energy is asked to come from nothing".

Kaku gives two grounds for the conservation of energy. The first ground is a *theorem* (a statement proved by mathematics) that the mathematician Emmy Noether proved in 1918. Noether's theorem says that whenever the laws stay the same through some change, an amount is conserved, that is, the amount never changes. When the laws stay the same from one moment to the next, the amount conserved is energy. When the laws stay the same through a change, Kaku calls the change a *symmetry*, in the physicists' sense of the word: a change that leaves a thing the same, as

a sphere looks the same however it is turned. Kaku's second ground is an observation. The light of the most distant galaxies shows the same laws at work billions of years ago as today.

I keep Noether's theorem as the exact mathematics it is, and I give conservation a reason that comes before the measurements, a reason not drawn from any measurement. I use the word "symmetry" in a sense of my own, built from two other words, content and context. The *content* is what a comparison finds. The *context* is the setting in which the content is found, such as a place or a moment. In the sense I give the word, *symmetry* is a sameness of content where there is a difference of context. My picture is a bottle with water in it and a cork in the neck. Five months pass, and the bottle still holds the same amount of water. I explain the picture this way: "The amount of water is the content, and it is the same; the moment at which we look is the context, and it is different". Energy is found as the amount of water is found: "Vary the context in time, and the content that does not vary is energy". From the bottle I conclude: "The conservation law is the symmetry itself, said in the form of a number that does not change".

The two senses of "symmetry" differ in what the word is said of. In the physicists' sense, the word is said of a thing, or of the equations of a law, and the word names a change, such as a turn, after which the thing or the equations are as they were. In the sense I give it, the word is said of what a comparison finds, and the word names a sameness: the same content found in a different context, as the same amount of water is found at a later moment. I keep the two senses apart, and I state how the two senses connect: what a change in the physicists' sense leaves the same is what a comparison finds the same.

Kaku leaves room for the conservation of energy to fail somewhere on the scale of the whole universe. I also find where conservation ends. A conservation law holds within a range of settings. No conservation law can hold perfectly across all conditions. At the end of the range of a conservation law there are, as I put it, "conditions under which the conservation fails, or under which the quantity it conserves stops being well

defined". The conservation of energy has one end of its range at the largest scale there is, the universe taken whole. Physicists find it hard even to define a conserved total energy for a universe that is curved and expanding, and I read the physicists' difficulty as one case of the end of the range. At the end of the range I find a bound that, as I put it, "forecasts no loss of energy in a laboratory", because a laboratory lies well inside the range where the conservation of energy holds. Every inventor's workshop lies well inside that range too. So I come by a route of my own to Kaku's verdict on the perpetual motion machine, and to the Academy's verdict of 1775.

A Country of Roads

Imagine a country where the only way to travel is by road: the road country. For a traveler in the road country, a town is a place because a road can join the town to the other towns. Whatever a road can reach is a place of the country.

Now imagine two travelers, each with a request for the road builders.

The first traveler says: "Take me to Highfold, the village in the far hills. There is no road to it". The builders shake their heads. There is no road yet. The hills are steep, the money is short, and the bridge over the gorge would need a kind of steel no one can yet make. The road may take a lifetime to build, or a thousand years. But Highfold is a place in the country. Highfold lies in the same land as every other town. A road to Highfold is a road like any other road, only harder to build. A road that reaches Highfold will bring the traveler to a town of the same country. If the builders learn something new and rewrite their rules of building, the road to Highfold is still a road waiting to be built. Kaku's Class I describes things like the road to Highfold: things not yet built.

The second traveler says: "Take me to the town that lies in this country and that no road could ever reach". The builders have nothing to estimate, because a town is a place in the road country when a road can join the town to the other towns, and the second traveler asks for a town that no

road could join to the others. A "town" that no road could ever reach has no position among the towns. For a traveler in the road country, then, the unreachable "town" is no place at all. The unreachable "town" differs in kind from a far town or a town that is hard to reach. Suppose the builders finished a road and the traveler arrived at the end of the road: the traveler would be standing in an ordinary town of the country, and the traveler would still not have the town the traveler asked for. In this book's words, the second traveler's request names nothing: the request asks for something that the road country has no place for.

Both requests sound alike: the request for Highfold and the request for the unreachable town. The builders answer both requests with the same word, "impossible". The builders' first "impossible" is a prediction about knowledge, money and skill. Predictions about knowledge, money and skill have turned out wrong over and over in history. Kaku's piecrusts are predictions about knowledge too, because the piecrusts are the limits some scientists set to what we can ever know. In Kaku's image the piecrusts are made to be broken. The builders' second "impossible" is a plain statement about what the second request asks for, and no prediction at all. No builder, in any century, can fail at the second request or succeed at it, because there is nothing there to build to. Kaku's Class II holds the things of which he himself writes, "If they are possible at all". For each thing in Kaku's Class II, we have still to ask which kind of "impossible" it is. The thing is either a road not yet built, or a request that names nothing.

North of the North Pole

The road country is a made-up land, so here is the second traveler's request on the real Earth. Stand anywhere you like and walk north. You can walk north from Paris, from Cairo, from the middle of the Pacific Ocean on a ship. Now ask for a point north of the North Pole.

The shape of the globe alone determines, before anyone sets out, that there is no point north of the North Pole. No law, fence or guard is needed. I give the reason in one line. A request to go north of the North

Pole, I write, "defeats itself in its statement, because on the Earth north ends at the Pole". North is a direction on the globe, and at the North Pole the direction north has nowhere further to point. So the request for a point north of the North Pole names nothing.

I draw the line exactly between the two kinds of "impossible", a constraint and an edge, and I begin with what a constraint is: "A constraint, a limit laid on something, could in principle be otherwise: a rule that might be relaxed, a wall that might be climbed, a limit that better instruments might exceed". A *constraint*, then, is a limit laid on something that could be otherwise. A domain, as we saw, is the whole range of places, or of things, that can be joined to one another: the surface of the Earth is a domain for the walker, and the towns and roads are a domain for the traveler. The *edge* of a domain is where the domain ends, with nothing beyond the edge to reach. I set the edge of a domain apart from rules, walls and limits: "the edge is what makes the domain the domain it is". A wall is a constraint, and a better ladder may one day get over the wall. The North Pole is an edge, and there is nothing on the far side of the North Pole to get to.

When I say that something cannot be, the words have one sense only: I mean that the request names nothing. I never mean that the thing is too hard, too costly, or waiting on a better machine. One more step follows directly from the meaning of "cannot be": "No future machine can satisfy a request that names nothing, so what is excluded in principle is excluded, for that reason, in all future practice".

Where This Account Reaches a Different Result

I sort the impossible into three boxes, one more box than Kaku's rule of thumb has. Kaku's rule has two boxes. Either a law forbids a thing, or no law forbids the thing, and then, given time, we find the thing. This account has a third box, and the request for a point north of the North Pole goes in the third box. No law forbids a point north of the Pole, and no one will ever find a point north of the Pole. I give a second request that no law

forbids and that no one will ever fulfill. The second request uses the *antipode*, the point of a globe directly opposite where you stand. The antipode is the farthest point from you that the globe has. The request asks for a point on the globe farther from you than the antipode. My answer is: "The answer is no, but not because there is a rule forbidding travel beyond the antipode". When a request asks for a point beyond the antipode or north of the Pole, I call the request *precluded*: a precluded request is shut out by the shape of the domain before the question of building arises. So when no law forbids a thing, two cases remain: either the thing is like Highfold, waiting on a road not yet built, or the thing is a request with nothing there for a law to forbid.

In his Epilogue Kaku cautions that in the physical sciences "it is always dangerous to declare that something is absolutely impossible". Kaku's caution is right of everything that rests on a law. Physicists learned each law of physics from measurement. A better measurement can change the law. When a request names nothing, the exclusion of the request rests on no law of physics. The exclusion rests instead on comparison itself, the act that every measurement already is, and on one result about comparison, the *Incommensuration Theorem* (*incommensurate* means having no common measure). In its own words, the Incommensuration Theorem says: "Symmetry and continuity cannot both be applied, simultaneously and fundamentally, to any event or comparison; and neither can asymmetry and discontinuity". The theorem uses *symmetry* in the sense I gave the word earlier in this chapter: a sameness of content where there is a difference of context, the same content found in different settings. *Continuity* is a sameness of content where there is a sameness of context: within one unbroken setting, the content does not jump. *Asymmetry* is a difference of content where there is a difference of context: a content that changes as the setting changes. *Discontinuity* is a difference of content where there is a sameness of context: a content that jumps within one setting. Put plainly, the theorem says two things. Symmetry and continuity can never both be applied, at the same time and at the foundation, to any event or to any comparison. Asymmetry and discontinuity can never both be applied in

that way either. In the Incommensuration Theorem, the word "fundamentally" means at the foundation of a comparison, exactly and not approximately. The things we find show symmetry and continuity together all the time, approximately: a still pond looks the same everywhere and smooth. Symmetry and continuity are never both found perfect at once, in any comparison. The Incommensuration Theorem is a structural fact about the nature of knowing. Every act of knowing is an act of comparison, or is built from acts of comparison, so the Incommensuration Theorem is inherent in every single act of knowing. No experiment, no physical theory and no particular kind of mathematics enters the theorem, and it was not learned from measurement.

The Incommensuration Theorem rests on comparison and on no law, so the change of law that Kaku allows for leaves the theorem untouched. A new law replaces an old law. The theorem is a fact about comparison, the act that every measurement is, and the theorem is no law of our world. So when a new law comes, there is nothing in the theorem for the new law to replace. I write of the theorem's result: "This is a claim about what holds permanently, whatever is later learned and whatever theory is later found". I also read a family of limits already known in physics and mathematics as cases of the theorem. One limit in that family is the logician Kurt Gödel's proof that arithmetic is incomplete. Some true statements of arithmetic cannot be proved within arithmetic. Kaku himself cites Gödel's proof in his Epilogue.

Physics, too, has impossibilities that hold for good, like the three geometry problems on the Academy's page from 1775. Kaku grants that mathematics has theorems showing that some things are impossible, and in physics he keeps every law open to change. Yet even in physics, Kaku names some things that will stay out of reach for good. "There will always be things that are beyond our grasp, that are impossible to explore", he writes. One of his two examples is "the world existing beyond the reach of the speed of light" (Epilogue, "Is Physics Incomplete?"). Kaku and I agree that the world beyond the reach of light stays out of reach for good, and I give the reason. The reason starts from what a place is: a place is a posi-

tion in the pattern of connection. When no signal from us, at the speed of light or slower, could ever reach a happening, the happening has no position in the pattern of connection that runs from us. For us, the happening is no place at all, as a "town" that no road could ever reach is no place at all for the traveler in the road country. When a request asks us to reach a happening that no signal from us could ever reach, the request names nothing. I find a few requests in physics that name nothing, and as with the proved impossibilities of geometry, no one has anything to wait for in a request that names nothing. I set out each request that names nothing in full, in a chapter of its own, and among those requests are two more besides the request to reach what lies beyond the reach of light. One request asks for a universe that runs like clockwork, with everything that will ever happen fixed from the start. The other request asks that everything we know be someone's program, running on a computer outside everything we know, with us inside the program.

I exclude the perpetual motion machine as Kaku does: by the conservation of energy, a law of our universe that physicists learned from measurement. When a thing is excluded by a law learned from measurement, I call the exclusion *empirical*. An empirical exclusion rests on what measurement has found, and an empirical exclusion stands as long as the law stands. I also give the conservation of energy a reason that comes before the measurements: the reason from symmetry set out earlier in this chapter. The reason from symmetry holds in every workshop, wherever the workshop stands. The perpetual motion machine therefore stays in Kaku's Class III. The exclusion of the machine is empirical. The machine is not among the requests that name nothing. Kaku's survey holds many more items than the machine and the requests that name nothing. I give my own verdict on one of Kaku's other items only where I say so. Every other item keeps the class Kaku gave it, and that class is Kaku's verdict alone. Thinking machines are one item on which I do give a verdict. My verdict on thinking machines agrees with Kaku's. Kaku counts robots and other thinking machines in his Class I (ch. 7, closing), and I hold that "Artificial intelligence is possible".

What We Now Know

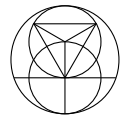
We now know that the word "impossible" says two different things. The first kind of "impossible" can change. The first kind comes in two forms, "not yet" and the empirical verdict, which fill two of the three boxes of this account. The first form is "not yet". A thing not yet built waits on knowledge and power, on money, skill and time. Kaku's Class I is the class of things not yet built. Predictions about things not yet built have often turned out wrong, and Kaku is right to be wary of such predictions. The second form is an empirical verdict, a verdict that rests on a law of physics. An empirical verdict stands as long as the law stands, and an empirical verdict can change, because a law, as we know it, may itself be revised when a measurement says so. Kaku's Class III verdicts rest on the known laws, which, as he says, can change, so every Class III verdict is empirical. The verdict on the perpetual motion machine has the second form: the verdict is empirical, and the machine is in Kaku's Class III. No change can touch the second kind of "impossible". The second kind is "names nothing", and it fills the third box. The shape of the domain itself excludes a request that names nothing, like a request for a point north of the North Pole, or for a town in the road country that no road could ever reach. No law within the domain is needed to exclude a request that names nothing. When a request names nothing, the exclusion of the request rests on comparison, and on the Incommensuration Theorem, which is inherent in every act of knowing. The exclusion rests on no law, so no change of law touches the exclusion. The three geometry problems of 1775 belong to neither kind that physics knows: they are impossible in logic, within the rules of compasses and ruler, as Wantzel and Lindemann proved, and like a request that names nothing, they hold for good. The three boxes sort the impossibilities of physics.

When a scientist tells you something is impossible, you no longer need to choose between believing the scientist and believing history, with its long record of "impossible" verdicts that were broken. You can ask which

box the scientist's verdict belongs in: "not yet", a verdict that rests on a law, or "names nothing". If the scientist means "not yet", Kaku's courage is the right response, and a later generation may well break the piecrust. If the verdict rests on a law, the verdict stands as long as the law stands, and measurement is the judge of the law. If the request names nothing, there is no piecrust to break, only a request to be read more carefully, and what can be had in place of the request is a coherent request that does name something.

Laws as we know them can change, but a request that names nothing is excluded in principle, and therefore in all future practice.

Kaku's two most famous dreams are a message sent faster than light and a journey back into the past. He places travel faster than light and the time machine in his Class II, among the things that, "if they are possible at all", might be realized thousands to millions of years from now. Which are Kaku's two dreams: roads not yet built, or requests that name nothing?



Chapter Two

Faster Than Light, and Back in Time

Will anyone send a message faster than light, or change the past?

What this chapter uses

Comparison: setting one thing beside another and telling them apart, the act by which anything is known (Preface and Chapter One).

The *road country*: a town is a place because a road can join the town to the other towns, and a request for a "town" that no road could ever reach *names nothing* (Chapter One).

A *domain* is the whole range of places, or of things, that can be joined to one another; its *edge* is where the domain ends, with nothing beyond the edge to reach (Chapter One).

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 (Chapter One).

The theorem's four words: *symmetry* is a sameness of content where there is a difference of context; *continuity*, a sameness of content where there is a sameness of context; *asymmetry*, a difference of content where there is a difference of context; *discontinuity*, a difference of content where there is a sameness of context. The *content* is what a comparison finds, and the *context* is the setting in which the content is found (Chapter One).

Michio Kaku's books leave many readers asking whether, if nothing in the laws of physics forbids a wormhole or a time machine, someone will one day send a message faster than light, or go back and change the past, and hoping that the answer is yes.

A Bridge Between Two Sheets

In the spring of 1935 Albert Einstein was working at the Institute for Advanced Study in Princeton, New Jersey. His young assistant, Nathan Rosen, was working with him. One feature of the physics of his day troubled Einstein: physicists pictured a particle of matter, such as the *electron*, as a single point. The electron is the tiny particle of electric charge that every atom carries. Close to the point, the particle's gravity grew without limit, and at the point itself the gravity became infinite. Einstein wanted a picture of a particle in which nothing became infinite. Einstein and Rosen looked for a particle without an infinity in Einstein's own theory of gravity. Einstein's theory of gravity is *general relativity*, which describes gravity as the shape of space and time: matter bends the shape of space and time, and the bent shape guides how things move.

On 8 May 1935 the journal *Physical Review* received the paper of Einstein and Rosen, "The particle problem in the general theory of relativity". In the paper, Einstein and Rosen picture physical space as "a space of two identical sheets, a particle being represented by a 'bridge' connecting these sheets". Imagine two sheets of paper held flat, one above the other, and joined at one spot by a short neck. In Einstein and Rosen's picture, the two sheets are space, and the neck that joins the sheets is the particle. Einstein and Rosen meant the bridge as a model of a particle, and not as a passage to travel through.

Kaku tells the story of the Einstein-Rosen bridge himself. In *Parallel Worlds* (2005) Kaku writes that Einstein and Rosen "were trying to use the black hole solution as a model for elementary particles" (*Parallel Worlds*, ch. 5, "Einstein-Rosen Bridge"). A *black hole* is a body whose gravity is so strong that not even light escapes from the body. In Kaku's sentence, a *solution* is one shape of space and time that Einstein's equations allow.

Later physicists read the shape of the bridge another way: as a short tunnel joining two regions of space. The later physicists called the tunnel a *wormhole*: a shape of space and time, allowed by Einstein's equations, in

which a short passage joins two places that are otherwise far apart. Half a century after Einstein and Rosen's paper, physicists took up the wormhole again because of a novel. Michael Morris and Kip Thorne were physicists at the California Institute of Technology. In May 1988 Morris and Thorne published a paper on a question taken from Carl Sagan's novel *Contact*, in which travelers cross our galaxy through a wormhole. The question was whether a traveler could really pass through a wormhole. Morris and Thorne found wormhole shapes through which a traveler could, in principle, pass. Every wormhole that Morris and Thorne found needs its *throat*, the narrowest part of the tunnel, to be held open. The throat can be held open only by what physicists call *negative energy*: a state with less energy than empty space has.

Kaku's Case for Hope

Kaku builds his case for hope with care, and the hope is for travel faster than light and travel into the past. Kaku begins from Einstein's *special relativity*, the theory of 1905 that says how lengths and durations compare for observers moving steadily past one another. Special relativity says that a body pushed closer and closer to the speed of light grows heavier without limit. So no rocket ever reaches the speed of light. Kaku calls the speed of light, taken as a limit that no rocket reaches, the *light barrier*. In *Physics of the Impossible* (2008) Kaku puts the light barrier in a picture: "Apparently the speed of light is the ultimate traffic cop in the universe". At once Kaku questions his own picture: "Or maybe not..." (*Physics of the Impossible*, ch. 11, opening section).

Kaku looks for loopholes in the light barrier, and he is careful about which loopholes count. Sweep a flashlight beam across the night sky. The spot where the beam lands can sweep across distant space faster than light could travel the same distance. Kaku sets the sweeping spot aside at once: "The image of the light beam has exceeded the speed of light, but the image carries no energy or information" (ch. 11, "Loopholes in Einstein's Theory"). The loopholes Kaku keeps come from gen-

eral relativity, in which space itself can bend and stretch. The first loophole is to stretch space. In 1994 the physicist Miguel Alcubierre proposed a *warp drive*. A warp drive would shrink the space ahead of a ship and stretch the space behind the ship. The ship would then be carried along without moving through the space around the ship. The second loophole is to rip space: to open a wormhole. Kaku writes that the warp drive and the wormhole need the same strange fuel: "negative mass or energy is essential for both the Alcubierre drive and the wormhole solution" (ch. 11, "Wormholes and Black Holes"). Kaku points to the *Casimir effect*, a tiny pull between two metal plates set very close together in empty space, and he reports that the Casimir effect has been measured in the laboratory. From the Casimir effect Kaku concludes that negative energy "actually exists, but only in minute quantities" (ch. 11, "The Alcubierre Drive and Negative Energy").

Kaku sorts the impossible into three classes, which Chapter One set out. Kaku's Class II holds things that "sit at the very edge of our understanding of the physical world", and of those things he writes that, "if they are possible at all", they might be realized thousands to millions of years from now (Preface, "Predicting the Future"). Kaku places travel faster than light, by wormholes and by stretched space, in Class II: "Because there is still controversy over the fundamental laws governing the fabric of space-time at the quantum level, I would classify this as a Class II impossibility" (ch. 11, closing).

Kaku sorts time travel with the same care that he gives to travel faster than light. Kaku counts travel into the future as plain fact: "time travel to the future is possible, and has been experimentally verified millions of times" (ch. 12, "Changing the Past"). A clock that moves fast runs slow compared with a clock that stays behind, so when a traveler makes a fast journey and comes back, she finds that less time has passed for her than for the people she left behind. Travel into the past is harder. Still, Kaku reports that Einstein's equations allow shapes of space and time in which a path loops back to its own past. Physicists call a path that loops back to its own past a *closed timelike curve*, or more

plainly a *time loop*: a path that a clock can follow and that returns to its own starting place and moment. In 1949 the logician Kurt Gödel found a time loop in a spinning universe. Physicists have found other time loops since. One of the time loops found since is a time machine built from a wormhole, which Kip Thorne and his colleagues found in 1988. Kaku also notes a limit of the wormhole time machine: "you would be able to go back in time only to the point when the time machines were built" (ch. 12, "Time Travel: Physicists' Playground").

In *Parallel Worlds* Kaku reports a saying that physicists often quote: "Everything not forbidden is compulsory". The saying comes from the ants of T. H. White's novel *The Once and Future King*. Kaku restates the saying in his own words: "if there isn't a basic principle of physics forbidding time travel, then time travel is necessarily a physical possibility" (*Parallel Worlds*, ch. 5, "A Universe in Your Bedroom"). In *Hyperspace* (1994) Kaku separates what the laws allow from what anyone can build: "The laws of physics tell us what is possible, not what is practical" (*Hyperspace*, ch. 11, "To Build a Time Machine").

Kaku takes up the old paradoxes of time travel directly. If you went back and stopped your own parents from meeting, how could you have been born to go back? Kaku sets out three ways out of the paradox. Of the three, he writes, one "seems to be the one consistent with the quantum theory": the universe splits in two at the moment you arrive (*Physics of the Impossible*, ch. 12, "Paradoxes and Time Conundrums"). In Kaku's picture the time line then forks into two *branches*, two universes running side by side from the moment you arrive, and the people you meet in your branch look just like your parents but are not your parents. Kaku concludes: "This means that all time travel paradoxes can be solved" (ch. 12, "Paradoxes and Time Conundrums"). Kaku's verdict on travel into the past matches his verdict on wormholes: "time travel seems to qualify as a Class II impossibility" (ch. 12, closing). Kaku writes that every problem of passing through a wormhole comes down to one place near the wormhole's entrance. At that place, Einstein's theory of gravity stops giving sensible answers. Kaku writes

that the physics of that place near the entrance is the key to understanding time travel, "and only a theory of everything can explain this" (ch. 12, "Paradoxes and Time Conundrums"). A theory of everything is the one theory of all the forces and all the particles, and it would join gravity with the quantum: the physics of the smallest pieces of matter. Kaku says that most physicists would agree that a theory of everything is one way to settle the time travel question for good.

Two particles that have met can stay linked after they part. When the two particles are measured far apart, their results agree in a pattern that no instructions carried separately by each particle could give them. Physicists call the link between two particles that have met *entanglement*. Kaku himself answers no to one hope: a message sent faster than light by entanglement. In *Quantum Supremacy* (2023) Kaku asks whether entanglement can carry a message faster than light. He answers: "So information can travel instantly between coherent particles, but useful information that carries a message cannot go faster than light" (*Quantum Supremacy*, ch. 3, "Entanglement"). By 'coherent particles' Kaku means particles that are entangled.

Where We Arrive Together

Kaku and this account agree on four results, and for each of the four this account has ground of its own: reasons that start from comparison, and not from Kaku's experiments and equations.

The first result is the light barrier itself. The light barrier follows from comparison. Every measurement is an act of comparison, and so is every *interaction*, every case of one thing acting on another. Picture a single firework bursting in a dark sky. The firework's light spreads out as a growing sphere. The *forward light cone* of the burst is everything the burst can affect. The forward light cone is made of every place and moment on or inside the growing sphere of the firework's light. The backward light cone of the burst is everything that can affect the burst: every place and moment from which a signal, traveling at the speed of light or slower, could have

reached the burst. Every message and every body that leaves the burst stays within the burst's forward light cone. An *event* is a single happening at one place and one moment, as the burst of the firework is. Space is the pattern of which events are causally connected with which. In plain words, space is the pattern of which events can affect which. I call the whole range within which comparisons can be made the *domain of comparison*. Seen from any one event, the speed of light marks the outer edge of the domain of comparison. For any one event, the outer edge is the event's light cone, and beyond the light cone no comparison with the event can be made at all. Where Kaku pictures a traffic cop, there is no rule. No rule is needed to keep any message within the light cone. In my picture, the edge is like the curve of the ground, which limits how far a traveler on open ground can see, and not like a fence. Someone puts up a fence, and someone could take the fence down, but the limit of the traveler's view comes from the shape of the ground itself. Kaku himself counts "the world existing beyond the reach of the speed of light" among the things that are "impossible to explore" (*Physics of the Impossible*, Epilogue, "Is Physics Incomplete?").

The second result is entanglement. Kaku says that no useful message can be sent by entanglement, and this account says the same. Physicists usually show that no message can be sent by entanglement with the *no-communication theorem*, a theorem of quantum theory. Three physicists gave the no-communication theorem a general form in 1980: Giancarlo Ghirardi, Alberto Rimini and Tullio Weber. I call the no-communication theorem correct, and I reach the theorem's result on deeper ground. My argument uses only three premises: that interaction is comparison, that comparison has edges built into it, and that the speed of light marks the outer edge. None of the three premises comes from quantum theory, so the edge of the domain would remain if quantum theory were modified or replaced. A reader may hope that a theory that comes after quantum theory will show a way to send messages faster than light, but no later theory will show such a way, because the edge of the domain of comparison never depended on quantum theory.

On entanglement, this account also says one thing more than Kaku says. Kaku writes that information travels instantly between entangled particles, and that the information is useless because it is random. I hold that nothing travels between the particles at all. Each of the two particles is measured at its own detector, and each detector keeps a record that, taken alone, is a random list. The agreement between the two records appears only when someone brings the records together afterward, "by ordinary means and at ordinary speed". Nothing crosses the distance. There is no signal. Experiments on entangled particles agree. In 2015 the physicist Bas Hensen and his colleagues set two entangled electrons one point three kilometers apart, at Delft in the Netherlands, so that no signal at the speed of light could pass between the measurements of the two electrons while the measurements were being made. Hensen and his colleagues found the agreement between the two records that quantum theory predicts, and the agreement was stronger than any set of instructions carried by the two electrons from the start could produce. So we now know that the agreement between entangled particles is real, and that the agreement carries nothing from one detector to the other.

The third result is that the past is not altered. In *Hyperspace* Kaku writes, "Thus perhaps we can fulfill the past, but never alter it" (*Hyperspace*, ch. 11, "World Lines"). This account agrees that the past is not altered, and its ground is the order that every comparison has: first the range of what is possible, then the act of comparison, then the record of the act. A *finding* is what one act of comparison yields: one outcome, laid down as a record. The record follows the act it records, and a finding, once laid down as a record, is not undone as a finding. Travel into the future is possible on this account, as it is for Kaku, who counts it as plain fact. A body can go anywhere its forward cone reaches, and its forward cone, given time, reaches a great deal.

The fourth result is the fuel that a wormhole needs. Kaku says that a wormhole needs negative energy to hold its throat open, and this account has the same requirement, because in this account space and time are the space and time of general relativity. I make no claim either way on whether negative energy exists in the amount a wormhole needs.

A Point North of the North Pole

On a message faster than light, Kaku's account and this account differ. The speed of light marks the edge of the domain of comparison, so if a message were sent to a happening outside the light cone, the message would need a comparison beyond the edge of comparison, where there is nothing to reach. So when someone requests a message outside the light cone, the request names nothing: there is no thing there for the request to ask for.

Chapter One asked for two points that a globe does not have: a point north of the North Pole, and a point farther from you than the *antipode*, the point of the globe directly opposite where you stand. On the globe, north ends at the Pole, and no point lies farther from you than the antipode, so each of the two requests is malformed, and no better boots will bring a walker to either point. I set the light cone beside the globe: "Asking whether one can signal faster than light is therefore a category error". A *category error* is a concept applied where it does not belong. A request that makes a category error is malformed rather than hard. A place, as I said in Chapter One, is a position in the pattern of what can affect what. Seen from one event, a happening outside the event's light cone has no position in the pattern of what can affect what. Happenings outside the cone are not places at all, in the sense that matters here, and so happenings outside the cone are not far places that travelers might one day reach with better technology.

Your question has two halves: a message faster than light, and a change to the past. The two halves are joined, because a message sent outside the light cone would be, for some observer, a message into the past.

Imagine a long railway carriage moving steadily along a straight track, with a lamp in the exact middle of the carriage. The lamp flashes once. For a rider in the carriage, the light reaches the front wall and the back wall at the same moment. For someone standing beside the track, the back wall moves toward the light and the front wall moves away from the light. So the light reaches the back wall first. For a passenger on a faster train overtaking the carriage, the light reaches the front wall first. Take two happenings: the light's arrival at the front wall, and its arrival at the back wall. The two arrivals are outside each other's light cones, because for the rider the two arrivals happen at the same moment, a carriage length apart, so no flash from one arrival could reach the other. Two happenings outside each other's light cones have no order that every observer shares. So if a signal were sent from one arrival to the other, the signal would, for some observer, arrive before the signal was sent, and for that observer the record of the signal would come before the sending, which is the act the record records. Yet a record always follows the act it records, and so "such a signal is no signal". Kaku joins the two questions too: in *Hyperspace* he rules out a favorite trick of the old stories, flying faster than light to turn time back (ch. 11, "Time Travel").

A request that names nothing is excluded in principle, and therefore in all future practice. So the verdict on a message faster than light depends on no theory of everything, no richer civilization and no cheaper fuel. So no civilization communicates faster than light, because no civilization can. When a civilization understands physics better than we do, the civilization has understood, among other things, that the edge of the domain of comparison is an edge and not a wall.

New Roads and Faster Cars

What, then, does this account say of the wormhole and the warp drive? The words "faster than light" have two meanings. In the first meaning, something arrives outside the light cone of its own departure, in the shape of space and time it travels in. In the first meaning, a message faster

than light is the request that names nothing. In the second meaning, something arrives sooner than the long way around would allow, by a shortcut in the shape of space and time, and still inside the light cone of its departure. The second meaning is a question about the shape of space and time.

The bridge that Einstein and Rosen drew is one part of the one shape of space and time that Einstein's equations describe, and the two sheets that the bridge joins belong to the same shape. Every shortcut is like the bridge in one way: each shortcut is a part of the one shape of space and time. Here a *geometry* means one whole shape of space and time. A shortcut is a feature of that 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. The cone in that sentence is the light cone.

Think again of the road country of Chapter One. A town that no road has reached yet is a place of the country that waits for its road. A "town" that no road could ever reach is no place at all for the traveler, however good the car. Now set the wormhole and the warp drive in the road country. A wormhole held open by negative energy would be a new road, and a warp drive a faster car. A new road, however short, arrives at a town of the same country. A faster car, however fast, arrives at a town of the same country. Whatever a wormhole or a warp drive reaches belongs to the one world, because the one world is everything any path can reach. In the same way, the far sheet of the Einstein-Rosen bridge is a part of the one shape that holds the bridge.

To Kaku's case I add the place where every journey by wormhole or warp drive arrives. The place of arrival is a town of the same road country that the journey set out from. In plain words, every journey by wormhole or warp drive arrives within the light cone of its departure, in the one world.

The Door Marked "Last Thursday"

The second half of your question is about the journey into one's own past: will anyone go back and change the past? When people speak of "time travel", they mean a journey into one's own past, to an earlier occasion as it was. "Time travel", in the sense in which the phrase is used, names no concept, and in this section I show why. When every reading of what would satisfy a phrase fails, the phrase names no concept. A reading can fail in two ways. A failed reading either describes something other than what the phrase is used to mean, or asks for conditions, all at once, that nothing satisfies. In the sense of a journey into one's own past, the phrase "time travel" picks out no thing at all, and so there is nothing for an engineer to build.

Picture a door with a small brass plate on it, and on the plate the words "Last Thursday". The writers of time-travel stories ask us to imagine that the door opens onto last Thursday itself: the same morning, the same rain on the same window, the same talk at breakfast, and you there among it all. An engineer who sees the door marked "Last Thursday" asks how to build the door, and how much energy the door would take. I ask a question that comes first: what would be on the other side of the door?

Ask three people what going back to last Thursday would mean, and you may get three answers. The first person unrolls a map of space and time, on which the days are laid out the way cities are laid out on a map of Europe, and she points to a spot earlier than the spot where she stands. I call the time on the map *geometric time*. Geometric time is the time laid out in the shape of space and time, read by a clock along each path. The second person holds up his notebook of findings, page after page in the order he wrote them, and he says that going back would mean the pages coming to stand in another order. I call the order of a traveler's findings *event time*. The third person says that she means more than a spot on a map, and more than a notebook in a new order. She means being at last

Thursday, the very day as it happened. She does not mean a copy of that day, or a day like it somewhere else. The third answer is what the phrase "time travel" means.

Take the map first. Suppose the shape of space and time contains a time loop, and a traveler follows the loop. The traveler carries a clock, and the clock reads later at every step of the way. The traveler carries the records made before setting out, and every finding along the loop is made after those records. Physicists who study time loops admit only histories that agree with themselves all the way round. In a history that agrees with itself, each place and moment has one state and not two. Physicists call the demand that every history agree with itself the principle of self-consistency, and seven physicists, among them Igor Novikov and Kip Thorne, set the principle out in 1990. For the traveler to return to the very moment of departure, every trace of the trip would have to be restored on the way round, including the clock's reading, and the restoring is itself a further act, made later. So the first answer, the map's, describes a later finding of the traveler, and not an arrival at last Thursday as it was.

Next comes the notebook. The order of findings runs one way. The reason is that the record follows the act it records, and a finding once laid down is not undone as a finding. The second person, the one with the notebook, asks for a later page to come before an earlier page. A later page before an earlier page is the one reversal that cannot happen in the order of findings.

Last comes the third answer, the one the phrase means, given by the third person, who means last Thursday itself. The third person asks that one time be found, in one act of comparison, both as a place on the map and as the occasion in the notebook, and that the time be exactly each. We can say in four words what is found of each of the two times, the map's time and the notebook's time. The four words have the senses they have in the Incommensuration Theorem, which I set out in Chapter One and list in the box at the head of this chapter. Every comparison has two verdicts: the first verdict says whether the content, what the comparison finds, is the same or different, and the second verdict says whether the context, the

setting in which the content is found, is the same or different. All four words describe what a comparison finds, so the word symmetry here has the theorem's sense: a sameness that a comparison finds. Chapter One set the theorem's sense apart from the physicists' sense, which Kaku uses. What is found of the map's time is continuous and asymmetric: smooth, and going somewhere. What is found of the notebook's time is discontinuous and symmetric. Each finding is one separate click, and the record of the finding reads the same each time the record is read. I prove the Incommensuration Theorem from comparison alone. Now suppose that one time were found both as the map's time and as the notebook's time, each exactly. The time would then have at least one of the two pairings that the theorem says cannot both be applied. The two pairings are continuity together with symmetry, and asymmetry together with discontinuity. So nothing satisfies the third answer, and since the map's answer, the notebook's answer and the third answer all fail, the phrase "time travel" names no concept.

My answer is plain: "You cannot go back". No one can go back because of what the two times are, and no engineering, energy or fuel changes what the two times are. "Back", said of time, is a direction of places on the map, and a speaker who says 'back' of time applies that direction to the order of findings, where there is no backward to be had. I give two everyday words, 'exist' and 'real', exact senses. When something stands as structure, timeless, the same pattern however and whenever it is consulted, I say that the thing *exists*. When something is given in an actual act of comparison, happening when it happens, I say that the thing is *real*. Both senses fit in one line: "A law exists; a measurement is real". Last Thursday lies in one stretch of the map, and in the exact sense of 'exist' that stretch exists, because the stretch is part of the laid-out shape of space and time, there to be described from any vantage. The findings of last Thursday were real when they were made, and what remains of them now is their record. The stretch of the map is not an occasion that anyone can attend a second time, and neither is the record.

In the road country, picture a traveler who drives back to the town where she was born. What she finds is this: "She arrives, and what she finds is the town as it is on the day she arrives, not the morning of her birth". Every road in the country arrives at a town after the traveler set out. Every arrival is a new finding of the traveler's own, made after every finding the traveler made before. So no road arrives at a town before the traveler set out.

We can now set Kaku's answer to the paradoxes beside this account. Kaku finds one answer consistent with quantum theory: the universe that splits in two. In 1991 the physicist David Deutsch showed that quantum theory near a time loop allows consistent histories in which a traveler arrives in the past of another branch, so that no paradox arises. Deutsch's result and the result of this account agree on the main point: no traveler arrives at an earlier occasion as the occasion it was. A morning in another branch, with people who look like your parents, is a likeness of last Thursday. The phrase "time travel" is used to mean last Thursday itself, and not a likeness of last Thursday.

What We Now Know

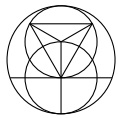
We can now answer each part of your question. If anyone ever makes a wormhole or a warp drive, the wormhole or warp drive will be a shortcut within the one shape of space and time: a new road or a faster car in the one country. I make no claim either way on whether a wormhole or a warp drive can be made, so I take no side on Kaku's Class II verdict on travel by wormhole and by warp drive. Two requests name nothing: a message to a happening outside the light cone, and a return to one's own past as it was. On separate ground, this account also agrees with two of Kaku's own results. The light barrier holds for every message, and entanglement carries no message at all.

If you share Kaku's hope of crossing the galaxy, you keep that hope whole, because the hope is about new roads and faster cars in the one country, and this account says nothing against new roads and faster cars.

No richer civilization was ever needed for the message outside the light cone or for the return to one's own past, because both requests name nothing. So there is nothing to wait for, and nothing to fear, from either request. Yesterday stays as it was found by those who were there, and what was done last Thursday stays done, for everyone.

Every road, however new and however fast, arrives at a town of the same country, and after the traveler set out.

By *hyperspace* Kaku means the dimensions beyond the four we know, three of space and one of time. He writes that hyperspace "may provide a means to tunnel through space and time" (*Hyperspace*, Preface). A tunnel through further dimensions needs the dimensions to be there, and so a question comes before any tunnel: if there really are further dimensions, how could anyone know, and why would there be ten in all?



Chapter Three

Ten Dimensions

If there are six more dimensions, how could anyone know, and why ten?

What this chapter uses

Comparison: setting one thing beside another and telling them apart (Preface and Chapter One). A *finding* is what one act of comparison yields: one outcome, laid down as a record (Chapter Two).

The *road country*, in which the country is everything any path can reach (Chapter One).

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 (Chapter One).

The theorem's four words: *symmetry* is a sameness of content (what is found) where there is a difference of context (the setting it is found in); *continuity*, a sameness of content where there is a sameness of context; *asymmetry*, a content that changes as the setting changes; *discontinuity*, a content that jumps within one setting (Chapter One).

Your questions about the six further dimensions go beyond how anyone could know of them, and why there are ten: what are the six, and could anything travel through them? The physicist Michio Kaku hopes for

one theory that covers every force of nature. Kaku's hope rests on dimensions beyond the four we know, three of space and one of time. So your questions about the six bear on the hope at the center of Kaku's books *Hyperspace* and *The God Equation*.

A Letter from Königsberg

In April 1919 the mathematician Theodor Kaluza wrote a letter to Albert Einstein from the University of Königsberg, in East Prussia, near the Baltic Sea, where Kaluza was then a junior lecturer. Kaluza had found a second theory inside Einstein's own theory of gravity, once the theory of gravity is written with one more direction. Einstein's theory describes space and time together as a *geometry*: a shape, with distances that can stretch and bend. In Einstein's theory, gravity is the bending of the shape. Einstein wrote his theory as a set of *equations*, statements that two quantities are equal. Einstein's equations say how matter bends the shape around the matter. Einstein had written his equations for the four dimensions we know, three of space and one of time. In the plain sense, a *dimension* is one independent direction in which things can differ: a table top has two dimensions, east and north, and the room around you has three. Kaluza wrote Einstein's equations for five dimensions instead of four. Then he looked at what came out. Einstein's gravity came out, as Kaluza expected. A second set of equations came out beside Einstein's gravity, and Kaluza recognized the second set. The second set were the equations that the physicist James Clerk Maxwell had written in the 1860s for *electromagnetism*, the force of electricity and magnetism, of which light is a traveling wave. So one geometry with one extra direction had produced both great theories of the age: Einstein's gravity and Maxwell's light.

Einstein answered on 21 April 1919. He wrote: "The idea of achieving [a unified theory] by means of a five-dimensional cylinder world never dawned on me". And he wrote: "At first glance I like your idea enormously". A *unified theory* is one theory that covers forces that physicists once thought to be separate. By a *cylinder world* Einstein meant Kaluza's five di-

mensions of space and time, taken with Kaluza's assumption that nothing changes along the fifth direction, as nothing changes along the length of a straight pipe. Then Einstein kept Kaluza's paper back for two years. In 1921 Einstein presented Kaluza's paper to the Prussian Academy of Sciences in Berlin. The Academy printed the paper under the title "Zum Unitätsproblem der Physik", "On the Unity Problem of Physics". Physicists still call Kaluza's idea *Kaluza-Klein theory*, after Kaluza and after the physicist Oskar Klein, who took up the idea in 1926.

String theory is the theory in which the smallest pieces of matter are tiny vibrating strings. In Michio Kaku's telling, the ten dimensions of string theory are descendants of Kaluza's letter. Your question has two halves, and Kaluza's letter raises both halves. In the first half you ask where the extra directions are, how anyone could find them, and whether anything could travel through them. In the second half you ask why there should be a fifth direction, or a tenth, at all.

What Michio Kaku Showed

Kaku tells Kaluza's story with real delight in his book *Hyperspace* (1994). He opens the story at the same moment as this chapter does: "In April 1919, Einstein received a letter that left him speechless" (*Hyperspace*, ch. 4, "The Birth of Kaluza-Klein Theory"). Kaku names four themes in the Preface of *Hyperspace*, and the first theme is that "the laws of nature become simpler and more elegant when expressed in higher dimensions" (*Hyperspace*, Preface). Later in the book he calls the first theme "our fundamental premise" (*Hyperspace*, ch. 7, "Modular Functions"). Kaluza's letter is Kaku's first great example of the first theme: the laws of nature grow simpler in higher dimensions. Kaku writes that the extra piece that came out of the five-dimensional equations was "precisely Maxwell's theory of light" (*Hyperspace*, ch. 4, "The Birth of Kaluza-Klein Theory").

Kaku also counts the numbers that Einstein's gravity and Maxwell's light need. His count is easy to follow. In four dimensions, Einstein's gravity needs ten numbers at each point of space to say how the shape is bent at the point. Physicists call the ten numbers the *components* of the geometry: the numbers that say how the shape is bent at a point. Maxwell's light needs four numbers at each point. Gravity in five dimensions needs fifteen components. Fifteen is ten for gravity, four for light, and one left over. Kaku says that the leftover component belongs to one further particle, and he sets the leftover component aside as unimportant for his story. So the larger geometry has "enough room" for both theories at once, in Kaku's phrase (same section).

Kaku sets Kaluza's discovery inside a larger picture, part Einstein's and part Kaku's own. The picture is a good one. Kaku tells us that Einstein likened the geometry side of Einstein's equations to marble, clean and beautiful, and the matter side to wood, a gnarled tangle of *particles* (the smallest pieces of matter), atoms, rocks and stars. Imagine a park with a great old tree at its center, and around the tree a plaza of the purest marble, laid in patterns that follow the roots. Kaku writes, "The presence of the tree determines the pattern of the marble surrounding it" (*Hyperspace*, ch. 4, "A Universe Made of Marble"). Kaku goes on: "Einstein's grand strategy was to turn wood into marble" (same section). In the picture the marble plaza is geometry and the tree is matter, and Einstein's strategy was to make the tree itself of marble, so that matter too would be nothing but geometry. Kaluza's letter was the first step toward Einstein's dream, because in Kaluza's five dimensions light had turned out to be geometry too.

Then Kaku asks the obvious question plainly: if there is a fifth direction, where is it? Kaku tells the answer that Kaluza and Klein gave: the fifth direction is small. Kaku writes that the fifth direction "collapsed down to a circle so small that even atoms could not fit inside it" (*Hyperspace*, ch. 4, "Life on a Cylinder"). In *Parallel Worlds* (2005), Kaku pictures a small, closed direction as a garden hose: seen from far away, a garden hose looks like a line, and only close up does the circle around

the hose appear (*Parallel Worlds*, ch. 7, "Problems in Hyperspace"). The length of the hose is like a direction we can see, and the circle around the hose is like the small fifth direction.

In the decades that followed, physicists added more extra directions, to make room for two more forces as well, the *nuclear forces*. The nuclear forces are the forces at work in the center of the atom: the *strong force* that binds the center of the atom, and the *weak force* behind some kinds of radioactivity. Kaku tells how, in 1984, the physicists John Schwarz and Michael Green showed that string theory was free of the problems that had stopped every earlier candidate for a unified theory. The problems included calculations that gave infinite answers or contradicted themselves. And string theory fixes its own number of dimensions. Kaku writes in *The God Equation* (2021): "But in string theory, the dimensionality of space-time is fixed at ten dimensions". He goes on: "The theory breaks down mathematically in other dimensions" (*The God Equation*, ch. 6, "Ten Dimensions"). Kaku writes that if string theory is correct, our universe might actually have ten dimensions. Four of the ten are the ones we know. The other six dimensions would be out of sight because they are so small: "our atoms are too big to enter these tiny higher dimensions" (same section).

Kaku says openly where the knowledge of physics ends. His openness is one of the pleasures of reading him. Kaku explains that a string stays *self-consistent*, free of any contradiction among its own laws, only by obeying a family of formulas called *modular functions*, found in the notebooks of the mathematician Srinivasa Ramanujan. The modular functions fix the number of dimensions at ten (*Hyperspace*, ch. 7, "The Mystery of Modular Functions"). Nobody knows why the modular functions single out ten: Kaku reports that when audiences ask why nature should have ten dimensions, "physicists are forced to answer, 'We don't know'" (same section). Kaku also restates his first theme to include self-consistency: "The laws of nature simplify when self-consistently expressed in higher dimensions" (*Hyperspace*, ch. 7, "Modular Functions").

A Test in Colorado

How could anyone know whether space has extra directions? Kaku describes a way to find out. The way uses nothing more exotic than gravity on a laboratory bench.

Start with a lamp alone on a dark night. The lamp's light spreads out in every direction, over the surface of a growing sphere. At twice the distance, the lamp's light is spread over a sphere with four times the area, so the light is a quarter as bright. At three times the distance, the light is a ninth as bright. Gravity spreads out as the lamp's light does, and physicists call the rule for gravity the *inverse square law*: the pull of a mass weakens with the square of the distance from the mass. Isaac Newton found the inverse square law. Engineers use the law to steer space probes across the solar system to this day.

Now suppose space had a fourth direction, open wide enough for gravity to spread into. Then the pull of a mass would spread over a larger kind of sphere, and the pull would weaken faster: with the cube of the distance, in place of the square. At twice the distance, the pull would be an eighth as strong. The number of directions of space shows in the rule for how the pull of a mass weakens. Kaku explains that a careful measurement of gravity at very short distances could find an extra direction of space, if the extra direction is at least as wide as the distances the instrument measures (*The God Equation*, ch. 6, "Testing the Inverse Square Law"; *Parallel Worlds*, ch. 9, "Measuring the Eleventh Dimension").

At the University of Colorado at Boulder, Joshua Long, John Price and their fellow physicists built an experiment to measure gravity at very short distances, and the team reported the experiment in the journal *Nature* in 2003. In the experiment, two thin plates hung about a tenth of a millimeter apart in a *vacuum*, a chamber pumped empty of air. The plates were made of *tungsten*, a heavy metal. The team set one plate vibrating about a thousand times a second, so that the gravity of the vibrating plate tugged on the other plate in time with the vibration. The team built the

other plate to respond to a tug repeated a thousand times a second. A thin shield between the plates kept out stray electric forces and sound. Then the team watched for the other plate to move in step with the tug. When the plates were a hundred and eight millionths of a meter apart, the team found no motion above the faint trembling that heat gives everything. Newton's law held. Kaku tells the result with a smile: "But this means only that there are no added dimensions in Colorado" (*The God Equation*, ch. 6, "Testing the Inverse Square Law").

Other physicists carried the search further. At the University of Washington in Seattle, Daniel Kapner, Eric Adelberger and their colleagues reported three experiments in 2007 that used a twisting balance to measure gravity down to about a twentieth of a millimeter. Newton's law held in Seattle too. So we now know from measurement how gravity weakens down to about a twentieth of a millimeter. Down to a twentieth of a millimeter, gravity weakens as gravity does in a space of three directions, to the full precision of the instruments, and no extra direction of space shows itself in the pull of one mass on another.

For every distance down to a twentieth of a millimeter, the first half of your question now has its answer: anyone can know by measuring gravity, as the teams in Colorado and Seattle did. We need a count of a different kind for the second half of your question: why the number of dimensions should be ten.

Ten, Counted Another Way

I count ten dimensions too, from a different starting point: comparison. A ruler laid beside a table is a comparison, and so is a clock read against a heartbeat, and so is a glance in which you see that one apple is red and the other is green. Every measurement is an act of comparison, and the measurement with the plates in Colorado is one act of comparison.

Now go back to the plain meaning of a dimension, put in terms of findings: a dimension is one independent way in which two findings can differ. A setting, in this chapter, is where findings are placed, as findings are placed in time and in space. I define the dimension of a setting as "the number of its independent ways of differing". Then I ask a question that sounds too simple to have an answer. The *structure of comparison* is the set of parts that every comparison must contain. If every finding comes from a comparison, what numbers can the structure of comparison itself supply? A comparison is made from one point of view, so a comparison supplies the number one. A comparison always involves a pair, this and that, so a comparison supplies the number two. Every comparison contains six ideas, and the six ideas come in three pairs. Same and different make the verdict of a comparison, what is found and the setting it is found in make the respect, and the one who compares and the thing compared together make the one point of view. So comparison supplies the number three, for the three pairs, and the number six, for all six ideas together. Four of the six ideas can each be followed apart from the point of view: same, different, what is found, and the setting it is found in. The one who compares and the thing compared cannot be followed apart from the point of view, because together the two ideas are the point of view. So the four ideas that can be followed apart supply the number four. The structure of comparison has sets of parts of five sizes only: one, two, three, four and six. The parts can also be combined. For example, a combination can take one member from each of the three pairs, and the three members can be chosen in eight ways. But each combination is made from parts already counted, so a combination brings no new part and no new independent way of differing. So only the sizes of the sets of parts count: one, two, three, four and six are the numbers the structure of comparison supplies, and every count of the dimensions of a setting has to be one of the five numbers.

Every comparison also has three settings in which findings are placed: time, space and possibility. Time is the setting of the order in which findings are found. Space is the setting in which a thing can be followed from

here to there. Possibility is the range of what could be found in a comparison. Each of the three settings has one of the five numbers as its number of dimensions, for a reason of its own.

Time has one dimension, because the comparing is done from one point of view, and from one point of view any two findings are simply earlier and later.

Space has three dimensions. Space cannot have one dimension, because with one dimension space could not be told apart from time. Space cannot have two dimensions, because two directions cannot mark the difference between themselves. The difference between two directions has to be placed by a third direction that is neither of the two. The familiar directions of a table top show how a third direction marks the difference between two. East and north are told apart by the rotation through a right angle that carries east into north, and the rotation is made about an upright line, a third direction that is neither east nor north. Three is the least number of directions in which every difference between two directions is marked by the third direction. The count stops at three because of a principle: a difference that no comparison can register is no difference. A fourth direction of space would mark only differences that the first three directions already mark. In a space of three directions the fit is exact: the distinction between any two of them is placed by the third, and each of the three places exactly one distinction. Four directions would place every distinction too, but a way of differing beyond the least number that meets every requirement of comparison is a difference that nothing in comparison registers as distinct from the other ways: a fourth direction that no requirement of comparison calls for would change no finding anyone could ever make. So no comparison could ever register a fourth direction as a direction of its own.

Possibility has six dimensions. Every possible finding has a place in each of the six ideas of comparison. Each possible finding has a verdict, same or different, and a respect, something found in some setting. Each possible finding also has a point of view, made of a comparer (the one who compares) and a thing compared. The two ideas of each pair always

come together, and still each idea of the pair is a way of differing of its own. In every comparison something is found the same and something is found different, and across all the findings that could be made, what is found the same and what is found different vary apart. So each of the six ideas varies on its own, and none of the six is made up from the other five. The range of what could be found therefore has six independent ways of differing.

Time has one dimension, space has three, and possibility has six: one and three and six make ten.

The count uses only what every act of measuring already contains, and no string, no particle, no force and no law of physics. So I can give a reason for each part of the ten, where Kaku's audiences heard "We don't know". I also derive the counts of time and space by a second route, which shares no step with the count just given. In the second route I start from the cycle that every comparison runs through. The cycle goes from the range of what is possible, to the act of comparison, to the record of the act, and back to a new range of what is possible. The cycle has three passages from one stage to the next, and I identify the three passages with the three directions of space. The cycle runs one way only, and I identify that one way with the one direction of time.

Dimensions of What Can Happen

String theory has ten dimensions, and so does this account: the two tens agree in number, but they differ in kind. In string theory there are nine dimensions of space and one of time, and the nine dimensions of space are all of one kind, with six of the nine small enough to hide. The ten are of three kinds: one of time, three of space and six of possibility. The three kinds cannot be exchanged for one another. Where the six are, and whether anything could travel through the six, both follow from the difference in kind.

Think again of the road country, in which the country is everything any path can reach. The three dimensions of space are the directions you can drive: north and south, east and west, up the mountain and down. Time is the drive itself, one mile after another, in one order. The six dimensions of possibility are of a different kind. The six are the dimensions of what can happen at each place in the country, and they are not more country to drive through. At any crossroads, the six contain everything that could be found at the crossroads: whether the traffic light is red, amber or green, whether rain is falling, and which of the things that could be found is the one that is found. The six are present at every town and every mile of road, and nothing travels along them.

A *located comparer* is anything that compares from a place in the world: you, a thermometer, the plates in Colorado. No located comparer travels through the dimensions of possibility as it travels through space. 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. At any place, the other possibilities are present to a comparer only as what could have been found at the place. The other possibilities are the range from which each actual finding is one selection.

In Kaku's account the six extra dimensions are hidden because they are small: atoms are too big to enter the six. In this account nothing can travel through the six dimensions of possibility because of their kind: the six were never directions of space at all, and no road runs along them. The count of three for space is also the reason the team in Colorado found nothing. Space has exactly three dimensions, so gravity spreads in three directions at every distance. I name the kind of test that the team in Colorado made: "A measurement of how the pull of a mass weakens with distance would show a fourth way of space if space had one". Every measurement of how the pull of a mass weakens, made so far, finds three directions of space.

One Pattern, Taken Two Ways

In this section I count the six further dimensions step by step, because the shape the count gives is the one shape that Chapter Six will need. Like string theory, the physics of this account has ten dimensions: the four of space and time, and six further dimensions beside the four. The six further dimensions have a shape. The shape has a plain meaning. The meaning of the shape comes from the smallest things: in the smallest things, a choice among alternatives stays unsettled until something is found. Think of a choice with three alternatives, red, amber or green, at a time before any of the three is found. Each alternative carries a *weighting*, which is its share of the chance of being the one found, and a *phasing*, which is a setting on a circle, like the angle of a dial. In the mathematician's sense, a *space* is all the possible states of something laid out together by how the states differ, and a mathematician's space has no place in the room around you. Count all the ways of weighting and phasing the three alternatives, without regard to overall size or overall phase. Together, the ways of weighting and phasing make the space of all the states of a three-way choice, a space in the mathematician's sense. A three-way choice has a space of states with four dimensions. The three weights must together make up the whole, so only two of the three weights are free. If all three dials are turned together by the same angle, nothing that could be found changes, so only the two differences between the three phases count, and the two differences add two more dimensions. Two and two make four. Count a two-way choice, such as heads or tails, in the same way as the three-way choice. Each of the two alternatives carries a weighting and a phasing, so a two-way choice has one free weight and one difference of phase, and its space of states has two dimensions. Four and two make six.

So the six further dimensions are a space of possibilities, in the mathematician's sense of space: the space of the states of a three-way choice, taken together with the space of the states of a two-way choice. I derive the shape of the six from six *measures*: six independent respects in which

what is found can vary, with one measure coming from each of the six ideas of comparison. In the derivation each measure has one direction of the shape as its own, and only one shape is left, while string theory has a vast number of candidate shapes and no rule for choosing among them. I identify the six dimensions of the shape with the six dimensions of possibility counted from comparison. Both sixes are counted by the same six ideas of comparison, one dimension for each idea, and by nothing else, so no comparison could register a difference between the two sixes.

The six further dimensions serve in two ways. I show the two ways with the face of a clock. Taken as the pattern of twelve hours, the face of a clock has no size at all: three o'clock is three o'clock on a wristwatch and on a tower clock alike, and you read the time in the pattern. Taken as a particular clock, the face has a width: two centimeters on the wrist, several meters on the tower. So the face of a clock is one pattern, taken two ways.

Taken as a pattern, with no size, the six are where the kinds of particle are read, as you read the time in the pattern of a clock face. The pattern of the six settles which kinds of matter there can be, and how the kinds of matter can join into atoms and bodies. The six can also be taken as *held*: present at every point of the four dimensions of space and time and kept finite there, with the four as their setting. Taken as held, the six have a definite extent, as a particular clock face has a width. The strength of gravity is tied to the extent of the six. The picture of the clock has one limit: a wall clock hangs at a place in a room, but neither way of taking the six is a place. Nothing travels through the six, whichever way the six are taken.

Kaluza's Method, Without the Merger

I use Kaluza's own method, in ten dimensions. I write a geometry of the ten dimensions with nothing in it but the shape itself, Einstein's marble, and then I read off what the ten-dimensional geometry produces in the four dimensions we live in. The ten-dimensional geometry produces Einstein's gravity. A *field* is something spread through space with a value at every point, as the temperature of a room has a value at every

point in the room. The ten-dimensional geometry also produces fields that join the six further dimensions to the four of space and time. So one ten-dimensional geometry produces both gravity in four dimensions and the fields that join the six to the four, as one five-dimensional geometry produced Kaluza's gravity and Kaluza's light. That is a unification in the sense of a common source.

The four and the six are joined. Yet the character of each stays distinct.

The *arena* is the setting of space and time in which everything is found. The arena is smooth, with nothing jumping. The arena runs one way, from before to after. So, in the theorem's sense, the arena is continuous and asymmetric. What is found in the arena comes in exact, countable kinds, and each kind is the same wherever and whenever it is found. So, in the theorem's sense, what is found in the arena is discontinuous and symmetric. The four dimensions of space and time carry the arena's character, and the six carry the character of what is found. A *merger* would be one geometry in which the same directions carried both characters at once. In a merger, the setting would become one and the same with what is found in the setting. A merged geometry would carry continuity together with symmetry, and asymmetry together with discontinuity, in one and the same set of directions: the two pairings that the Incommensuration Theorem states cannot be applied, simultaneously and fundamentally, to any event or comparison. A *no-go result* is a result showing that a program cannot be carried through. So I conclude that a program of physics built on merging the four and the six, "treating all ten dimensions as of one character, meets the theorem as a no-go result". In plain words, the Incommensuration Theorem shows that a program of physics that merges the four and the six cannot be carried through.

Under the Incommensuration Theorem, Kaluza's extra components of the geometry also turn out to be something other than light. In Kaluza's five dimensions, four of the extra components were light. The extra components are the fields that join the six to the four, and the joining fields belong to the six taken as held, with the extent of the six. The vibrations of the joining fields affect ordinary matter only through gravity. In the physi-

cists' sense, which is Kaku's sense, the *symmetries* of a force are the changes that leave the laws of the force the same, as a sphere stays the same however it is turned. I read the symmetries of light and of the two nuclear forces from the six taken the other way: from the six taken as the pattern where the kinds of particle are read.

The six taken as held also have a size and a shape. The geometry has two more fields, apart from the joining fields, and the two fields set the size and the shape of the six. Physicists call the two fields the *moduli* of the six. One modulus mostly sets the size, and the other modulus mostly sets the shape. A vibration of either modulus would carry a pull of its own between masses, beside the pull of gravity. The pull of a modulus reaches a shorter distance when a vibration of the modulus takes more energy to start. I compute how far the pull of each modulus reaches. *Compactification* is the physicists' name for holding extra dimensions finite. As I use the word, compactification means only that the four dimensions of space and time hold the six. The pull of either modulus reaches a distance about a million million million million million times shorter than a twentieth of a millimeter, which is the shortest distance that the tests of gravity have reached.

We can now use Kaku's park for a new purpose: to picture how this account joins gravity and matter. I identify gravity with the arena itself, the setting in which everything is found. So gravity is marble in exactly Einstein's sense: gravity is geometry. The particles and the forces between the particles are what is found in the arena, so the particles and their forces are the wood. Kaku's own sentence fits this account closely: the presence of the tree determines the pattern of the marble around the tree. I say of the arena and the content found in the arena what Kaku says of the plaza and the tree: "the arena is the setting in which every content is found, and the content is what curves the arena". The tree and the plaza belong to one park, joined at every root, and neither can be taken away from the other. And the tree stays wood: matter does not become geometry. Einstein dreamed of a tree carved from marble. A tree carved from marble would be a merger, and by the Incommensuration Theorem no

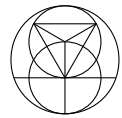
merger can be carried through. The unity that agrees with the theorem is the park itself: a living tree in its marble plaza, side by side and never merged.

Where We Have Arrived

Kaku and the physicists he writes about meant the extra dimensions to make room: to give every force a place in one larger geometry, so that in the end the forces would be one. In this account the ten dimensions of time, space and possibility are one structure for gravity and for the kinds of matter, and in the ten dimensions the forces of the particles stay apart from the arena the forces act in. I read the symmetries of the forces of the particles, in the physicists' sense, from the six dimensions of possibility, and I find that no single larger symmetry, in the physicists' sense, joins the forces of the particles into one at any energy, even in the most violent collisions, like the collisions of the first instants of the universe.

There are ten dimensions: one of time, three of space, and six of possibility, which nothing travels through. The count of ten follows from the structure of comparison, and the six dimensions of possibility serve in two ways.

If the forces do not merge into one in the ten dimensions, is there still one equation for everything?



Chapter Four

One Equation?

Is there one equation for everything, and what holds the world together?

What this chapter uses

Comparison: setting one thing beside another and telling them apart (Preface and Chapter One). The *content* of a comparison is what is found; the *context* is the setting in which it is found (Chapter One).

A request that *names nothing*, like a request for a point north of the North Pole (Chapter One).

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 (Chapter One).

The theorem's four words: *symmetry* is a sameness of content where there is a difference of context; *asymmetry*, a difference of content where there is a difference of context; *continuity*, a sameness of content where there is a sameness of context; *discontinuity*, a difference of content where there is a sameness of context. In the physicists' sense, which Kaku uses, a symmetry is a change that leaves a thing or a law as it was (Chapter One).

The *arena*: the setting of space and time in which everything is found; the ten dimensions, one of time, three of space and six of possibility (Chapter Three).

Readers of Michio Kaku carry one picture away from his books above all others: a single equation, perhaps an inch long, that unites every force of nature. If there is no such equation, what holds the world together?

A Hammer and a Feather on the Moon

On 2 August 1971 the astronaut David Scott stood in front of the television camera on the plain of Hadley, at the foot of the Moon's Apennine mountains, in the last minutes of the third and final moonwalk of Apollo

15. In his right hand he held a geologist's hammer. In his left hand he held a falcon's feather, brought from the United States Air Force Academy, whose mascot is the falcon. Scott had come down to the surface in a lunar module named *Falcon*. He told the people watching on Earth: "Well, in my left hand, I have a feather; in my right hand, a hammer". He said that a gentleman named Galileo had made a discovery about falling bodies long ago. The Moon, he said, was a fine place to check the discovery. Then he opened both hands at the same moment. The hammer and the feather fell side by side and struck the dust together. "How about that!" said Scott. "Which proves that Mr. Galileo was correct in his findings".

A coin and a small scrap of paper show why Scott needed the Moon for his test. Drop the coin and the paper side by side, and the coin lands first, because the air holds the paper back. Now lay the scrap flat on top of the coin and drop the two together: the coin pushes the air aside, and the paper rides down with the coin, all the way to the floor. On the Moon there is no air at all. So nothing on the Moon holds a falling body back, and every body falls there at the same pace, whatever the body is made of and however heavy the body is. Scott let everyone watching on Earth see the equal fall happen.

The fall on the Moon was the same for metal and for feather, whatever each was made of, and the same for heavy and for light, though the hammer weighed many times what the feather weighed. If a pull took hold of each thing according to what the thing is made of, the pull would treat different things differently, the way a magnet lifts an iron nail and leaves a wooden match lying on the table. The pull of the Moon treated the hammer and the feather exactly alike. In 2022 the scientists of a French satellite named MICROSCOPE reported the result of the finest test ever made of whether different things fall alike: titanium and platinum, falling together around the Earth, fall alike to within a few parts in a million billion.

Kaku tells the story of the man who first saw what the equal fall means. One day Albert Einstein leaned back in his chair and nearly fell over, and in that instant he saw that a man falling freely would feel no weight at all. Einstein later called that moment "the happiest thought of

his life" (*The God Equation*, 2021, ch. 2, "Gravity as Curved Space"). Picture the falling man with a hammer in one hand and a feather in the other. If the falling man lets the hammer and the feather go, the two float beside him, because all three, the man, the hammer and the feather, are falling at the same pace. Kaku makes the falling man's point, that a man falling freely feels no weight, with an elevator whose cable is cut: "the floor falls at the same rate, so inside the elevator, you begin to float" (same section). Einstein drew a second picture beside the falling man. The second picture is a closed room far out in space, pulled steadily upward by a rope. Put the man in the closed room and let him open his hands, and the floor rushes up and meets the hammer and the feather at the same moment, because the floor moves and the hammer and the feather do not. Every body falls at the same pace because in every body two masses agree. One is the mass that gravity pulls on, and the other is the mass that resists being moved. As I have put it, physicists followed the agreement of the two masses "to something that does not depend on what a body is made of, which in the end was the arena of space and time itself". Kaku puts Einstein's lesson in six words of his own: "gravity does not pull; space pushes" (*The God Equation*, ch. 2, "Gravity as Curved Space").

So when a fall does not depend on what falls, the fall is a feature of the setting, the arena, and not the work of a force that acts on the things in the arena.

What Kaku Hopes to Find

Kaku's hope for one equation is old, and he states the hope beautifully. An *equation* is a statement, written in symbols, that two quantities are equal, and physicists use equations to calculate what will happen. A *force* is a push or a pull that changes how a thing moves, or turns one kind of thing into another. Physics today counts four forces: gravity; electromagnetism, which carries electricity, magnetism and light; the strong force, which binds the smallest pieces of matter into the cores of atoms; and the weak force, which turns one kind of particle into anoth-

er in radioactive decay. The final theory Kaku hopes for would be, in his words, "a single formula from which, in principle, one could derive all other equations" (*The God Equation*, Introduction).

Where does the figure of one inch come from? Kaku tells us exactly. The inch begins as Einstein's wish: Einstein wanted "an equation, perhaps no more than one inch long", to read the mind of God (*The God Equation*, Introduction, "Einstein's Dream"). In two of his earlier books Kaku uses the inch to measure Einstein's finished theory of gravity. In *Hyperspace* he writes that Einstein's equations, written out in full, "are only about an inch long" (*Hyperspace*, 1994, ch. 5, "Beyond the Standard Model"). In *Parallel Worlds* he writes that Einstein could sum up his theory "in an equation about an inch long" (*Parallel Worlds*, 2005, ch. 2, "Force as the Bending of Space"). Kaku then uses the inch to measure his own work. In Kaku's telling, *string theory* says that the smallest things in the world are tiny vibrating strings. Each note a string can sound is a different particle. Kaku and his colleague Keiji Kikkawa wrote the whole of string theory, in one of its versions, as one equation, "just one inch long" (*The God Equation*, ch. 6, "String Theory"), or "barely an inch and a half long", short enough to fit on a fortune cookie (*Parallel Worlds*, ch. 7, "History of String Theory").

Then Kaku tells us, with the honesty of a working physicist, how much of string theory the equation of Kaku and Kikkawa covers. String theory comes in five versions, and each version needs its own equation: "we need five such equations", he writes (*The God Equation*, ch. 6, "Revealing a Pyramid"). In 1995 the physicist Edward Witten found one larger theory behind all five versions. The larger theory is called *M-theory*. Witten showed why there are five versions: each version is M-theory seen in one of five ways (*The God Equation*, ch. 6, "M-Theory"). No one has yet written the single equation of M-theory, as Kaku says plainly in *The God Equation* and in *Parallel Worlds* (*The God Equation*, ch. 6, "Revealing a Pyramid"; *Parallel Worlds*, ch. 7, "The End?"). Kaku is

waiting for the single equation from which the whole of M-theory would follow, and he gives that equation its name: "this one-inch-long equation" (*The God Equation*, ch. 6, "Revealing a Pyramid").

In Kaku's books the inch measures three lengths: the length that Einstein wished for; the length of Einstein's own equations of gravity; and the length of the string equation that Kaku and Kikkawa wrote. The string equation of Kaku and Kikkawa is one of the five equations that string theory needs, one for each of its versions. The single inch-long equation for everything is Kaku's hope, and he presents the equation as a hope.

What would the single equation govern? Kaku answers in the fourth chapter of *The God Equation*. The Big Bang is the hot, dense beginning to which the history of our universe, traced backward, runs. Kaku writes that at the instant of the Big Bang the four forces of physics, gravity, electromagnetism, the strong force and the weak force, "were merged into a single superforce that obeyed the master symmetry", and that "The equation that governed the superforce was the God equation" (*The God Equation*, ch. 4, "Higgs Boson; The God Particle"). In the physicists' sense that Kaku uses, a *symmetry* is a change that leaves a thing the same, as a sphere looks the same however the sphere is turned. Kaku's master symmetry was a symmetry in the physicists' sense, a change that "could rotate all the particles of the universe into one another". Kaku writes that the master symmetry broke, as the young universe cooled, into the separate pieces we see today (same section).

In Kaku's search for one equation, the deepest part is about gravity and the quantum. *Quantum theory* is the physics of the smallest things, whose findings come in separate, countable amounts called *quanta*. Kaku calls the two theories the two great pillars of physics, "based on two different principles, two different mathematics, and two different philosophies", and he writes: "The next great revolution, we hope, will be to unify these two pillars into one" (*The God Equation*, ch. 6, opening section). In the last chapter of *The God Equation* he writes that, if his thinking is correct, "There is only one equation that can describe the

universe, because all others are mathematically inconsistent" (*The God Equation*, ch. 7, "My Own Point of View"). He closes *The God Equation* with a picture of the union he hopes for, a story of a flat world (*The God Equation*, ch. 7, "Conclusion"). Long ago, in a flat world, a beautiful crystal of three dimensions shattered into a million pieces. Over the centuries the people of the flat world gathered the pieces into two great pieces, gravity and the quantum theory, and could never fit the two together. Then one of the people of the flat world proposed to lift one piece, by mathematics, into an imagined third dimension, so that the two pieces fit together one on top of the other, and a shimmering jewel appeared before the people of the flat world.

Kaku keeps one more picture of the laws of physics beside the inch, and the second picture is a different one. In *Physics of the Impossible* (2008) he writes that the laws that govern all known physical phenomena can be written on a single sheet of paper. "On that sheet of paper", he goes on, "would be just two equations, Einstein's theory of gravity and the Standard Model" (Epilogue, "Is Physics Incomplete?"). The *Standard Model* is the theory of the particles and of the three forces that act among the particles. Physicists have tested the Standard Model in every particle accelerator for half a century. And he adds his own conviction: "the fundamental laws, I believe, are knowable and finite" (same section).

Where We Reach the Same Place

Kaku and this account agree on four points. Kaku reaches each point by one route of reasoning, and I reach each point by another.

The first point is that the world should have one account that leaves nothing out. There is one account of everything, and it is made of two descriptions joined together. Kaku hopes that physics will someday have a theory of everything, in the sense of an account in which every finding has its place. This account has the same aim, and this account is itself an account in which every finding has its place.

The second point is that gravity is the shape of the arena. Kaku reaches the second point through Einstein: space curves, and the curve of space does the pushing. This account shows by four marks that gravity is the shape of the arena. A mark is a feature by which a thing can be recognized. Gravity carries each of the four marks, and any arena must carry each of the four marks. Each mark comes with its reason. The first mark is that gravity takes hold of everything: gravity acts on every thing there is. The electric force takes hold only of things that carry electric charge, and passes a neutral thing by, but gravity passes nothing by. An arena has the first mark because everything is found somewhere in the arena. If the arena did not take hold of a thing, the thing would be found nowhere. The second mark is that nothing shields gravity. A sheet of metal can screen a radio from a broadcast, but no material of any kind screens one mass from the pull of another. An arena has the second mark because a region of space is itself a stretch of the arena, so a shield that kept the arena out of a region would leave no region there at all. The third mark is that the mass gravity pulls on is the same mass that resists being moved. The hammer and the feather show the third mark: each is pulled in exact proportion to how hard each resists being moved, so each falls at the same pace. An arena has the third mark because two things about a body are both how much the body takes part in the arena: how strongly the arena takes hold of the body, and how strongly the body resists a change of its place in the arena. I identify the arena's hold on a body and the body's resistance to a change of place as one quantity, so for an arena the mass that gravity pulls on and the mass that resists being moved are one mass, whatever the body. The fourth mark is that gravity carries no charge of its own that comes in steps. A *charge*, in physics, is the amount by which a force takes hold of a thing. Electric charge comes in whole steps of one smallest amount, so that every electric charge can be counted. Gravity has no charge that comes in countable steps. An arena has the fourth mark because the arena is smooth, and a smooth setting has nothing in it that comes in countable steps. Only what is found in the arena comes in countable steps.

The third point is that a full account of the forces of the particles should derive the forces from one principle, and should not join separate theories of the forces together by hand. Kaku writes that the Standard Model "was created by splicing together by hand the theories that described the various forces" (*The God Equation*, ch. 4, "Theory of Almost Everything"). He also writes that Einstein's search for a unified theory failed because Einstein never found a guiding principle (same chapter, opening section). I derive the structure of the particles from one principle: the structure of comparison. The structure of comparison is what every act of comparing must contain. A *premise* is a statement an argument starts from. Ali Chamseddine and Alain Connes reach the same structure by a second route of reasoning, from other premises. The last section of this chapter describes the route of Chamseddine and Connes.

The fourth point concerns the strengths of the three forces of the particles (electromagnetism, the weak force and the strong force) at high energies. The *strength* of a force is a single number that says how strongly the force acts. Each strength changes slowly as the energy of a collision rises. *High energies* are the energies of the most violent collisions, like those of the first instants of the universe. Physicists measure the three strengths at the energies that experiments reach, and then calculate, by the Standard Model's own rules, what the strengths become at higher energies, and calculated that way the three strengths draw close at high energies without meeting. Kaku reports the same result himself: when physicists calculate backward with the Standard Model, they find that the three forces "seem to converge in strength near the big bang. But they are not precisely equal" (*Parallel Worlds*, ch. 7, "Supersymmetry"). Kaku and this account agree on that result of measurement and calculation. Kaku and I reach different results on two questions: what the drawing close of the strengths means, and what joins gravity to the quantum.

Two Descriptions of One World

We need one tool to see what joins gravity to the quantum. The tool is comparison, and this whole book reasons from comparison. Every measurement is an act of comparison. In every comparison something is found, and the two things compared differ in some respect. The *content* of a comparison is what is found. The *context* of a comparison is the respect in which the two things compared are two, such as two places or two moments.

Four words name the four characters a comparison can have: symmetry, asymmetry, continuity and discontinuity, in the senses of the Incommensuration Theorem that I set out in Chapter One and list in the box at the head of this chapter. Each of the four words says how the content of a comparison is related to its context.

The Incommensuration Theorem says how the four characters can be joined, and I draw from the theorem what follows: "Any comparison, perfected at its foundation, is either continuously asymmetric or discontinuously symmetric". To be *perfected* is to hold exactly, at the foundation of a description. A comparison held exactly is either symmetric or asymmetric, and either continuous or discontinuous, so four joinings of its characters are possible. By the theorem, two of the four joinings cannot hold, symmetry with continuity and asymmetry with discontinuity, so two joinings remain. So when the characters of a comparison hold exactly, at its foundation, the comparison is either smooth and different from place to place, or exactly repeating and coming in countable steps.

The two great theories of physics fall on the two sides of the Incommensuration Theorem: quantum theory has one of the two joinings that the theorem allows, and general relativity has the other. I identify quantum theory as the description of the content of physics. The findings of quantum theory repeat exactly and come in countable steps. I identify general relativity as the description of the context of physics, the arena, which is smooth and changes from place to place. Each theory is perfected

in one of the two remaining joinings: in each theory the joining is exact, at the foundation of the theory. Each theory describes what the other theory leaves out.

Now the phrase "theory of everything" has two meanings. I set the two meanings apart. The first meaning is "an account that leaves nothing out: every finding, of every kind, has its place in it". The second meaning is "an account written as one description, with one character throughout, from which everything else follows as a special case". In the second meaning, a "character" is a whole joining of characters: one of the two joinings that the theorem allows. Then I add: "The theorem allows the first and forbids the second". Kaku hopes for one equation from which every other equation would follow. Kaku's one equation would be a theory of everything in the second meaning. This account is a theory of everything in the first meaning: gravity and the quantum are two descriptions of one world, joined side by side and never merged.

Picture a tide table pinned up in a harbor office, and the sea outside the window. The table lists high water and low water as separate entries you can count, each entry written in the same exact form. The sea is one unbroken body of water, changing from one shore to the next. Every fisherman in the harbor uses both the table and the sea. The table and the sea are used together at every quay, at every hour. Nobody asks the sea to be made of table entries, or the table to be made of water. In the picture, the table stands for quantum theory, whose findings are separate, countable and exactly repeating, and the sea stands for general relativity, whose arena is smooth and changes from place to place. Suppose someone asks for a single thing that is, in the same respect, both a list of separate entries and one unbroken, changing sea. That request names nothing, in the sense of Chapter One: the request asks for something that has no place to be. The request is like a request for a point north of the North Pole: north ends at the Pole, and there is no place beyond the Pole for the point to be.

The hammer and the feather now come back: at the start of this chapter their equal fall showed that gravity is a feature of the setting, the arena. So gravity is the shape of the arena, and not one more force acting

within it. A quantum theory of gravity would describe the arena itself in quanta, as made of separate countable steps, the way the particles and their forces are described. The arena would then have the joining that belongs to what is found in the arena, exactly repeating and coming in countable steps, and so the smooth setting in which every description is made would be gone. To quantize the arena (to describe the arena in quanta) "is therefore to apply a concept where the concept does not belong. That is a category error, and it is the error behind the search for one theory". A *category error* is a concept applied where the concept does not belong, like asking how much the number seven weighs.

Return to Kaku's shattered crystal, whose two great pieces are gravity and the quantum theory. In this account the two great pieces already fit together, side by side, in every laboratory every day. Every comparison you make uses both pieces: the countable steps of what you find, and the smooth arena in which you find those steps. If someone lifted one piece on top of the other, so that the two pieces became one jewel, gravity and the quantum would have to be one description in the very respect in which the two differ.

Three Forces That Draw Close

Kaku places all four forces in a single superforce at the instant of the Big Bang. What, then, becomes of the superforce? The three forces of the particles are inseparable and distinct: their strengths draw close, and the three forces never become one force.

The first matter is the count of the forces. Kaku counts four forces to be joined. This account counts three forces of the particles, and this account treats gravity as the arena itself. A *carrier* is the particle that passes a force from one thing to another, as the *photon*, the particle of light, carries electromagnetism. Gravity is not a fourth force with a carrier of its own: it is the arena, context and not content. The three forces come from the three positions that every comparison has. The three positions are the act of

comparing, the thing compared, and the thing that the thing compared is compared against. Three positions, three forces. There is no fourth force, because comparison has no fourth position.

The second matter is the measurement of the strengths. Kaku tells us that at everyday energies the strong force is about thirty times stronger than the weak force and a hundred times stronger than electromagnetism (*Parallel Worlds*, ch. 7, "Supersymmetry"). Physicists have measured the three strengths with great care, and they have calculated, with the Standard Model's own rules, how each strength changes as the energy rises toward the heat of the first instants of the universe. The physicists found that the three strengths draw close to one another, and that the strengths cross in pairs, at three different energies, and never all three at one energy. Kaku writes that if every known particle had a heavier partner, joined to the particle by a symmetry in the physicists' sense called *supersymmetry*, the three strengths would fit perfectly and be equal. In 2005 he wrote of supersymmetry that "at present there is absolutely no experimental evidence to support it", and he gave the likely reason that no evidence had been found: the partners might be too heavy for the accelerators of the day (*Parallel Worlds*, ch. 7, "Supersymmetry"). Since then physicists have searched for the heavier partners that supersymmetry gives each known particle, at the Large Hadron Collider, the great particle accelerator near Geneva, and they have found none. So physicists still calculate how the strengths change by the Standard Model's own rules, and by those rules the three measured strengths draw close to one another and are equal at no energy.

The third matter is the reason the strengths behave as they do. An *axiom* is a starting statement from which the rest of an account is reasoned. The Immanent Metaphysics has three axioms, and I give the first two here in plain words, with the third after them. The first axiom says that the act of comparing is the most fundamental of the three positions, and that the thing compared and the thing it is compared against are conjugate: each of the two can be made perfect only at the cost of the other. The second axiom gives the order within every comparison: first the range of what is

possible, then the act of comparing, then the record of the act, and the record shapes what is possible next. The third axiom of the Immanent Metaphysics says that the three positions of comparison are distinct, inseparable and non-interchangeable: each position is itself, no position is ever found without the other two, and no position can stand in for another. In *An Immanent Metaphysics*, aphorism 1.3-1, I state the third axiom whole: "The (classes/instances) of the immanent, omniscient, and transcendent are distinct, inseparable, and non-interchangeable"; the immanent is the act of comparing, the omniscient the thing compared, and the transcendent the thing it is compared against. I explain the measured strengths by two clauses of the third axiom: "Because the three forces are inseparable, their strengths draw close; because they are distinct, they never become one force".

Picture a braid of three strands. You cannot pull one strand out and keep the braid, because the strands belong together. Each strand stays a strand of its own from one end of the braid to the other, and no two strands fuse into one cord. The three forces are like the three strands: the forces are bound together in the one structure of comparison from which every particle comes, so their strengths draw close, and each force stays itself at every energy, so no two forces fuse into one.

The three forces stay three back to the beginning of the universe. Of the forces I say, "In this account the forces were never one larger force". Of the symmetries of the forces, in the physicists' sense, none of the three is what is left of a larger symmetry that broke. Kaku's master symmetry would turn every particle into every other. In this account, and in the physicists' sense of symmetry, the three symmetries of the forces were three from the start. None of the three symmetries turns a *quark* into a *lepton*. A quark is one of the particles inside the *proton*, and a lepton is the electron or one of its relatives. The proton is the particle at the center of the hydrogen atom. In full: "There is no force that turns a quark into a lepton, and no single force of which the three are parts".

One Structure for the Particles

If no single equation holds the world together, what does? The world is held together by one source and one structure. The source is the act of comparison. Gravity and the quantum have the two joinings that the Incommensuration Theorem allows, and both joinings come from comparison. The structure is the one structure from which all the particles come.

I describe the structure of the particles with the picture of a board game. A board game comes with a rulebook. The rulebook says which pieces exist, how they move, and what counts as a legal play. However many games are played, no new kind of piece appears, because the pieces are all listed in the rulebook. Physicists call the rulebook of a physical structure its *algebra*. The algebra of a structure is the set of rules for combining and transforming the quantities that the structure can show. Find the rulebook, and you know what kinds of thing the structure can produce.

The rulebook of comparison has three chapters, one for each of the three positions, because the positions are distinct and can neither share chapters nor trade chapters. Once the content of a comparison has a structure of its own, parts held in a definite order, the content carries three marks, three features that the act of comparing can work on, and each of the three marks belongs to one position. The act of comparing reads the content by its *phase*. A phase is a setting on a circle, like the position of the pointer on a dial. The phase is the mark of the act of comparing, because every state of the content carries a phase, and the act of comparing is the position that is always present and always acting. The chapter for the phase produces the force that acts on the phase, which we know as electromagnetism, carried by the photon. The content also presents two sides: the content comes in pairs, each pair one thing with two sides, as the two kinds of quark called up and down are the two sides of one pair. A pair shows one side and keeps the other side turned away. The two sides of a pair are the mark of the thing compared against, because the thing com-

pared against is the position that the one comparing reaches toward and never contains. The chapter for the two sides produces the weak force, which turns one side of a pair into the other side. The content also holds three colors inside it, which can be blended among themselves. *Color* is the physicists' name for three ways a quark can be, and has nothing to do with the colors we see. The three colors hold the whole pattern of the comparison inside the content, all three positions at once. The three colors are the mark of the thing compared, because the thing compared is the position that the one comparing has fully in view, the whole of the thing compared at once. The chapter for the three colors produces the strong force. The three chapters of the rulebook produce the three forces, with their carriers, and the kinds of particle that the Standard Model lists. The rules of the rulebook follow from starting statements about the structure of comparison. The starting statements "make no reference to particles". Nothing in the starting statements was chosen in order to produce the Standard Model. I have put the result in four words: "The Standard Model fell out". The four words mean that the Standard Model came out of the derivation without being put in.

Two other people reached the same rulebook by a second route of reasoning, from a different start: the physicist Ali Chamseddine and the mathematician Alain Connes. Chamseddine and Connes started from mathematics, in the branch of geometry that Connes founded. The branch is called *non-commutative geometry* because in it the order in which two quantities are combined can change the result. In non-commutative geometry a geometry is described entirely by the rulebook of its quantities, its algebra, with no picture of distances needed. A geometry described by its algebra alone can even be *finite*: made of a few points, with no extent at all. Chamseddine and Connes sorted all the finite geometries of one exactly defined kind, under a short list of starting conditions, and found the rulebook of the particles singled out among them: the starting conditions pick out the rulebook of the particles. So two routes of reasoning, on different premises, arrive at one structure. In Kaku's telling, Einstein never

found a guiding principle. In this account the guiding principle is the structure of comparison, and the forces follow from the structure of comparison.

Is the rulebook the one equation, after all? No: the rulebook governs the particles, and the whole account has more parts than the rulebook. Physicists usually look for a master formula of one kind, an *action principle*: one quantity from which every *equation of motion* follows, where an equation of motion is an equation that says how things move and change. I call this account's way of reasoning, from comparison to the physics of the world, the *comparison route*, and I state the result in one sentence: "The comparison route therefore has no single action principle". This account has three parts in place of one action principle, and each part comes from its own source. The first part is the form of the physics of the particles, which comes from the rulebook of the particles. The second part is the equations of the arena, which come from the ten dimensions met in Chapter Three (one of time, three of space and six of possibility), together with a theorem of the mathematician David Lovelock, applied in the four dimensions of space and time, which are the arena; the theorem shows that the equations of the arena can take only one form. The third part is the numbers of physics, such as the masses of the particles, and each number comes from its own route of reasoning, or from measurement. The description of the arena and the description of its content "are composed side by side and not merged".

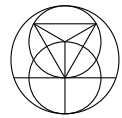
Look again at Kaku's sheet of paper. On the sheet are two equations: Einstein's theory of gravity, and the Standard Model. The sheet holds the description of the arena on one side and the description of the content on the other, side by side, and in each description its own joining is exact. I read Kaku's sheet of paper as the answer to his own question, drawn by his own hand. The sheet shows two descriptions of one world, side by side.

What We Now Know

We set out with Kaku's inch, and we now know what it measures: Einstein's wish, Einstein's own equations of gravity, and Kaku's equation for string theory, one of the five that string theory needs. If you know the Incommensuration Theorem, you should expect a different future for physics from the future Kaku hopes for. If you wait for the inch-long equation, you are waiting for a theory of everything in the second meaning. The theorem forbids every theory of everything in the second meaning. Look at Kaku's sheet of paper, and you already hold the two descriptions. You need only to see why the descriptions are two and how the two fit together.

For us there is one world, everything any path can reach, and the one world has no single equation. Gravity and the quantum are two descriptions of one world, joined side by side and never merged. The three forces of the particles are inseparable and distinct, so their strengths draw close and they never become one force. And the particles come from one structure.

Kaku hopes for one thing more from a single equation. He writes: "It would be a truly historic event if the known parameters of the universe could emerge from a single equation" (*The God Equation*, ch. 6, "Revealing a Pyramid"). Kaku's *parameters* are the numbers of nature, such as the masses of the quarks and the strengths of their forces, and physicists who use the Standard Model take the numbers of nature from measurement and put them in by hand. If there is no one equation, what fixes the numbers of nature, and would deriving them prove a theory right?



Chapter Five

The Numbers of Nature

Would deriving the constants prove a theory right?

What this chapter uses

Comparison: setting one thing beside another and telling them apart; every measurement is an act of comparison (Preface and Chapter One).

The two senses of *symmetry*: in the physicists' sense, a change that leaves a thing or a law the same, as a turned sphere is the same sphere; in the sense of the Incommensuration Theorem, the same content found in different settings (Chapter One).

A force's *strength* is a single number that says how strongly the force acts; the three forces of the particles are inseparable and distinct, so their strengths draw close and never become one (Chapter Four).

Suppose a theory worked out, by pure reasoning, every number that physics now has to measure. Would the derivation prove the theory right? In this chapter's question, a *constant* of nature is a number that stays the same everywhere and is found by measuring: how heavy a given kind of particle is, or how strongly a given force acts.

Michio Kaku thinks that a derivation of all the constants would prove the theory right. He says so plainly near the end of his book *The God Equation* (2021). The chapter's question is two questions in one: what kinds of number nature has, and what it takes to know that a claim about the world is true.

Four Lines of Hydrogen

Pass an electric current through a thin tube of hydrogen gas, and the gas glows. Send the glow through a *prism*, a wedge of glass that spreads light out by its colors. The light does not make a smooth rainbow. The light comes out as a few sharp lines of color with darkness between them: one red, one blue-green, and two violet. Each color of light has its own *wavelength*, the length of its wave, and the wavelength sets the color. In the nineteenth century the Swedish physicist Anders Ångström measured the wavelengths of the four lines of hydrogen with great care.

In 1885, in Basel, Switzerland, a schoolteacher named Johann Balmer looked at Ångström's four numbers. Balmer taught at a girls' school in the city and was then about sixty years old. Balmer found a rule, made of whole numbers, that produces all four wavelengths. Take a whole number, starting from three, and square the number. Divide the square by the square less four. Multiply the result by one fixed number, which is the same for every line. The number three produces the red line, four the blue-green line, and five and six the two violet lines. Each wavelength agrees closely with Ångström's measurement.

Then the rule produced something more. Starting from seven, the rule produced a fifth line, and a friend of Balmer's, the physicist Eduard Hagenbach-Bischoff, told Balmer that a line had already been observed at the wavelength of the fifth line, along with further lines of hydrogen. Balmer published his rule in 1885, in a short note to the society of naturalists in Basel, and the note was reprinted the same year in the German journal *Annalen der Physik*.

Balmer now had a rule that produced every line from one fixed number and a run of whole numbers. The reason for the rule was still to be found. In 1885 no theory of the atom showed why Balmer's rule should hold. For twenty-eight years the rule kept agreeing with the lines of hydrogen, line after line, and the reason for the rule stayed unknown.

In 1913 the Danish physicist Niels Bohr explained the rule. Bohr proposed that an atom of hydrogen can hold only certain fixed amounts of energy, its *energy levels*, spaced by a rule of whole numbers. Bohr also proposed that the atom gives off light when the atom drops from a higher level to a lower one. On Bohr's account, the lines of Balmer's rule are the drops from the third, fourth, fifth and sixth levels down to the second level. The four in the rule is two times two: the square of two, the number of the level on which all the drops end. Bohr worked out Balmer's fixed number from the charge and the mass of the *electron*, the tiny particle of electric charge that every atom carries, and from two other measured numbers of physics. Bohr's number agreed with Balmer's. Balmer's rule had agreed with measurement for twenty-eight years, and the rule then became one of the doors into *quantum theory*, the physics of the smallest things. Bohr's explanation of the rule was one of the first steps physicists took into quantum theory.

I have a name for a number like Balmer's: a *value that lands*, which means a value that agrees with what is measured.

Kaku's Twenty Numbers

In *The God Equation* Kaku follows the long search for one theory of all the forces. In the fourth chapter he reviews the best theory physics has, the *Standard Model*: the established theory of the kinds of particle that make up matter and of the forces that act among those particles, apart from gravity. Kaku admires how much of the world the Standard Model describes, and he is frank about what troubles him in the theory. One of the troubles, he writes, is that "there are about twenty constants

that had to be put in by hand, with no understanding whatsoever of where these constants came from or what they represented" (*The God Equation*, ch. 4, "Theory of Almost Everything").

Kaku has worked on *string theory* since 1968. String theory is the proposal that every particle is a vibration of a tiny string, and Kaku calls string theory the leading candidate for the one theory of all the forces and, to his mind, the only candidate. In his Introduction, Kaku states fairly what he calls the most glaring problem of string theory: "we have no solid, testable evidence" (*The God Equation*, Introduction, "An Army of Critics"). In his sixth chapter he explains that a direct test of string theory would probably need "a particle accelerator the size of the galaxy" (ch. 6, "Can It Be Tested?"). So, he writes, physicists listen instead for the "echoes" of string theory: evidence of string theory that may be hidden all around us and can be found indirectly, as most of science is done (same section).

In a section he calls "Revealing a Pyramid", Kaku then offers a way to test string theory without an accelerator the size of the galaxy. Kaku first sets down a principle: "The correctness or incorrectness of a theory should rest on concrete results, not the subjective desires of physicists" (ch. 6, "Revealing a Pyramid"). Then he names the concrete result he has in mind. Kaku writes: "A theory of everything is also a theory of ordinary things". If string theory could derive the masses of the quarks and the other known particles "from first principles", he goes on, the derivation might be "convincing evidence that this is the final theory" (same section). The *quarks* are the particles that make up the *proton* and the *neutron*, the two particles of which the center of every atom is made. To work a number out *from first principles* is to reach it by reasoning from the foundations of a theory, with nothing taken from measurement. In the next lines Kaku goes further. He sets his test beside the "plenty of experimental data" that physics already has on the masses and strengths of the particles. If string theory can "precisely calculate

> these fundamental constants from first principles, without any assumptions", he writes, "then this would, in my opinion, prove its correctness" (same section).
>
> Kaku sets out his test with his usual warmth and humor. In the same section he recalls the giant computer in Douglas Adams's comic novel *The Hitchhiker's Guide to the Galaxy*: after eons of calculating, the computer "finally concluded that the meaning of the universe was 'forty-two'" (same section). The joke works because the computer gives forty-two with nothing beside it: no reason, no stated step, no measurement.

Counting the Numbers

Picture a recipe card. The shape of the recipe is printed: which ingredients, in what order, mixed how, baked how long. The amounts are blanks, and someone filled in the blanks by tasting. The Standard Model is a recipe card with a printed shape and blanks. The printed shape of the Standard Model is the form of the theory: which particles there are, and how the forces act on them. The blanks of the Standard Model are the numbers that Kaku says were "put in by hand". I use the recipe card as the picture of the Standard Model, and I begin by counting the blanks aloud.

The Standard Model as first written has nineteen adjustable numbers. Nine of the nineteen are the masses of the particles of matter that carry electric charge: the six kinds of quark, and the electron with the two heavier particles like the electron, the *muon* and the *tau*. Four of the nineteen describe how the kinds of quark are mixed when the *weak force* acts on the quarks. Three of the nineteen are the strengths of the three forces that act among the particles: the force of light, the weak force and the *strong force*. The strong force holds quarks together, and physicists call the charge of the strong force *color*. Two of the nineteen belong to the *Higgs field*. A *field*, in physics, is something spread through all of space that has a value at every point, as the air in a room has a temperature at every point. The

Higgs field is the field that gives the particles of matter their masses. The two numbers of the Higgs field are the mass of the field's particle, the Higgs particle, and the field's *vacuum value*, the steady size the field holds everywhere in empty space. The last of the nineteen is an *angle of the strong force*: a number that would let the strong force treat matter and its mirror image differently if the number were not zero. The *neutrinos* are the lightest particles of matter, and neutrinos carry no charge at all. The neutrinos add seven more numbers: three masses and four numbers of their mixing. Nineteen and seven make twenty-six.

So Kaku's "about twenty" is right, and the count can be made exact. The count is nineteen numbers, each with a name, and twenty-six when the neutrinos are counted in. For each of the twenty-six, I ask why the number is what it is, and I give an answer of one of four kinds, or I carry two answers side by side.

Four Ways a Number Can Stand

I give every number with its *standing*: my answer to where the number's value comes from, which is the way the number stands toward the world. There are four standings, and I give each standing its own picture. All four standings depend on the structure of comparison: the set of parts that every act of comparison must contain. For short, I call the structure of comparison the structure. Every measurement ever made is an act of comparison.

The first standing is *set by the structure*. A chessboard has sixty-four squares. Nobody measures the sixty-four: the number of squares is eight times eight, and you check the number by counting. A number with the first standing follows by argument from the structure, and I set the number beside its measurement as a check. Three of the twenty-six numbers stand partly in the first way, and none stands wholly in the first way. The first of the three is the angle of the strong force. The angle of the strong force is the sum of two parts. The structure sets one of the two parts, the strong force's own angle, at exactly zero. The second of the three is the

strength of the weak force. Physicists, and I with them, write the strength of the weak force as an angle, the *weak angle*. The number given for the weak angle is the strength of light (how strongly light acts on electric charge) divided by the strength of the weak force. In the structure, the three forces have equal weight (the same strength for each force), and at that equal weight the structure sets the weak angle's number at exactly three eighths. The third of the three is the mass of the muon. The structure sets the muon's mass at the first, simplest level of the calculation of that mass. For each of the three numbers, the rest of the number stands in the fourth way, which I describe below: measured, with its reason still a question. Besides the twenty-six numbers, the structure also sets features of the printed shape of the recipe card, features that the Standard Model includes as given. Among the features the structure sets are the electric charges and the generations of matter. Every charge in the world is a whole number of thirds of the electron's charge. And there are three *generations* of matter: three copies of the whole set of particles of matter, alike in charge and different in mass.

The second standing is *set by the structure once a stated step is taken*. Picture a surveyor's deed that says a lot runs a hundred feet north from the iron stake at the lot's corner. Take the stake you find in the ground to be the stake the deed names. Then every line of the lot follows by measuring from the stake you found. No one can tell from the arithmetic of the deed whether the stake in the ground is the stake the deed names, because the answer is a fact about the ground. A number with the second standing follows by argument once one *identification* is made. An identification is a stated step in which something in the structure is taken to be a quantity of the world, as the surveyor takes the stake in the ground to be the stake the deed names. I name each identification where I make it. The mass of the tau has the second standing. The identification for the tau concerns a rule called *Koide's relation*, after the physicist Yoshio Koide. Koide's relation is a rule about a single number made from the masses of the electron, the muon and the tau. The rule uses the *square root* of each of the three masses: the number that, multiplied by itself, gives the mass. Any three

numbers can be described in two parts: the size the three numbers share, which is their average, and the amounts by which each number stands above or below that average. For example, the heights of three children can be given as one average height and how far each child stands above or below the average. In the same way, Koide's relation has two parts, for the square roots of the three masses: the part the three square roots share, and the part by which the three square roots differ. In the identification, each part is measured by its share of the total of the three masses. Once the identification is made, the argument from the structure shows that the two parts have equal shares, half of the total each. Koide's number is the total of the three masses divided by the square of the sum of their square roots. When each part is half of the total, the total of the masses is two halves, and the square of the sum of the square roots is three halves, so Koide's number, the first divided by the second, is exactly two thirds. Once the identification is made, the tau's mass follows from the masses of the electron and the muon. When the tau's mass is found from the masses of the electron and the muon, the result agrees with the measured mass to within less than half the measurement's *give or take*, the amount by which a measurement could reasonably be off.

The third standing is *measured*: I take the number from measurement. A tailor's pattern gives every proportion of a coat. The one thing the pattern cannot give is the size of the person who will wear the coat. So the tailor measures the wearer. Four of the twenty-six numbers have the third standing. The first of the four is the electron's mass. I give every mass as so many electron masses, as a length can be given in feet or in meters. Take a board twice as long as it is wide: the board is twice as long in feet and twice as long in meters. The "twice" is a fact about the board, and the feet and the meters are bookkeeping. So the electron's mass is the unit in which every other mass is read, and a unit is a choice of bookkeeping. Choosing a different unit never changes the answer of a comparison (same or different, more or less), so no argument can fix a unit. The second of the four is the *strength of light*: how strongly light acts on electric charge, about one part in a hundred and thirty-seven. The structure of

comparison is the same at every value of the strength of light. So no argument from the structure, however long, fixes the strength of light. The third of the four is the strength of color, which is the strength of the strong force. I tie the strength of color to the mass of the proton, so that once either one is measured, the other follows. The fourth of the four is the vacuum value of the Higgs field.

The fourth standing is *measured, with its reason still a question*. Picture two clocks that keep the same time to the second, week after week, in different rooms of a house. You find that the two clocks agree by looking at them. Why the clocks agree is a question, and a good one. You keep the clues beside the question: perhaps both clocks run on the same wall current. The full mass of the muon has the fourth standing. When the calculation of the muon's mass is carried one step past its first level, the calculation needs one more number, seven ninths. With seven ninths, I get a value for the muon's mass that agrees with the measured mass to eight figures. The reason the number is seven ninths is still to be found. So the muon's full mass stands as measured. I write the muon's question beside the mass: why does the number land on seven ninths? The angle of the strong force has another part with the fourth standing. The part with the fourth standing comes from the masses of the quarks. Experiments place the whole angle below about one part in ten billion, and because the strong force's own angle is exactly zero, the part from the quarks lands on zero. Beside the part from the quarks I write a question: why do the masses of the quarks add nothing to the strong force's own angle? At the energies that experiments reach, the weak angle's number also has the fourth standing. The weak angle's number changes slowly with the energy of a collision, as every strength does. At the energies experiments reach, the number is measured, with its reason still a question. Kaku's own example also stands in the fourth way: the masses of the quarks. By one rule I use, the mass of each charged particle of matter is a counted number of *halvings* below the mass of the heaviest quark, which physicists call the *top*. A halving is a step of a factor of two in mass. The rule has three families of three: the top and the two lighter quarks with the top's

charge; the *bottom* quark, the heaviest quark of the other charge, and the two lighter quarks with that charge; and the tau, the muon and the electron. For the top's family the count starts at the top itself, and for each of the other two families the count starts from a number found from the measured mass of the family's heaviest member, the bottom or the tau. In each family the halvings are counted down from the heaviest member to the lightest. Each of the five lighter quarks has its place in the count of halvings. Every quark's mass is measured, and why each mass lands where it does is a question that I keep with its clues.

The Fork and the Legend

Seven of the twenty-six are the numbers of the neutrinos. The seven numbers stand in a further way, which I call standing *at a fork*. For each of the seven, I carry two arguments side by side until a measurement shows which argument is right, as a doctor keeps two diagnoses open until a test shows which diagnosis is right.

The four standings and the fork are different relations between a number and the world: each says where a number's value comes from, not how sure anyone is of the value. Each standing is a different claim about its number, and keeping the standings apart is most of what it means to know what one knows.

I put the whole account of the standings into one picture. A mapmaker can draw every proportion of a valley correctly, every bend of the river and every angle between the fences, and the map still needs a line in its legend (the key printed beside the map) saying how many meters one centimeter stands for. The mapmaker reads the scale line off the ground, not off the drawing. The structure draws the proportions; measurement writes the legend. The proportions of the map are the numbers that the structure sets by argument, and the lines of the legend are the numbers taken from measurement. I count the lines of the legend in two ways, and both counts are true. In the first count the legend has six lines, and four of the six are the four measured numbers of the third standing: the electron's mass, the

strength of light, the strength of color and the vacuum value. The other two lines are the two numbers at which the count of halvings starts for the bottom's family and for the tau's family, found from the measured masses of the bottom and the tau. In the second count, a stated step lets the electron's mass alone carry the drawing to three more numbers: with that step, the vacuum value, the mass of the top and the mass of the Higgs particle all follow from the electron's mass. For the vacuum value, the mass of the top and the mass of the Higgs particle, the legend of the second count has one line, the electron's mass. The vacuum value stands as measured, and I set beside the measured value the value that follows from the electron's mass. When the legend needs fewer lines, the structure draws more of the map. In either count the legend is short, and each line of the legend has its standing.

A Number That Lands Is a Question

Go back now to Basel. For twenty-eight years Balmer's rule stood in the fourth standing: the rule landed, and no one knew why.

What should be written beside a number that lands before anyone knows why? I answer with a question: why does the number land? A value that lands, before its reason is found, is a question, and it is evidence of a reason not yet known. The question has its clues, and the clues show where the reason is. Balmer's rule used whole numbers, and Balmer himself guessed that the four in the rule, two times two, might be one of a family of squares, each square giving another family of lines. Balmer's guess showed where to look: at something in the atom that comes in whole steps, counted one, two, three. Bohr found the reason in the energy levels of the atom, which come in whole steps. Physicists held the rule as a question and looked for its reason, and so the rule became a door into quantum theory: in finding the reason, Bohr took one of the first steps into quantum theory.

I hold every number that lands as a question, with its clues. When a measured number has its question written beside it, the number and its question are a complete state of knowledge. A number with its question is not a blank on the recipe card. Kaku says that the twenty or so numbers come with "no understanding whatsoever". Here each of the twenty-six comes with something written beside the number. What is written beside a number is an argument from the structure, a stated step, a measurement, a question with its clues, or, for the seven numbers of the neutrinos, two arguments carried side by side.

Where Kaku and This Account Agree

On three points this account agrees with Kaku.

The first point is the count. Kaku's "about twenty" are the nineteen numbers of the Standard Model as first written, and I count the same nineteen. I add the seven numbers of the neutrinos, and my argument itself fixes the count at seven. Every particle of matter has an *antiparticle*, its mirror partner with every charge reversed. Physicists consider two kinds of mass a neutrino could have: the kind the electron has, with which a particle stays distinct from its antiparticle, and a kind that would make the neutrino its own antiparticle. The structure sets the neutrino's mass as a mass of the first kind, the electron's kind, and a mass of that kind comes with seven numbers, where the second kind would come with nine.

The second point is Kaku's principle that the correctness of a theory "should rest on concrete results, not the subjective desires of physicists". I reach the same principle from a study of how anything at all is *validated*, which means shown to be so. A claim comes to be counted as validated in only three ways, which are measurement, proof and agreement among people. The first way is *measurement*: a comparison made here and now, by the one who compares, as in physics. The second way is *proof*: an argument laid out so that the argument holds the same for whoever checks the argument, as in mathematics. The third way is agreement among people: a claim counted as settled because many people have said so. Measure-

ment and proof validate truth. Proof validates the truth of one kind of claim: that a conclusion follows from its *premises*, the statements an argument starts from (if these premises, then this). Measurement validates the truth of the other kind of claim: whether a claim holds of the world, here and now. Agreement among people validates nothing by itself. At most, agreement among people is circumstantial evidence, standing in for a measurement where no measurement can be made. A desire is neither a measurement nor a proof, and so Kaku is right that the desires of physicists validate nothing about the world.

The third point is Kaku's sentence that "A theory of everything is also a theory of ordinary things". I take up the ordinary things of Kaku's sentence: the masses and strengths that laboratories measure. I take the twenty-six numbers one at a time. For each number I say which part the structure sets and which part is left to measurement.

Where This Account Reaches a Different Result

On Kaku's test itself, I reach a different result, for three reasons.

The first reason is that a complete account of the numbers states the standing of every number, and for two of the twenty-six, the electron's mass and the strength of light, I give the argument that no argument from the structure of comparison supplies them. A value shown not derivable is closed under reason as fully as a derived value. A value shown not derivable has an argument that states exactly why no law fixes the value, as a derived value has an argument that fixes the value. A carpenter can prove that the two diagonals of a square frame must be equal, or prove that nothing in the plan fixes the color of the paint, and either way the carpenter has left nothing about the frame unaccounted for. The equal diagonals are like a derived value, and the color of the paint is like a value shown not derivable. So when Kaku asks for every constant to be calculated "from first principles, without any assumptions", he asks, for the

electron's mass and the strength of light, for something that no argument from the structure of comparison can produce. No argument can produce the two numbers, and the reason lies in the numbers themselves.

The second reason is that every derivation has premises, and I name the premises. Kaku's "first principles" are premises too. A derivation of a constant is a proof. A proof validates one thing, the same for whoever checks it: that the number follows from the derivation's premises. Measurement validates whether the derivation's premises, and so the number, hold of the world: the derived number is set beside the measured number. So I mark each stated step where I take the step, as the surveyor's deed names its stake. Every derivation has its stake, a stated step on which the derivation depends. Once the stake is named, anyone can check the deed against the ground, that is, check the derived number against its measurement.

The history of physics has a clear case of a derived number set beside the world. In 1929 the Cambridge astronomer Arthur Eddington derived the strength of light as exactly one part in a hundred and thirty-six. When better measurements came closer to one part in a hundred and thirty-seven, Eddington revised his argument so that it produced exactly one part in a hundred and thirty-seven. Later measurements showed that Eddington was wrong: the strength of light is one part in a hundred and thirty-seven and a small fraction more. Eddington treated the strength of light as a count in his argument, but the strength of light is no count: the equations of the electron hold at any value of the strength of light. I leave the strength of light to measurement for a reason of the same form as the reason Eddington's argument failed: the structure of comparison is the same at every value of the strength of light. Eddington's case shows what a derived number is, taken alone: a claim that the number follows from premises, which measurement then tests.

The third reason is about what makes derived numbers evidence. Kaku sets the numbers a theory would calculate beside the "plenty of experimental data" physics already has, and I do the same. When a derived number agrees with its measured value, the number is one strand of evid-

ence that the theory holds of the world. Kaku writes that calculating the constants "would, in my opinion, prove its correctness". I find instead that measurement validates the derived numbers strand by strand.

A Strand in a Cable

Hang a heavy load from a chain. Every link carries the whole of the load, and if one link cracks, the load falls, however strong the other links are. Now hang the same load from a cable, the kind that lifts a crane's hook: many strands of steel wire twisted together, so that each strand grips the others along its length. Cut one strand, and the cable holds. A cable is stronger than its strongest strand. The strength of a cable comes from the number of its strands and from how closely the strands are bound together.

In 1868 the American philosopher Charles Sanders Peirce asked philosophy to reason as the successful sciences reason, trusting "rather to the multitude and variety of its arguments than to the conclusiveness of any one". Philosophy's reasoning, he wrote, "should not form a chain which is no stronger than its weakest link, but a cable whose fibers may be ever so slender, provided they are sufficiently numerous and intimately connected". I carry Peirce's picture from philosophy to every inquiry into the world. A proof in mathematics is a chain, because each step of the proof depends on the steps before it, and for a proof the rule of the weakest link is exactly right. An argument about the world is a cable: the strength of the argument comes from the number and the independence of its strands. The strands of an argument about the world are independent when the strands rest on different sources, so that a mistake in one strand does not carry into the others. When independent routes of reasoning, resting on different premises, arrive at one value, the meeting of the routes is called *convergence*. Convergence is the strongest evidence that inquiry into the world can have.

In the first strand of one cable, I reach the charges in thirds (every charge a whole number of thirds of the electron's charge) by argument from the structure of comparison. In the second strand, physicists reach the charges in thirds by a separate route: from the requirement that the effects of quantum theory never break the symmetry of the forces. In the second strand, *symmetry* has the physicists' sense: a change that leaves a thing the same, as a turned sphere is the same sphere. For the symmetry of the forces, the change is made to the particles, and the laws of the forces stay the same. An effect of quantum theory would break the symmetry of the forces if the laws of the forces came out different once the change was made to the particles. The quarks produce effects of quantum theory on the symmetry of the forces, and so do the lighter particles of matter, the electron and its neutrino. The second strand depends on taking the quarks and the lighter particles together, a whole generation at once. When the quarks and the lighter particles of a generation are taken together, the effects of the quarks and of the lighter particles cancel, and the charges that make the effects cancel are the charges in thirds. The third strand is measurement, and measurement agrees with the charges in thirds. The proton is made of three quarks, two with a charge of two thirds and one with a charge of minus one third. Two thirds and two thirds, less one third, make exactly one: the electron's charge with its sign reversed. Experiments measure the electric charge of whole atoms and molecules, and they find that the proton's charge and the electron's charge cancel to better than one part in a hundred billion billion. So an atom of hydrogen is neutral, and the thirds in the atom's proton add up to exactly one. Three strands from three sources hold one result, the charges in thirds: the argument from the structure, the requirement of symmetry, and measurement.

A second, smaller cable holds the result that the structure sets three generations of matter and no fourth, and that each generation has a neutrino of its own. Physicists have counted the light kinds of neutrino by measuring how quickly a heavy *carrier* of the weak force *decays*, which means breaks up into lighter particles. A carrier is a particle that carries a

force from one piece of matter to another. Each kind of neutrino gives the carrier one more way to break up, so each kind of neutrino shortens the carrier's life. The measured count differs from three by half the measurement's give or take. The second cable has two strands, the argument from the structure and the measured count, and both strands hold one result: three generations of matter.

So a theory is judged by its whole cable: by how many of its numbers have their standing, by how many of its values are reached by independent routes, and by whether each number the theory predicts agrees with its measurement.

What We Now Know

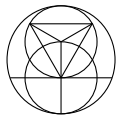
We now know that each of the twenty-six constants has its standing or its fork. Three of the twenty-six are set by the structure in part. The structure sets the strong force's own angle at exactly zero, the weak angle's number at exactly three eighths at the forces' equal weight, and the mass of the muon at the first level of the calculation of that mass. Besides the twenty-six, the structure sets the charges in thirds and the three generations. Some of the twenty-six are set by the structure once a stated step is taken, like the mass of the tau. Four are measured: the electron's mass, the strength of light, the strength of color and the vacuum value. For the electron's mass and the strength of light, I give the argument that no argument from the structure of comparison supplies them, and showing that no argument supplies them is itself a result. Many of the numbers land on measurement with their reason still a question, like the full mass of the muon and the masses of the quarks, and I carry each of those numbers with its question, as Balmer's rule was carried for twenty-eight years. And the seven numbers of the neutrinos stand at a fork.

We also know what validates a claim about the world: measurement and proof validate truth, and agreement among people validates nothing by itself, however wide the agreement is. Kaku hopes that the ordinary

numbers will one day speak for a theory, as evidence that the theory is right. Kaku's hope is a good hope. In this account the numbers already speak: each number has its standing or its fork.

Would deriving all the constants prove a theory right? Deriving the constants proves that the constants follow from a theory's premises, and measurement shows whether the constants hold of the world. A theory holds as a cable holds, strand by strand: each derived number that agrees with its measurement is one more strand of evidence.

Kaku turns to the next question himself, in the lines that follow his test. The equation of string theory, he has explained, has countless solutions, and "each solution of string theory is an entire universe" (*The God Equation*, ch. 6, "Can It Be Tested?"). If every solution is a universe, which solution is ours, and is our universe one bubble among countless others?



Chapter Six

One Bubble Among Many?

Is our universe one bubble among many, and is that why its laws suit us?

What this chapter uses

Comparison: setting one thing beside another and telling them apart (Preface and Chapter One). The *road country*: whatever a road can reach is a place of the country, and a "town" that no road could ever reach is no place at all (Chapter One).

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. In the theorem's sense, *symmetry* is a sameness of content (what is found) where there is a difference of context (the setting in which it is found), and *continuity* is a sameness of content where there is a sameness of context. In the physicists' sense, a symmetry is a change after which a thing or a law is as it was (Chapter One).

To *exist* is to stand as structure, laid out and timeless; to be *real* is to be given in an actual act of comparison (Chapter Two).

The ten dimensions: one of time, three of space, and six of possibility, which nothing travels through (Chapter Three). The three positions of every comparison, from which the three forces of the particles come, three from the start (Chapter Four).

The *standing* of a constant: set by the structure of comparison, set by it once a stated step is taken, measured, or measured with its reason still a question; or at a fork (Chapter Five).

Many readers finish Michio Kaku's books with a large and beautiful picture of many universes, and with a question about our own: is our universe one bubble among countless others, and are the many bubbles the reason that the laws of nature are just right for us?

A Hiss from Every Direction

In 1964 the radio astronomers Arno Penzias and Robert Wilson were working at the Crawford Hill laboratory of Bell Telephone Laboratories, in Holmdel, New Jersey. Penzias and Wilson had a large antenna shaped like a horn, known as the twenty-foot horn. The horn had been built for work with the first communication satellites, and the two men wanted to turn the horn to the sky for radio astronomy. The radio waves they wanted to measure were faint. So Penzias and Wilson had to find every source of noise in their own instrument and allow for each one.

One source of noise would not go away. Wherever in the sky Penzias and Wilson pointed the horn, the receiver picked up the same faint hiss. The hiss stayed the same through the seasons, from the summer of 1964 to the spring of 1965. A pair of pigeons had been roosting in the narrow throat of the horn. The pigeons had coated the throat with what Wilson later called "a white material familiar to all city dwellers". The two men evicted the pigeons, cleaned the horn, and covered the riveted seams of the horn with aluminum tape. The hiss stayed.

Then Penzias mentioned the puzzle of the hiss to the radio astronomer Bernard Burke, while the two were talking about other matters. Burke remembered a group at Princeton, led by Robert Dicke. The Princeton group expected the whole sky to give off a faint glow of radio waves. The glow would be left over from a hot early universe. In a receiver, the glow would be heard as a faint hiss from every direction. Penzias telephoned Dicke. Dicke and his colleagues came to Holmdel, looked at the horn and the measurements, and were convinced. In July 1965 the *Astrophysical Journal* printed two short letters side by side. The letter from the Princeton group proposed what the glow might be: the radiation left over from a hot early universe. The letter from Penzias and Wilson reported a temperature about three and a half degrees above what the two men had expected. The excess was the same in every direction Penzias and Wilson had looked. In 1978 Penzias and Wilson shared the Nobel Prize in Physics for the discov-

ery. Kaku tells the story of the hiss, bird droppings and all, in his book *Parallel Worlds* (2005). Kaku calls the section "Bird Droppings and the Big Bang" (ch. 3).

What had Penzias and Wilson found? They had found the *microwave background*: light left over from the time when the whole universe was hot and glowing. The expansion of space has stretched the light ever since, and astronomers have since measured the temperature of the light with far greater care: about two and seven tenths degrees above *absolute zero*, the coldest anything can be. The glow comes from every direction of the sky, because in every direction we look back to the same early time. The glow is the plainest relic of the *Big Bang*, the hot, dense beginning to which the history of our universe, traced backward, runs.

The hiss carries a puzzle with it: the glow is the same from every direction. In 1992 the satellite called the Cosmic Background Explorer measured the temperature of the glow across the whole sky, and found that the temperature differs from place to place by only about one part in a hundred thousand. Yet trace the history of the Big Bang back to the moment the glow was released, and you find that by that moment too little time had passed for any signal to travel between two regions of the sky more than about a degree apart. A degree on the sky is about twice the width of the full Moon. How did regions that had never sent each other a signal come to agree so exactly? The story of Kaku's bubble universes begins with the puzzle of how the hiss came to be the same in every direction.

What Kaku Showed

Kaku is a generous guide to the physics of the universe as a whole, and he begins on solid ground. He insists, rightly, that the Big Bang is well founded. In *Parallel Worlds* he writes that the Big Bang rests "on hundreds of data points taken from several different sources", all of which agree (*Parallel Worlds*, ch. 3, opening). Three kinds of measurement fit one history of a hot, dense beginning: the *galaxies* (the great wheels of billions of stars) are moving apart as space expands, the glow

that Penzias and Wilson heard comes from every direction, and the light chemical elements are present in the amounts that such a beginning would produce.

Then Kaku takes the next step that most *cosmologists*, the physicists who study the universe as a whole, take. In 1981 the physicist Alan Guth proposed a way to explain two features of the sky: the sameness of the glow in every direction, and the *flatness* of space, which has no overall bend on the largest scales. Guth's proposal was *inflation*: a brief burst of ever faster expansion that stretched a tiny region, whose parts had once been in touch, to far beyond everything we can now see. So regions now far apart on our sky were once parts of the one tiny region. While the regions were together in the tiny region, they had time to come to agree. Kaku writes that inflation "is not the only cosmological theory, but is by far the simplest and most credible" (*Parallel Worlds*, ch. 4, "Birth of Inflation").

In *Physics of the Impossible* (2008) Kaku counts "at least three types of parallel universes" (ch. 13, opening): higher dimensions, the *multiverse*, and quantum parallel universes. The multiverse is Kaku's word for the whole collection of universes, ours among them. Chapter Three was about the first of the three types, higher dimensions. Chapter Three asked how anyone could know of six more dimensions too small to see. Kaku comes to the multiverse by more than one route, and one route is inflation. The physicist Andrei Linde proposed that inflation never stops everywhere at once. In Linde's proposal, here and there a region stops inflating and becomes a universe, while the space around the region goes on inflating and buds off more regions. When inflation goes on without end in some places while it stops in others, physicists call it *eternal inflation*. Kaku sums up Linde's proposal in one line: "In the chaotic inflationary model, the multiverse is eternal, even if individual universes are not" (*Parallel Worlds*, ch. 4, "Chaotic Inflation and Parallel Universes"). Kaku also quotes Guth: "Inflation pretty much forces the idea of multiple universes upon us" (*Parallel Worlds*, ch. 1, "The Multiverse"). And Kaku gives the picture that runs through *Parallel Worlds*,

of bubbles forming in boiling water: "Perhaps, scientists speculate, Genesis occurs repeatedly in a timeless ocean of Nirvana" (*Parallel Worlds*, ch. 1, opening). In *The God Equation* (2021) Kaku draws the picture of bubbles once more, still as a possibility. Perhaps, Kaku writes, Big Bangs are happening all the time, and our universe is "a three-dimensional bubble floating in a much larger space of eleven-dimensional Nirvana in which other universes continually arise" (ch. 7, "Did the Universe Have a Beginning or Not?").

Kaku's second route to the multiverse runs through *string theory*. String theory is the theory in which every particle is a tiny vibrating string. String theory needs ten *dimensions*, ten independent directions in which things can differ. The eleven dimensions of Kaku's Nirvana belong to *M-theory*, the larger theory behind five versions of string theory, which Chapter Four described. String theory, Kaku writes, is the eleven-dimensional M-theory brought down to ten dimensions (*The God Equation*, ch. 6, "M-Theory"). The equations of string theory have an enormous number of solutions. Each solution could be a universe with its own laws. Kaku states frankly a new way of thinking about the many solutions: "if we cannot find the unique solution to string theory, it's probably because there is none. All solutions are equal" (*Parallel Worlds*, ch. 7, "The End?"). Kaku gives his own view in *The God Equation* with a condition, "If my thinking is correct", and on that view the master equation is one, while its solutions may be endless: "a landscape of solutions, but the equation itself is unique" (ch. 7, "My Own Point of View").

Kaku calls his third type the quantum parallel universes. The third type comes from *quantum theory*, the physics of the smallest pieces of matter. Physicists describe a quantum particle by a *wave function*: a spread of possibilities that says how likely each result of a measurement is. In 1957 the physicist Hugh Everett proposed that every possibility in the wave function happens, each possibility in its own branch of the world. Everett's idea is called *many worlds*. Kaku takes Everett's idea into your living room. If Everett's interpretation is correct, Kaku writes,

"The worlds of *The Man in the High Castle* and *The Twilight Zone* are among the universes existing in your living room" (*Parallel Worlds*, ch. 6, "Many Worlds"). Kaku adds that we can no longer interact with the other universes in the living room. In *Hyperspace* (1994) Kaku follows the physicist Stephen Hawking in giving the whole universe one wave function. Then Kaku says what follows if we take Hawking seriously: "the definition of the word universe is no longer 'all that exists'. It now means 'all that can exist'" (*Hyperspace*, ch. 12, "Wave Function of the Universe").

The eighth chapter of *Parallel Worlds* asks a question in its title: "A Designer Universe?" A *constant* of nature is a number that is the same everywhere and always, such as the strength of gravity, and many of the constants of nature have values inside a narrow band that allows stars, chemistry and life. Physicists call the fit of the constants to life *fine-tuning*. The constants of nature look as if someone had set them with care. Kaku reports, with sympathy, the answer of the astronomer Martin Rees: "If there is a large stock of clothing, you're not surprised to find a suit that fits". In Rees's picture the stock of clothing is the many universes, and the suit that fits is a universe whose constants allow life. And Kaku draws the moral himself: "our universe is the way it is because of the law of averages over many universes in the multiverse, not because of a grand design" (*Parallel Worlds*, ch. 8, "Multiverse").

Kaku is clear about what is at stake: in *Physics of the Impossible* he writes that "what is at stake in this debate about various parallel universes is nothing less than the meaning of reality itself" (ch. 13, opening). Kaku rates detecting and reaching other universes a Class II impossibility: "impossible today, but not in violation of the laws of physics" (ch. 13, closing paragraph).

Where We Arrive at the Same Place

Several of Kaku's results also follow in this account, which starts from the act of comparison and not from the experiments of physics.

This account agrees with Kaku that our history, traced backward, runs to a hot, dense beginning, and agrees, too, that we find the beginning the way a detective finds out about a crime: from relics. The detective was not there when the crime happened, and works the crime out from the clues it left behind. No one saw the beginning, just as the detective did not see the crime. We work the beginning out from the relics it left, such as the glow and the light elements. We build our whole picture of the past from what arrives now: the light of distant galaxies, the oldest glow, the amounts of the chemical elements, the records of every instrument. From those impressions we piece together one history. Kaku's hundreds of data points are the impressions that arrive now. From the data points we piece together one history. So Kaku and this account describe one body of evidence from two sides: the data, and the history built from the data.

This account also agrees with Kaku's picture of Genesis in a timeless ocean of Nirvana on one point: the history we trace can have a true beginning, while there is no first beginning of all. In this account the whole history we can trace belongs to one *epoch*: one long stretch of history, complete in itself, which is one in a sequence of epochs under the same law. Each epoch has its own true beginning, which anyone who traces the history of the epoch backward finds as the epoch's Big Bang, and the sequence of epochs has no first epoch. Kaku arrives at both points through many bubbles in one ocean. Each bubble has a true beginning, and the timeless ocean has none.

And this account agrees with Kaku that the meaning of reality depends on how the debate about parallel universes comes out. Kaku, taking Hawking seriously, gives the word "universe" a new meaning, while I keep the word "universe" in its old meaning and instead give exact senses to two older words, "exist" and "real".

What "Exists" and What Is "Real"

Everything in this account rests on one act, the act of comparison. Every measurement is an act of comparison, and so is every look, every reading of an instrument, and every thought. When a person or an instrument makes a comparison, I call the person or the instrument a *comparer*.

Everyday speech runs the two words "exist" and "real" together. We can tell the two words apart by using the act of comparison. When a thing stands as structure (laid out, timeless, the same in every instance, as a map or a law is), I say, as in Chapter Two, that the thing *exists*. The equation of a pendulum exists, while the swing you see is real.

Now ask Kaku's question with "exist" and "real" in the senses just given: is there one world, or are there many? I answer the question directly: to say "there exists only one world", or "there exist more than one world", "is to apply the concept of existence outside its range of meaning". In the two quoted sentences each "world" is what I call a *domain*: a whole range of things that can be joined to one another, in this case by acts of comparison. Chapter One gave a case of a domain: the surface of the Earth is a domain for a walker. Existence is always relative to a particular domain. There is no single ground beneath all domains on which anyone could settle whether the domains exist. I go on to write: "What can be said is that many worlds are real". Unlike existing, being real is given in acts of comparison, and every act of comparison is made within some domain, so each domain is real in its own acts of comparison. Each epoch, before ours and after ours, is a domain of its own. So each epoch is one of the many worlds that are real. The epochs are worlds, each real in its own acts of comparison, and no act is real in two of them.

The words "many worlds are real" hold in a second way as well. The second way is this book's answer to Everett. For each comparer, one outcome of a measurement is real: the outcome that the comparer finds.

Kaku's ocean is a different claim, one ocean that holds every universe at once, seen from a place outside all of the universes, and in this account there can be no such ocean, for a reason that comes in two steps.

The Road Country, and the Ocean of Bubbles

The first step uses the road country of Chapter One: a town that no road has reached yet is still a town of the country, waiting on a road, while a "town" that no road could ever reach is no place at all for the traveler, however good the car.

In the physics of this book, space is the pattern of which events a signal can join. The roads of the road country stand for the paths of signals, and the towns stand for events. Take a bubble universe floating in Kaku's ocean. If some path could reach the bubble, through a wormhole or anything else, then the path itself joins the bubble into our pattern, and the bubble is part of our own world. If no path from here could ever reach the bubble, the bubble has no position in our pattern and is no place at all for us, so our own world, the one world, is everything that any path from here can reach. A journey to another universe therefore asks for one of two things, and neither is another universe. The two things are a place that a path can reach, which is part of our own world, and a place that no path can reach, which is no place at all.

The second step against Kaku's ocean is about the ocean itself. Kaku's picture is a view of many universes at once, all floating in one larger space, as someone standing somewhere would see them. If one ocean is to hold every universe as a single whole, the ocean must do two things perfectly at the same time. First, the ocean must count every bubble as a universe in exactly the same sense, wherever each bubble floats: one way of belonging, the same for every bubble. Second, the ocean must join every bubble to every other bubble, with no bubble cut off from the rest.

Both demands have exact names, taken from the Incommensuration Theorem, the theorem about comparison on which this book rests. The names are symmetry and continuity, in the theorem's sense, which the

box at the head of this chapter recalls. The ocean's first demand is symmetry made perfect, in the theorem's sense: one way of belonging, the same across every bubble. The ocean's second demand is continuity made perfect, in the theorem's sense: every bubble joined to every other in one setting, with no gap anywhere. The Incommensuration Theorem shows that symmetry and continuity cannot both be made perfect in one comparison. Every act of knowing is a comparison, so the theorem holds wherever anything is known at all. So no comparer can hold all the bubbles together as one whole in any one comparison, and I put the same conclusion in one short phrase: "no domain contains every domain". The timeless ocean is a picture drawn from a place outside every universe. There is no place outside every universe for anyone to stand.

Does the Sky Need Inflation?

Two questions remain: does inflation make Kaku's bubbles, and does the hiss from Holmdel, the same in every direction, need inflation to explain it?

The Big Bang has its place in a longer story. I tell the longer story here in brief, and it has four steps: the black holes of an epoch, the emptying of the space outside them, three conditions that fail together at the end of their insides, and a new large space that opens from that end. Every epoch has ten dimensions: one of time, three of space, and six of possibility. The *six dimensions of possibility* are the dimensions of what can happen at each place, as Chapter Three told, and nothing ever travels along the six: a comparer encounters the six only as the range of what could be found.

In every epoch, much of the matter gathers into *black holes*, bodies whose gravity is so strong that not even light escapes them. Inside every black hole, everything falls toward an end that lies ahead in time.

Call the space outside the black holes, the space in which the stars and the galaxies lie, the large space. Over an enormous span of time, the large space thins out and empties.

The large space is the context of the six dimensions of possibility, and the six are content within the large space. While three conditions are met, the large space holds the six in their one shape. First, the large space is present. Second, the large space is smooth in space and time. Third, the distant stars of the large space mark what it means to stand still and not spin. Standing still is always standing still relative to something, and the distant stars are that something: a *gyroscope*, a wheel spinning freely in its frame, keeps pointing at the same distant stars. At the end of the interiors of the black holes, all three conditions fail together. The large space has emptied. The smooth picture of space and time stops applying, and nothing is left to mark what standing still means.

Then the ten dimensions form a new large space, the large space of a new epoch: three directions of space open up while the six close in. I call the passage from the old epoch to the new one *the turn*. I identify the Big Bang, which we find when we trace our history backward, with the turn as the turn appears from our side.

Now the sameness of the sky has a plain reason. In the epoch before ours, the interiors of all the black holes end in one end. A comparer could tell one interior from another only within the large space of the old epoch, and the end of the interiors comes at no moment of the old epoch's time, so no comparer, in any comparison, could tell the ends of the interiors apart. A difference that no comparison can register is no difference at all. So the ends of the interiors are one end. The large space of the new epoch forms from the one shared end. Think of two villages far apart whose people share an accent, though the people of one village have never spoken with the people of the other: the two villages share the accent because settlers from one place founded both villages. Regions on opposite sides of our sky are like the two villages: the regions are alike because they come from one origin, the one end, and no signal needed to pass between them.

The reason for the flatness of space also lies at the turn. Physicists call an overall bend of space on the largest scales its *curvature*. A curvature would need a length to set it, as the radius of a circle sets how sharply the circle bends, and no length of the old epoch passes through the turn. The turn has one length of its own: the length at which the smooth picture of space and time stops applying. If a bend were as tight as the turn's own length, the bend would close the new epoch within moments of its start, or leave the space of the new epoch bent everywhere. Every epoch goes on to make stars and black holes. An epoch that makes stars and black holes neither closes within moments nor stays bent everywhere. So no length is left to set a bend, and space is flat on the largest scales.

Physicists built inflation to solve a third puzzle as well. The third puzzle comes from theories in which the three forces of the particles (the force of light, the weak force and the strong force) were once one larger force that later broke apart. The breaking would leave behind heavy particles, each carrying a single magnetic pole, a north with no south, and on the theories of one larger force the heavy particles should be everywhere, yet no one has found any. The three forces were never one larger force: Chapter Four showed that the three forces come from the three positions of every comparison (the act of comparing, the thing compared, and the thing it is compared against) and were three from the start. So no larger force breaks apart, and the puzzle of the missing heavy particles does not arise. I put the answer to all three puzzles in one sentence: "The account answers every puzzle inflation was introduced to solve, from the turn and from the structure of the forces, so it needs no inflation".

The First Ripples, and No Long Inflation

This account says more than that the sky needs no inflation. Take a *long inflation*: one long enough to take the lengths we see across today's sky, which once lay within the greatest distance a signal could have

crossed since the turn, and stretch them beyond that distance. A long inflation cannot have happened, and there are two grounds for that conclusion.

The first ground is the faint ripples in the glow: the differences of one part in a hundred thousand that the Cosmic Background Explorer measured. The galaxies grew from the ripples, as plants grow from seeds. In the theory of inflation, the ripples are the trembling of empty space (small random changes in empty space), stretched to great size. The *form of the content* is what the matter is, and which alternatives the matter has taken. I identify the ripples with the form of the content carried through the turn. Everything that fell into the black holes of the epoch before had taken some alternatives and not others, and the form of the content crosses the turn with the old distinctions averaged, and not erased. Picture the steps of an old stone stair, worn into one curve by many feet, with no single footstep picked out and none wiped out. The footsteps are the distinctions of the old epoch, and the worn curve is the averaged form that crosses the turn: every footstep has a part in the curve, and no one footstep can be read off the curve.

A long inflation would itself make the ripples on the lengths we see across today's sky, as the trembling of its own empty space. Every ripple we see across today's sky is the carried form, and not the trembling of an inflating empty space. So, on my identification, a long inflation cannot have happened.

The second ground for excluding a long inflation is the *dark matter*, the unseen matter whose weight holds the galaxies together. The dark matter is a lasting vibration of the six dimensions of possibility, made at the turn. In the theory of inflation, the inflating empty space makes the first waves in the shape of space itself, and the more energy the inflating empty space holds, the stronger the first waves are. In 2021 astronomers at the South Pole searched the glow for the first waves with the BICEP and Keck telescopes, and set a limit on how strong the first waves can be. So any inflation that made the ripples had at most a limited amount of energy, and the end of such an inflation could therefore hand on only a limited

amount of heat to the young universe. An inflation stretches space so much that whatever was made before the inflation is spread too thin to matter, so in a history with inflation the dark matter made at the turn would have been spread too thin, and the dark matter measured today would have had to be made after the inflation, by the heat that the end of the inflation handed on. So, after an inflation that made the ripples, the young universe would have been too cool to make the dark matter in the amount measured.

Kaku's bubbles come from eternal inflation. An eternal inflation that made our universe would be a long inflation in our own past. Setting the work of other physicists beside this account, I draw the consequence: this account needs no inflation, and in this account a long inflation cannot have happened, "so there is no eternal inflation to make the regions". The regions in the quoted words are Kaku's bubble universes. No region buds off from inflating space, and no ocean makes new bubbles beside our universe.

The Cars of One Train

This account has a sequence of epochs in place of an ocean of bubbles. Each epoch begins at the one end shared by the interiors of the black holes of the epoch before. No act of comparison spans the turn, so no finding made in one epoch is real in the next epoch, and no one ever sets a record of one epoch beside a record of another. What crosses the turn is the form of the content, as one averaged form, while the same law holds again on the far side of the turn and is not carried across.

No path crosses the turn. The reason is that the end of the interiors lies at no moment of the old epoch's time, and the new epoch begins at that end. So the epochs before and after ours are no place at all for us, like a bubble that no path could ever reach. Of the next epoch I say, in one sentence: "The next epoch is joined to ours by no path and no act, and

whatever a path can reach belongs to our own one world". So the one world lies within our own epoch. The epochs before and after ours are real in their own acts of comparison, and in no act of ours.

I give a picture of the sequence: the epochs follow one another like the cars of one train, each car coupled to the car before it, and not like the branches of a tree. Two things couple each car to the car before it: the sameness of the law, which holds again in each epoch, and the averaged form of the content, which crosses the turn. No path and no act runs from one car to the next. So the epochs are not bubbles side by side in one ocean, for someone to see together from a place outside all of them. Each epoch is found only in comparisons made inside that epoch. The physicist Lee Smolin proposed that each black hole might give birth to a universe of its own, and Kaku reports the proposal (*Parallel Worlds*, ch. 8, "Evolution of Universes"). In this account all the interiors of an epoch end together. So the interiors give one new epoch, and not one new universe for each black hole.

The train has no first car. Each epoch begins its own *count of disorder*: the measure of how far the matter of the epoch has mixed and run down. So no disorder piles up from one epoch to the next, and the sequence of epochs needs no first epoch. In 1934 the physicist Richard Tolman asked a question about a universe that expands and falls back again and again. Tolman asked whether disorder would pile up from one round to the next, so that the rounds would need a first round. Tolman's question has its answer in the fresh count of disorder in each epoch: disorder does not pile up from one epoch to the next, so the epochs need no first epoch.

One Vacuum

Kaku's second route to the multiverse runs through the many solutions of string theory. In this account, the answer to the second route rests on the six dimensions of possibility again.

Picture a range of hills with many hollows, and a ball dropped onto the hills from the sky. The ball can come to rest in any hollow. Which hollow the ball rests in is a fact about where the ball happened to fall, and no fact about the shape of the hills. Physicists call the bottom of a hollow a *vacuum*, in a second sense of the word: the settled state of lowest energy that a system rests in, from which small pushes roll back. A ball at the bottom of a hollow is in a settled state of lowest energy: give the ball a small push, and the ball rolls back. Chapter Three used the word vacuum in its first sense: a chamber pumped empty of air. The vacuum value of the Higgs field, met in Chapter Five, belongs to the second sense: the vacuum value is the steady size the Higgs field holds while empty space rests in its settled state. String theory has the same ten dimensions as this account. In string theory the six dimensions beyond our four are further directions of space, small enough to hide, while in this account the same six are the six dimensions of possibility. The air of a room is like a field, with a temperature at every point. In string theory a field can wrap around the six dimensions a whole number of times, like threads wound around a spool. The field can wrap around the six in countless ways, and each way of winding has its own hollow. Physicists estimate the number of hollows at ten to the five hundred, a one followed by five hundred zeros. The *landscape* is the range of hills with ten to the five hundred hollows, and in the landscape our universe is one hollow among the many.

Gravity comes from the geometry of the ten dimensions alone. No further field wraps around the six. So there is nothing to wind around the six, and there are no whole numbers of windings to choose among. The six have one shape, and two routes of reasoning that start from different places arrive at that one shape. One route goes through the algebra of the particles. The algebra of the particles is the rulebook of Chapter Four: the rules for combining and transforming the quantities that the particles can show. The other route goes through the mathematics of shape. On neither route does anyone pick the shape from a list of candidates. The six have one shape and nothing wound through them, so the six have only one hollow. So there is one vacuum, and no landscape.

At each turn from one epoch to the next, the six dimensions re-form in the same shape, with the same one vacuum. The laws of the old epoch hold again in the new one. Kaku places variety among the universes, with other laws in every bubble, and this account has no such variety.

Many Worlds, at Two Scopes

Kaku's third type of parallel universe remains: the quantum parallel universes of Everett's many worlds, with the other lives in your living room. I first credit Everett's program for what the program achieves. In Everett's program, quantum theory is one rule of change, which applies to the whole universe just as it applies to a single atom. And the probabilities of Everett's program can be read as the bets a reasonable person must make, as the physicist David Deutsch and the philosopher of physics David Wallace have shown.

On one point this account agrees with Kaku's own picture of the world as a stage. In the physics of Newton and Einstein, Kaku writes, the actors on the stage of the world speak lines from a script written beforehand. The script stands for laws that fix every event in advance. In a quantum play the actors throw the script away and act on their own: "The puppets cut their strings" (*Parallel Worlds*, ch. 6, "Twilight Zone"). Kaku and this account agree that the world does not run from a script written out in advance.

This account says two things about Everett's many worlds. Each of the two claims holds at its own scope, over its own range of cases. The first claim is at the scope of the whole world: as a description of the whole world, taken as everything at once and fixed completely by one law, many worlds is excluded. In Everett's account one law fixes the whole completely: every branch, every outcome, every moment. In Everett's account one law carries every state into the next, so the same rule is found again in every setting, and the same rule in every setting is symmetry made perfect, in the theorem's sense. The law also fixes every state at every point, with no gap. Every state fixed with no gap is continuity made perfect, in

the theorem's sense. The consequence: "A whole world completely fixed by a law perfects symmetry and continuity together, whichever account describes it, and the theorem forbids that pairing".

The second claim is at the scope of outcomes, and the second claim is about what the branches are. The branches exist, as structure: the branches are the laid-out range of what could be found. And for each comparer, one branch is real: the branch that the comparer finds. For every comparer, one outcome is real, the one found. You found one outcome, another comparer elsewhere found another outcome, and each outcome is real where it was found. Kaku places other worlds in your living room, and in this account the other worlds are possibilities: the range of what could have been found. What is real in the room is what you find there.

Just Right for Us?

The second half of your question remains. If there is one vacuum and no ocean of bubbles, why are the laws just right for us?

Picture a lottery. A ticket is a one-in-a-million winner only if there are a million tickets and someone can tell the tickets apart. Every lottery needs one thing, which I state in exact words: "An improbability is a comparison of the actual case with alternatives that some context distinguishes". In the lottery, the actual case is the winning ticket and the alternatives are the other tickets. The context is whatever lets someone tell the tickets apart. I apply the lottery's need to our own beginning. Our beginning was smooth: the matter of the early universe was spread almost evenly. The physicist Roger Penrose reckoned that so even a beginning is one draw among an enormous number of possible beginnings, nearly all of them far less even. At the turn, the large space of the old epoch has emptied, so nothing is there to tell the other possible beginnings apart, and so our beginning was no draw in any lottery. The lottery's need applies to Rees's rack of suits as well. If our universe is to be the lucky ticket, someone would have to lay out the other universes side by side and tell

them apart. A collection of other universes would have to be laid out from a vantage no comparison can occupy. The lottery of universes needs someone who holds all the tickets and can tell the tickets apart. There is no place where anyone could stand to do so.

This account has a further reason, which does not depend on any lottery: there is nothing to select from. There is one shape for the six, one vacuum, and no windings of a field to count. I sum up the reason: "the structure of comparison yields one world, with its constants fixed". Each constant has one value in our world, and no rack of other universes is laid out side by side for anyone to pick the value from, as Rees's suit was picked from a rack. Some constants follow from the structure of comparison in part, or once a stated step is taken, as Chapter Five told. Other constants are measured. One measured constant is the *strength of light*: the number that says how strongly light and electric charge act on each other. The structure of comparison is the same at every value of the strength of light, as Chapter Five showed, so no argument from the structure fixes the value. So no constant needs a lottery: each of the twenty-six constants has its standing or its fork, as Chapter Five set out.

The Energy of Empty Space

The most famous fine-tuned number is the *cosmological constant*: the energy of empty space, which drives the speeding-up of the expansion of the universe. Kaku reports that physicists used the best theory of the smallest particles to compute the energy of empty space, and that the computed number is too large by a factor of a one followed by a hundred and twenty zeros (*Parallel Worlds*, ch. 1, "The Age of the Universe"). Kaku calls the gap between the computed number and the measured one "the largest mismatch in the entire history of science" (*The God Equation*, ch. 5, "Runaway Universe"). For decades physicists have looked for something that would cancel almost all of the computed energy and leave only the small amount measured. Physicists who accept the landscape of countless hollows most often explain the small number by selection instead: among

so many universes, we live in one where the energy of empty space happens to be small. I answer the puzzle in two parts. Neither part needs a cancellation or a selection.

The first part is about the enormous number. If the energy of empty space is taken as one total, the total would be the same at every place and for every comparer moving steadily, and the total would run without a break anywhere. In the theorem's sense, sameness at every place and for every comparer is symmetry made perfect, while running without a break anywhere is continuity made perfect. The Incommensuration Theorem says that no comparer, in any comparison, finds symmetry and continuity perfected together. So a comparer, in a comparison, takes in only part of the energy of empty space, never all of the energy. Whatever no comparer can ever find has no effect on anything. So the enormous total never acts on space at all. The mismatch came from setting a measurement beside something that no measurement could find, and so the mismatch never needed to be canceled.

The second part is about the small number. A comparer inside the universe does find a share of the energy of empty space. The share is the part open to a measurement made from inside empty space. I identify the cosmological constant with the share open to a measurement from inside. A piano shows the size of the share. Picture the empty space within the edge of everything whose light has reached us as a piano with an enormous number of strings. Each string stands for one independent way in which empty space holds its energy, as each string of a piano is one independent way in which the piano can sound. I count the strings out to the edge, because nothing beyond the edge has yet reached the one who measures. Nothing makes one string differ from another in what the string holds. So each string holds an equal part of the energy. Three reasons settle how many strings a comparer takes in: what is found comes in whole steps, the positions of comparison are distinct, and the one who measures is one. A comparer measuring from inside takes in three strings. One string is for each of the three positions that every act of comparison has, which Chapter Four described: the act of comparing, the thing compared, and

the thing it is compared against. I hold that each position takes in one whole string, because what is found in a comparison comes in whole, countable steps, as Chapter Four told. And each position takes in a different string, because the three positions are distinct, and none can stand in for another. A telescope and a thermometer used together still take in only three strings, because the one who measures is one place from which every finding is made. So the share is three strings' worth of the energy, out of the enormous number of strings. The strength of gravity sets the whole energy that the strings share, while the expansion of the universe has set the size of the edge, and the size of the edge sets the number of strings.

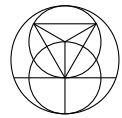
There is a second way to reckon the energy of empty space. Picture the energy of the universe as a pie. The law of the expansion of the universe comes from Einstein's theory of gravity. In a universe whose space is flat on the largest scales, as ours is, the law says that the rate of expansion and the strength of gravity together fix the size of the whole pie. The energy of empty space is one slice of the pie, and matter is nearly all the rest. The rate of expansion enters the piano reckoning and the pie reckoning of the energy of empty space in exactly the same way, and so does the strength of gravity. So when the two reckonings are set equal, the rate of expansion and the strength of gravity drop out, and what is left is one equation in plain numbers, which depends on no unit and on no measured rate. The equation fixes the slice of the pie that is matter: thirty-one point one percent. The Planck satellite was a spacecraft that mapped the glow across the whole sky. The measurements of the Planck satellite give thirty-one and a half percent, give or take seven tenths of a percent: the amount by which the measurement could reasonably be off. So the value lands: the computed thirty-one point one percent agrees with what was measured. The value comes from an equation with no number left to adjust, and I registered the value before the coming surveys, which will measure it to a thousandth. No universe was chosen to get the value.

Where We Have Arrived

We now know the answer to your question. For us there is one world, everything any path can reach, with one vacuum, and no bubbles float beside the one world. Our epoch is one of a sequence of epochs. Each epoch has the same one vacuum and the same laws, and each epoch is real in its own acts of comparison. The epochs follow one another like the cars of one train, and not like the branches of a tree. The glow is the same from every direction because the large space of our epoch formed from one end, the shared end of the interiors of the black holes of the epoch before, so no inflation is needed to explain the sameness of the glow. A long inflation is excluded, on two grounds: the first ripples are the carried form of the content, and the dark matter could not have been made after a long inflation. Many worlds is excluded as a description of the whole world taken as everything at once, fixed completely by one law. At the scope of outcomes, the words "many worlds are real" hold: for each comparer, one outcome is real, the outcome that the comparer finds. And the laws suit us without a lottery, because no rack of other universes is laid out to choose from.

Kaku has three later hopes, and all three assume many places to go and many universes to choose among: the hope of escaping a dying universe, the hope of a lifeboat to another bubble, and the hope of choosing our universe out of the landscape. In one world with one vacuum, each of the three hopes has to be asked again, as a question about what the one world holds.

In *Quantum Supremacy* (2023) Kaku hopes that a quantum computer will one day search the countless solutions of string theory and pick out our universe. Kaku writes that quantum computers "may be the final step in finding the Theory of Everything" (*Quantum Supremacy*, ch. 16, "Quantum Computers May Hold the Key"). If there is no list of universes to search, what can a quantum computer do?



Chapter Seven

The Quantum Machine

Is there anything a quantum computer cannot do?

What this chapter uses

The *road country*: whatever a road can reach is a place of the country, and a "town" that no road could ever reach is no place at all (Chapter One).

A *finding*: what one act of comparison yields, one outcome laid down as a record. *Entanglement*: the agreement found between particles that once met, which carries no message (Chapter Two).

The ten dimensions, one of time, three of space and six of possibility (Chapter Three); the rulebook, or *algebra*, of the particles (Chapter Four); the *landscape* of string theory and the one vacuum of this account, the settled state of lowest energy that empty space rests in (Chapter Six).

Michio Kaku tells us that a *quantum computer*, a computer built from the smallest pieces of matter and working by their rules, can tackle problems that ordinary computers can never solve. You may ask: if a quantum computer can do what no ordinary computer can, is there anything a quantum computer cannot do?

A Keynote at Endicott House

About fifty people met at MIT's Endicott House, in Dedham, Massachusetts, from the sixth to the eighth of May, 1981, for the first Conference on the Physics of Computation. MIT and IBM had called the meeting. Some of the fifty worked on computers and some on physics. Together the fifty asked what the laws of physics allow a computing machine to do. The physicist Charles Bennett, of IBM, photographed the group on the lawn. The physicist Richard Feynman stands in Bennett's photograph. So do the physicist Freeman Dyson and Konrad Zuse, the German engineer who built one of the first working programmable computers.

Feynman had at first turned down the invitation to give the keynote talk. He agreed when he was told that he could speak about anything he liked. He brought no written paper. The talk was recorded and written out afterward, and the written talk was published the next year under the title "Simulating Physics with Computers". Early in the talk he said plainly: "I want to talk about the problem of simulating physics with computers and I mean that in a specific way which I am going to explain". In Feynman's sense, a *simulation* is a calculation that follows a piece of the world step by step, so that the results of the calculation can be set beside what the world itself is found to do. A weather forecast is a simulation of the air.

Feynman's concern was the smallest pieces of the world. The smallest pieces obey *quantum* physics: the physics of the tiny, indivisible amounts in which energy and matter come. An ordinary computer can follow a group of the smallest pieces directly only by keeping a list of every way the pieces could turn out together. For pieces of the simplest kind, each with two possible states, the list doubles in length each time one more piece joins the group. So Feynman proposed a different machine: "Let the computer itself be built of quantum mechanical elements which obey quantum mechanical laws". Later in the talk he put the whole idea in one line: "nature isn't classical, dammit, and if you want to make a simulation

of nature, you'd better make it quantum mechanical". In Feynman's line, *classical* means the physics before the quantum, in which every piece of the world has a definite state at every moment.

The history of the quantum computer begins with Feynman's talk, and Kaku begins his story of the quantum computer there too: "In 1981, Feynman emphasized that only a quantum computer can truly simulate a quantum process" (*Quantum Supremacy*, ch. 4, "Quantum Turing Machine"). Four decades of work on quantum computers have followed from Feynman's talk. The talk leaves you a question. If a machine built of quantum parts can follow the smallest pieces of the world better than any other machine, how far can the machine follow them? Is there a place where even a quantum machine must stop?

What Michio Kaku Showed

Kaku has followed the quantum computer for most of two decades. He has reported each stage of the machine's growth with care. In *Parallel Worlds* (2005) he wrote that a quantum computer able to beat an ordinary one would need thousands to millions of atoms working together, "so quantum computing is still decades away" (*Parallel Worlds*, ch. 6, "Quantum Computing and Teleportation"). In *Physics of the Impossible* (2008) he gave the record at the time: a quantum computer had worked out three times five. He also named the obstacle to larger machines: quantum computers and quantum teleportation "share the same fatal weakness: maintaining coherence for large collections of atoms" (*Physics of the Impossible*, ch. 4, "Quantum Computers"). *Coherence* means, as Kaku explains, that the atoms of the machine are "arranged precisely so that they vibrate in unison" (*Quantum Supremacy*, ch. 1, "Speed Bumps to Quantum Computers"). Then he opened *Quantum Supremacy* (2023) with the news that two groups had announced *quantum supremacy*, the point at which a quantum computer "could decisively outperform an ordinary digital supercomputer on specific tasks" (*Quantum Supremacy*, ch. 1, opening).

Kaku states what quantum supremacy means at three strengths. The first strength is his definition of quantum supremacy, the phrase that gives his book its title. A *supercomputer* is the largest and fastest kind of ordinary computer. "Specific tasks" means particular problems, chosen one at a time.

Kaku states the second strength a few paragraphs later, in the opening of his first chapter (*Quantum Supremacy*, ch. 1, opening):

> They are a new type of computer that can tackle problems that digital computers can never solve, even with an infinite amount of time.

Kaku's example is chemistry: how atoms combine in the reactions that make life possible.

Kaku states the third of his three strengths in his fourth chapter, where he explains how a quantum computer could break the secret codes that guard the internet. In the fourth chapter he writes that "a classical computer can, in principle, compute anything that a quantum computer can compute, and vice versa", and he adds at once that "if the data is too complex it can overwhelm classical computers". In the next sentence he writes: "The key advantage of a quantum computer is time" (*Quantum Supremacy*, ch. 4, "Shor's Breakthrough").

Kaku expects that perhaps the greatest benefit of the new machine will be to simulate "hundreds of vital chemical processes" (*Quantum Supremacy*, ch. 1, "Simulation"). He writes of the repair of DNA in the body as the body ages: "Quantum computers may play a decisive role, because only a quantum system can fully explain another quantum system like molecular interactions" (*Quantum Supremacy*, ch. 13, "Digital Immortality"). In his Epilogue, at the end of the book, Kaku sets a limit on his own machine. Even a quantum computer, he writes, would need many more states than there are in the universe to simulate one protein

> molecule "without any approximation whatsoever". His conclusion is that "the smallest object that can simulate the universe is the universe itself" (*Quantum Supremacy*, Epilogue, "Universe as a Simulation").
>
> Kaku's hope for his machine belongs to one question about any computer, and the limit he sets on his machine belongs to a different question.

How Far, and How Fast

Imagine a computer set to follow a piece of the world, and two questions you could ask about that computer. The first question is how far the computer can go: how close can its results come to what the world is found to do, and does any stage of the computer ever contain what the world does? The second question is how fast the computer gets there: how many steps does the computer need for a given closeness? The first question is a question of *reach*. The second question is a question of *cost*, counted in steps, and so in time. I keep the two questions apart. I give a result of my own on the question of reach. On the question of cost, I state no result of my own.

Start with reach, and with a picture. A mosaic can follow a curve as closely as anyone likes. Make the tiles smaller, and the steps along the edge shrink, until no eye can see them. The mosaic is still made of tiles, and the curve is still not made of anything. Every simulation is like the mosaic: the simulation is the mosaic, and what the simulation follows is the curve. The reason takes two steps.

The first step is about the machine. Whatever kind a computer is, the computer runs a *program*, a finite list of instructions written in a fixed set of symbols. And at any stage of a computer's work, what the computer hands back is a finite record: so many digits, so many readings. A quantum computer, too, runs a finite program and hands back a finite record. A quantum computer's program is a finite sequence of operations

chosen from a small fixed set. A quantum computer builds every number it reports from finitely many readings at the end of the program, each reading a string of zeros and ones.

The second step is about the world. The positions and times in which everything happens vary smoothly: between any two positions, or any two times, there is always another, with no gaps. Mathematicians call a smooth range with no gaps, like the range of positions and times, a *continuum*. In 1874 the mathematician Georg Cantor proved that no list, however long it is allowed to run, can name every point of a continuum. The finite records a computer can produce can all be put into one list, first, second, third and so on without end. So there are values in the world that no stage of any computer ever holds exactly, though every one of those values can be approached.

Put the step about the machine beside the step about the world. Together, the two steps show that a simulation approaches what it simulates and never arrives. I state the result in two terms. A simulation reaches what it simulates *densely*, which means as close as one wishes, and *never exhaustively*, which means never all of it. A simulation can be refined without limit, and every refinement brings it closer; at no stage of refinement does it become what it describes. I establish that a simulation of space and time themselves, on any computer, reaches space and time densely and never exhaustively. The argument needs only two facts about the machine: the program is finite, and the record is finite. In plain words, "The limit is the same for both kinds of computer", because a quantum computer's program is a finite string of symbols and everything the quantum computer reports comes from finitely many readings.

The question of cost is a question of another kind. Computer scientists call the study of how the number of steps grows with the size of the task *computational complexity*. A count of steps is a measure of time: the time a computation must take. On a given machine, the particular program the machine runs fixes the number of steps that a given closeness needs, and computer scientists work out that number of steps with the methods of computational complexity.

Where This Account Meets Kaku

Kaku wrote two sentences on breaking codes, in his fourth chapter, and each sentence is an answer to one of the two questions, the question of reach and the question of cost. “A classical computer can, in principle, compute anything that a quantum computer can compute, and vice versa” is his answer to the question of reach. “The key advantage of a quantum computer is time” is his answer to the question of cost.

I arrive at Kaku’s sentence about reach by a route of my own. Kaku states the sentence as a plain fact. I derive the sentence from what any machine is: a finite program that hands back a finite record. My argument uses only two facts about a machine: the program is finite, and the record is finite. Both facts are true of the quantum machine and the ordinary machine alike, so the boundary of reach is the same for both machines. Kaku and this account arrive at one sentence by two separate routes.

This account also agrees with Kaku’s sentence about time. Computational complexity counts steps, and a count of steps is a measure of time. Because reach is the same for both machines, a difference between the two machines is a difference in how long they take. When Kaku says the advantage is time, he names exactly the difference in how long the two machines take.

This account agrees with Kaku again at the end of his book. In his Epilogue Kaku concludes that the smallest thing that can simulate the universe is the universe itself. He reaches his conclusion by counting: the states needed to simulate one protein exactly outnumber the states the universe has. Kaku’s count shows that the full task is too large for any machine anyone could build. I add a reason that holds even with unlimited resources: a machine with a finite program and a finite record, set against a continuum, approaches what it simulates and never arrives. Both routes end in one place: no machine carries the world inside itself. At no stage does any machine contain all that the world does.

A Faster Car on the Same Roads

Recall the road country of Chapter One, where a "town" that no road could ever reach is no place at all for the traveler, however good the car. A faster car is still a car on the roads of the road country. In the picture, a computer is a car, and each answer the computer hands back is a town. Every answer a computer hands back is a finding made in the one world (an outcome found and laid down as a record), and so every answer is a town of the road country.

A quantum computer is a faster car on the same roads as an ordinary computer. Given time enough, an ordinary computer can arrive at every town that a quantum computer arrives at. The quantum computer arrives sooner at some of the towns that both computers can reach. Which towns, and how much sooner, depends on the journey, that is, on the task. The two cars share one boundary of where they can go.

In 2019 a team at Google made the first measurement of a quantum computer's lead in time. The team built a chip called Sycamore, with fifty-three working *qubits*. A qubit is the quantum computer's unit of memory. An ordinary computer's unit, the bit, holds a zero or a one. A qubit can hold a blend of the two, and the qubit gives one or the other only when it is read. The team chose a task suited to the machine. A *circuit* is a fixed sequence of operations on the qubits. The team picked circuits at random, ran each circuit, read the qubits at the end, and ran the same circuit again and again. Each circuit was new, and each circuit was run between half a million and two and a half million times, enough to build up the pattern of answers that the circuit produces. Kaku opens his book with Google's announcement: Sycamore could solve in two hundred seconds a mathematical problem that would take ten thousand years on the world's fastest supercomputer.

A reply in 2022 shows what an advantage in time is. Programmers of ordinary computers took up Sycamore's task. In 2022 Feng Pan, Keyang Chen and Pan Zhang produced a million samples for the fifty-three-qubit

circuit of the 2019 experiment, and the three took about fifteen hours on a cluster of five hundred and twelve graphics processors, the chips first made for drawing pictures on screens. Sycamore's lead was real, and it was a lead in a race. The ordinary computers did the same task as Sycamore, and a cleverer program cut the time the ordinary computers took. In the picture, both cars made the same journey on the same roads. The cleverer program was a shorter way through the roads for the ordinary car.

We now know what quantum supremacy is: an advantage in time, on particular tasks. Every result like Sycamore's is a statement about one journey (one task) and one margin of time. I state one plain fact of counting about cost. Suppose an ordinary computer follows a group of quantum particles directly, keeping track of every way the particles could turn out together. Then the computer pays a cost that is multiplied by a fixed factor with every particle added to the group. I make no claim that a quantum computer outruns every classical method.

Where This Account Reaches a Different Result

At his second strength Kaku says that a quantum computer can tackle problems that digital computers "can never solve, even with an infinite amount of time". I reach a different result on Kaku's second strength. If an ordinary computer has unlimited time, the ordinary computer reaches whatever a quantum computer reaches, because the finite program and the finite record set the boundary of reach, and the two machines share both. Kaku's own fourth chapter agrees: a classical computer can, in principle, compute anything that a quantum computer can compute.

Some questions cannot be answered by any machine, even with unlimited time, and the limit those questions set holds for both machines alike. In 1936 the mathematician Alan Turing showed that no general procedure can decide, for every program, whether that program will ever stop. In general, there is no way to know what a program will do except by running it. Turing's result is about every program, and a quantum computer

runs a program. Where Kaku's phrase "can never solve, even with an infinite amount of time" has an exact meaning, as in Turing's result, the limit that the phrase names holds for every computer, quantum and ordinary alike, and so the limit draws no line between the two kinds of computer.

Kaku gives his principle that "only a quantum system can fully explain another quantum system" as the reason for his hope in chemistry. In his fourth chapter, after Feynman's line that nature isn't classical, Kaku writes the same principle at his second strength: "Classical digital computers, no matter how powerful, can never successfully simulate a quantum process" (*Quantum Supremacy*, ch. 4, "Birth of Nanotech"). Kaku reports, in parentheses beside his sentence on classical computers, a comparison that Bob Sutor, vice president of IBM, likes to make. A simulation *one to one* matches every part of the molecule exactly, with nothing approximated. Sutor's comparison is about caffeine, a simple molecule: an ordinary computer would need a number of bits equal to one tenth of the number of atoms that make up the Earth to simulate caffeine one to one. Sutor's figure counts the bits of memory the task needs, and so Sutor's figure belongs to the question of cost. In the same fourth chapter Kaku also writes his third strength: in principle the two kinds of computer can compute the same things, and the advantage of the quantum computer is time.

On Kaku's principle, the answer on cost differs from the answer on reach. On cost, this account agrees with Kaku, as this account agrees with his first and third strengths. I cite a proof by Seth Lloyd for the agreement on cost. In 1996 the physicist Seth Lloyd showed that a quantum computer follows any quantum system built of parts that act on their near neighbors, and does so *efficiently*, which means without the cost that multiplies with every particle. For the chemistry of molecules, Kaku looks forward to a saving of time that removes the cost multiplying with every particle. Kaku's second strength states the principle as "no matter how powerful, can never", and I reach a different result on the principle at the second strength: given unlimited time, an ordinary computer reaches whatever a quantum computer reaches. On reach there is one more answer, and the answer holds for every machine: a quantum computer follows a molecule

as closely as one wishes, and no stage of the computer is the molecule. I agree with Kaku that the molecules of chemistry are quantum systems: chemistry "is made of nothing but electrons, nuclei and light, and that is not in question". The same passage states the limit on reach: "in principle no description, however refined, contains everything that it describes".

I reach a different result on one more of Kaku's hopes. Kaku reports that string theory may have an endless range of solutions. Physicists call the range of solutions of string theory the *landscape*, as Chapter Six told. Each solution is a whole possible universe, and string theory has no rule to say which solution is ours. Kaku offers his own view: perhaps a quantum computer could survey the solutions and find our universe as the only stable one. He writes that "quantum computers may be the final step in finding the Theory of Everything", his name for one theory of all the forces of nature (*Quantum Supremacy*, ch. 16, "Quantum Computers May Hold the Key"). I find one structure for the particles (the algebra of the particles, the rulebook of Chapter Four) and one space for the six dimensions of possibility. I reach the structure and the space by two routes from different premises. The one structure and the one space together "leave nothing to select". So empty space has one state, the one vacuum, the same at every place in the world. No machine is needed to choose among universes, because on this account there is one world and nothing to choose among.

Where the Power Comes From

If a quantum computer's advantage is time, where does its saving of time come from? Kaku gives three answers. In one picture, an ordinary computer in a maze tries one path after another, while a quantum computer, a "quantum mouse", "simultaneously sniffs out all possible paths at the same time" (*Quantum Supremacy*, ch. 4, "Quantum Sum Over Paths"). In his second answer Kaku credits *entanglement*, the agreement found between quantum particles that once met, an agreement that no record of either particle alone can show. Entanglement, he writes, is "re-

sponsible for the fantastic computational ability of quantum computers" (*Quantum Supremacy*, ch. 3, "Entanglement"). And he reports the answer of the physicist David Deutsch, that the electrons are calculating in parallel universes (*Quantum Supremacy*, ch. 4, "Parallel Universes in Your Living Room").

A quantum computer is described by a body of mathematics, which I call its *formalism*: the description in which all the blended possibilities are held at once. At the end the machine hands back a *finding*: one outcome, read off and recorded as a string of zeros and ones. So, in this account, the many paths of Kaku's mouse belong to the formalism, and the answer the mouse brings back is one finding. I answer Deutsch in the same way, within one world: "A quantum computer does its work in possibility, where the alternatives interfere, and the work becomes a result in one finding, in one world".

In the rest of this section I show, with one picture of a globe, which steps of a quantum program an ordinary computer can follow cheaply and which it cannot, because that is where the quantum computer's saving of time comes from. Two proved results of quantum computing show what entanglement does in a quantum computer, and I build on both results. A quantum program is made of *gates*, the small operations a quantum computer applies to one or two qubits at a time, as an ordinary computer applies its additions and comparisons. Some gates are easy for an ordinary computer to follow, and some are not.

The states of one qubit can be drawn as the points of a globe. On the globe mark six points: the north pole, the south pole, and four points spaced evenly around the equator. Join the six points, and they are the corners of an *octahedron*, a shape like two pyramids set base to base, sitting inside the globe. The easy gates only rotate the globe so that the six corners trade places. An ordinary computer can keep track of the six corners as the corners trade places. The researchers Daniel Gottesman and Emanuel Knill proved that an ordinary computer can follow the easy

gates efficiently for any number of qubits, even when the easy gates have tied the qubits together in entanglement. So entanglement alone does not take a quantum computer beyond what an ordinary computer can follow.

The gates of the second kind are the gates that are not easy for an ordinary computer to follow. A gate of the second kind rotates the globe by one eighth of a full rotation about the axis through the poles. The one-eighth rotation carries a corner of the octahedron to a point on the globe between two corners, outside the octahedron. When one-eighth rotations are added to the easy gates, the short list of gates that results comes as near as one wishes to every point of the globe, and to every way of rotating the globe. When a state of a qubit lies off the octahedron, where the easy gates alone never bring it, physicists say that the state has *magic*. I identify magic as what lets a finite list of gates reach the whole continuum of the formalism (every point of the globe, and every way of rotating it) as close as one wishes.

Entanglement is still needed, and the researchers Richard Jozsa and Noah Linden proved why entanglement is needed. Jozsa and Linden proved their result for qubits in *pure states*, states known as completely as quantum theory allows. An ordinary computer can follow a computation on pure states efficiently whenever the computation keeps its qubits in separate groups no larger than a fixed size, with no entanglement between the groups. So a computation on pure states can outrun an ordinary computer only by entangling more and more qubits as the problem grows. I put the result of Gottesman and Knill and the result of Jozsa and Linden together. The gates of the second kind supply the magic, and entanglement carries the magic across the qubits. The amount of magic a computation holds is limited by the number of gates of the second kind that the computation uses, and not by the number of qubits those gates act on.

Even with the gates of the second kind, every simulation approaches what it simulates and never contains what it simulates. The rotations come as close as one wishes to every point of the globe. Yet the rotations a finite program makes can all be listed, and Cantor proved that no list

names every point of a continuum, so the listed rotations never fill the globe. A quantum computer gains in how few steps it needs. A quantum computer's reach toward the world stops at the same edge as every other machine's reach.

The Fragile Machine Made Steady

Kaku named the obstacle in 2008: keeping coherence for large collections of atoms. The obstacle is still the central problem in building a quantum computer. In 2023 he called the same obstacle "the trillion-dollar question": "Can we control decoherence?" (*Quantum Supremacy*, ch. 1, "Speed Bumps to Quantum Computers"). *Decoherence* is what happens when the surroundings of a qubit (a flaw in the material of the chip, a stray particle of light in the wiring) come to carry a trace of the qubit's state. The blend held by the qubit then spreads into the surroundings, and the calculation is spoiled.

The answer that physicists found to decoherence is *error correction*. In error correction the machine stores one qubit of the calculation across many physical qubits and checks the physical qubits over and over, so that the machine can find and undo a fault in a few of the physical qubits without ever reading the stored value itself. Physicists call the stored qubit a *logical qubit*. The carriers decohere, and the logical state does not. In that sentence the carriers are the physical qubits, and the logical state is the value the physical qubits store together.

The threshold theorem of quantum computing says how far error correction can go. Suppose each single operation fails less often than a certain rate, called the *threshold*, and each failure touches only a few neighboring qubits, nearly independently of the other failures. Then a calculation of any length can be carried out with as small a chance of error as one wishes, by making the code larger. The *distance* of a code is how many of its physical qubits a fault must reach before the fault can change the stored value. A larger code has a larger distance. Quantum theory sets the only limits on the distance of a code, and the limits come through the

number of physical qubits, through the strength of the *noise* (the faults that the surroundings cause), and through how far the faults are tied to one another. The account sets no ceiling of its own on the distance of a quantum error-correcting code.

A team at Google Quantum AI published the measurement of error correction below the threshold in December 2024, the year after Kaku's book appeared. The team ran codes on a chip of one hundred and five qubits and measured the rate of errors in the stored qubit as the distance of the code rose from three to five to seven. Each time the distance grew by two, the rate of errors fell by a factor of a little more than two. The largest code kept its logical qubit alive more than twice as long as the best single physical qubit on the chip. When the rate of errors falls as the code grows, the machine is working below the threshold. We now know that a larger code makes the fragile machine steady, as the threshold theorem says. Codes that grow are the answer to the weakness Kaku named in 2008.

What We Now Know

We began with Feynman on the lawn at Endicott House, asking for a machine built of quantum parts to follow the smallest pieces of the world. Machines built of quantum parts now exist, and the machines work.

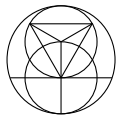
A question about what a computer can do is two questions. How far can a computer go, and how fast does it get there? On how far, the answer is the same for every machine, because every machine runs a finite program and hands back a finite record. Kaku arrives at the same boundary of reach in his fourth chapter, in his sentence on what a classical computer can compute in principle. Kaku sets a limit on exact simulation in his Epilogue, by counting. I arrive at the boundary of reach from what any machine is. On how fast, the quantum machine has the advantage on particular journeys (particular tasks), and the advantage was measured in 2019

for one of them. The race on each journey is a race in time. A quantum computer's speed comes from gates of the second kind, which an ordinary computer cannot follow cheaply.

With the two questions kept apart, you can keep everything Kaku's book promises about speed (for chemistry, for medicine, for new materials) as the hope of a faster car. You can also see where the boundary lies for every car. On the journeys where a quantum computer has the advantage, the quantum computer will follow a molecule sooner than an ordinary computer can, and at no stage will the quantum computer hold the molecule inside itself. A quantum computer will report what it finds as one outcome at a time, in the one world it runs in.

Any machine, quantum or classical, approaches what it simulates as closely as one wishes and never contains what it simulates, while a quantum computer's advantage is in time, on particular tasks.

If no machine can hold the world inside itself, can anything carry us out of a dying universe?



Chapter Eight

When the Stars Go Out

Is there any way out, and does anything last?

What this chapter uses

Comparison: setting one thing beside another and telling them apart; every measurement and every thought is an act of comparison (Preface and Chapter One). The *road country*: the country is the one world, everything any path can reach (Chapter One).

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. In the theorem's sense, *symmetry* is a sameness of content where there is a difference of context, the same thing found in different settings, as the same law is found in one city and the next; *continuity* is a sameness of content where there is a sameness of context, changing without a break, as a ramp rises with no step anywhere. In the physicists' sense, a symmetry is a change that leaves a thing the same (Chapter One).

The ten dimensions: one of time, three of space, and six of possibility, the dimensions of what can happen at each place, present everywhere and traveled by nothing (Chapter Three). The three axioms, and the three positions of every comparison (Chapter Four).

An *epoch*: one long era in which stars, galaxies and black holes form; the *large space*, the space in which the stars and the galaxies lie; the *turn*, the passage from one epoch to the next; and the one *vacuum*, the one settled state of empty space (Chapter Six).

In three of his books Michio Kaku asks whether a civilization could escape a dying universe, once every star goes out and the universe freezes, and in *Parallel Worlds* his answer is a plan of escape in eleven steps; behind the plan stands a second question, whether anything we are or do lasts.

New York, Autumn 1978

In the autumn of 1978 the physicist Freeman Dyson came to New York University to give four lectures. The four lectures were the James Arthur Lectures on Time and its Mysteries. Dyson came from the Institute for Advanced Study in Princeton. Dyson opened the first lecture with a book. A year earlier the physicist Steven Weinberg had published *The First Three Minutes*, a book for general readers about how the universe began. Near the end of *The First Three Minutes*, Weinberg turned from the beginning of the universe to its far future, and he summed up the far future in one sentence: "The more the universe seems comprehensible, the more it also seems pointless". Dyson quoted Weinberg's sentence and answered Weinberg in one line of his own: "If Weinberg is speaking for the twentieth century, I prefer the eighteenth".

Dyson then set out the view of the far future that he was answering: on that view, as Dyson put it, "we have 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 gives way to a collapse. An *open* universe is a universe that expands forever. Dyson favored the open universe, and he asked three questions about it. Does an open universe freeze into a permanent quiet? Can life and intelligence survive in an open universe forever? Can societies keep sending messages to one another across the ever greater distances of an open universe? "Tentatively", Dyson said, "I shall answer them with a no, a yes, and a maybe". The lectures were printed in 1979 in the journal *Reviews of Modern Physics*, under the title "Time without end".

Dyson's yes to the second question, whether life and intelligence can survive in an open universe forever, rested on two strategies. A thinker could run colder and think more slowly, spending less energy on each thought. A thinker could also think in bursts, sleeping between the bursts. Dyson called thinking in bursts *hibernation*: a life spent mostly asleep,

waking only for short stretches of thought. By Dyson's reckoning, a society that ran colder and also hibernated could think forever on a finite store of energy.

What Michio Kaku Showed

Kaku tells the end of the universe in three books: *Hyperspace* (1994), *Parallel Worlds* (2005) and *Physics of the Impossible* (2008). Kaku tells the story vividly and fairly, and he takes the far future seriously.

In *Parallel Worlds* Kaku starts from a measurement: the expansion of the universe is speeding up. Kaku follows the speeding up forward in time. He states one condition: that the speeding up continues for billions or trillions of years. On Kaku's condition the other *galaxies*, the great wheels of billions of stars, are carried away from us faster and faster. In the end the other galaxies pass beyond our *horizon*, the farthest distance from which any signal can ever reach us. The stars burn out. Temperatures fall toward *absolute zero*, the coldest anything can be. Kaku calls the frozen end of the universe the *big freeze*, and he states plainly what the big freeze means for us: "intelligent species will have to face their ultimate fate: freezing to death" (*Parallel Worlds*, ch. 10, opening).

Kaku then tells of Dyson's hope, and of the reply that the physicists Lawrence Krauss and Glenn Starkman gave to Dyson's hope. About twenty years after Dyson's lectures, Krauss and Starkman worked out what would become of Dyson's plan in a universe whose expansion speeds up. Krauss and Starkman found that where the expansion speeds up, empty space never cools below a faint floor of temperature, and a thinker with a finite store of energy can do only a finite amount of thinking. Kaku sets Dyson's hope beside the reply of Krauss and Starkman, and for a universe like ours, whose expansion speeds up, he gives his verdict: "All intelligent life is doomed to perish" (*Parallel Worlds*, ch.

10, "Can Intelligence Survive?"). Kaku also defines death in a way of his own: "Death can be defined as the final cessation of all information processing" (*Parallel Worlds*, ch. 10, "Leaving the Universe").

If staying means death, Kaku asks, could a civilization leave? Kaku asks for a demonstration that the laws of physics would allow the escape, for a civilization advanced enough to attempt the escape: "Physicists want a 'proof of principle'", he writes (*Parallel Worlds*, ch. 11, opening). Kaku leaves one question to civilizations billions of years in the future. The question is whether a civilization has enough resources to build the machines that an escape would need. In his words, the question of resources is "a lesser, practical detail".

Kaku's plan of escape comes in eleven steps. First, complete a *theory of everything*: one theory joining gravity and the quantum, the physics of the very small, and then use the theory of everything to learn whether a passage to another universe would hold. Search the sky for natural passages. A *black hole* is a region where matter is packed so densely that nothing, not even light, gets back out of the region. Send probes into a black hole, and then build a black hole slowly. The aim is to study the passage that Kaku hopes lies at the center of a spinning black hole. Make a *baby universe*: a tiny region squeezed and heated until the region swells into a universe of its own. The baby universe would be joined to ours by a thin tunnel. Build atom smashers the size of solar systems, and banks of lasers on moons and asteroids that fire at once onto one point, to reach the energies at which, Kaku says, space and time themselves become unstable. Travel between the stars by *warp drive*: a ship that would shrink the space ahead of it and stretch the space behind it. A warp-drive ship cannot leave the universe, Kaku notes. But a warp-drive ship could help build a machine that might leave the universe. Gather *negative energy*, which is needed to hold a passage open: a state of a *field* (something spread through space with a value at every point) with less energy than empty space. And wait, with slowed minds, for a passage to open by chance. Most of the passages in Kaku's plan are

some kind of *wormhole*: a shape of space and time, allowed by Einstein's equations of gravity, in which a short tunnel joins two places that are otherwise far apart.

Kaku calls the eleventh step "The Last Hope". Suppose every passage that can be made is far too small or too violent for any body to survive. Then, Kaku writes, a civilization would have one option left: "to inject enough information into a new universe to recreate our civilization on the other side of the wormhole" (*Parallel Worlds*, ch. 11, "Step Eleven: The Last Hope"). The civilization would send a seed, a small package carrying the information, as an oak sends an acorn. On the far side of the wormhole the seed would build a tiny machine, and the machine would find a planet, where new people would be grown, with the memories and personalities of the old civilization placed in the brains of the new people. Kaku calls the seed a "cosmic egg", and he closes on the point of the whole plan: "My point is that the ultimate death of our universe may not necessarily mean the death of intelligence" (same section).

In *Hyperspace* Kaku offers an escape of another kind. In 1994 physicists did not yet know how the universe would end. The universe might freeze, or the universe might fall back on itself in a final collapse, which Kaku calls the *Big Crunch*. For the case of a collapse, Kaku looks to six further *dimensions*, directions beyond the three of space and the one of time. The six further dimensions belong to *string theory*, the theory in which every particle is a tiny vibrating string. String theory needs ten dimensions in all. Kaku reports calculations in which the four familiar dimensions grew at the expense of the other six, just after the beginning of the universe, so the fates of the four and the six are linked. Kaku uses the word hyperspace for a space of more dimensions than our three. If the calculations Kaku reports are correct, he suggests, the six might open as the four collapse. The way out, in his words, would then be to "escape via hyperspace", "making an escape hatch possible for any intelligent beings smart enough to calculate the dynamics of space-time" (*Hyperspace*, ch. 14, "Escape Through a Higher Dimension").

> In *Physics of the Impossible* Kaku puts the whole matter in one sentence: "The laws of physics are a death warrant for all intelligent life, but there is an escape clause in those laws" (*Physics of the Impossible*, ch. 13, "Contact Between Universes?").
>
> The first half of this chapter's question is whether there is any way out for us. Kaku's answer to the first half is a hopeful yes: the universe dies, and a civilization advanced enough might leave the dying universe, in body or at least as a message. The second half is whether anything we are or do lasts, and Kaku's answer to the second half follows from his first answer: what lasts is whatever makes the journey out of the dying universe.

Where This Account Reaches the Same Result

I reach several of Kaku's results on the far future on ground of my own. My ground is comparison. Every measurement is an act of comparison, and so is every thought.

The first result that Kaku and I share is the emptying of the sky. In the autumn of 1997 Adam Riess was working through the measurements of distant exploding stars for the team led by Brian Schmidt. Riess found the distant explosions too faint for a universe whose expansion was slowing down. A second team, led by Saul Perlmutter, measured forty-two distant exploding stars and found them too faint as well. We now know from the measurements of the two teams that the expansion of the universe is speeding up, and I follow the speeding up forward in time, as Kaku does. Our own small group of galaxies is held together by gravity. Every galaxy beyond our group is carried out of reach. In 2007 Lawrence Krauss and the physicist Robert Scherrer calculated the speeding expansion forward in time, and they found every galaxy beyond our own group carried past our horizon within about a hundred billion years. I give a hundred billion to a trillion years for the emptying of the sky beyond our group, and the

figure of Krauss and Scherrer, about a hundred billion years, is the near end of the span I give. The stars of our group then burn out, and their remains end inside black holes or drift apart.

I also find that the emptying is the course our epoch takes. Our epoch does not end in a final collapse. The space of our epoch is *flat*, with no overall bend at the scale of the whole sky, and the energy of empty space, which drives the speeding up, is a positive amount, one number for all of our epoch's time. The rate of the expansion is set by three shares added together: one from the matter, one from the bend of space, and one from the energy of empty space. In a flat space the share from the bend is zero, the share from the matter is never less than zero, and the share from the energy of empty space is positive and stays the same while the matter thins out. So the sum never falls to zero, and neither does the rate of the expansion, whatever the amount of matter: more matter only adds to a sum that is already positive. Gravity holds the expansion back, and gravity never stops the expansion. The long, cold emptying happens in this account too. From inside our epoch, the long, cold emptying is the true view of the far future.

The second result that Kaku and I share is about the thinker. Kaku, following Krauss and Starkman, holds that no thinker who stays in our universe goes on thinking forever. I agree, on a different ground. A thought is a finding: one comparison, made against something actually there outside the thinker, and kept as a record in a lasting structure of the thinker's own. Every thinker belongs to some structure that gravity holds together: a planet, a star or a galaxy. The emptying leaves every thinker at one of two ends. Either the thinker falls into a black hole and comes to the end of the hole's inside, or the thinker is left alone while everything else passes beyond the thinker's horizon. Inside a black hole the way inward is the way forward in time, and every path inside the hole runs to an end: a limit that the path approaches and never passes through. At either end, nothing is left outside the thinker for the thinker to compare against. The *six dimensions of possibility* are the six further dimensions of this account: as Chapter Three showed, they are the dimensions of what can happen at

each place, present everywhere and traveled by nothing. In our epoch matter takes the forms of atoms, molecules and cells, and those forms depend on the shape of the six dimensions of possibility. The six keep their shape only while a large space is there around them, with things in it to compare against, and at either end no large space is left around the thinker. So at either end the thinker also loses the forms of matter, the atoms, molecules and cells, in which the thinker compares and keeps records. My conclusion that no thinker thinks forever does not use the size of the thinker's store of energy, the thinker's temperature or the speed at which the thinker thinks. Krauss and Starkman reached the same conclusion from a finite store of energy and a floor of temperature. I reach the conclusion without either.

The third result that Kaku and I share is the one Kaku saw as an escape hatch: the trade between three dimensions and six, in which one set shrinks while the other set grows. I find the same trade by a route of my own. An *exact solution* is a history of space and time that Einstein's equations allow exactly, with nothing approximated. When Einstein's equations are written for all ten dimensions, they have an exact solution near the end of the inside of a black hole, on which the three directions of space shrink while the six grow. Imagine everything around you, the street, the buildings and the sky above them, shrinking in length, width and height together, while the six dimensions of possibility, present at every point of the shrinking space, grow in their extent. Now run the picture backward, like a film: space opens out in three directions while the six close in, and the film shows the history of a large space like ours coming to be, at the beginning of an epoch. The trade of three and six works like a seesaw: when one side goes down, the other side goes up. The seesaw tips one way inside each black hole and tips back at the beginning of each epoch. This account has the seesaw, as Kaku's calculations do. I part from Kaku on where the seesaw tips and on what the tipping leads to.

Where This Account Reaches a Different Result

Kaku's plan rests on three things: that the universe ends in a final cold dark; that there is another universe that a passage can reach; and that something of us, a body, a seed or at least a message, can cross into another universe as itself. On each of the three, I reach a different result.

The long emptying ends in a turn to a new epoch, not in a final dark. The turn begins where the insides of the black holes of an epoch end. The insides end at the limit that every path inside a black hole approaches and none passes through. The insides of all the black holes of the epoch end in one end, because the ends cannot be told apart by any comparison. Three grounds show that the cold dark at the end of the emptying cannot be final.

The first ground is that content cannot be without a context. Picture a thermometer that compares this morning's warmth with this evening's. The temperature that the thermometer finds is the *content* of the comparison, what is found, while the two times of day are the *context* of the comparison, the respect in which the temperature is found. A temperature can be found only at some time and at some place. The *third axiom*, which I gave in Chapter Four, holds of the three positions of comparison and of the pairs of ideas that fill the positions, and content and context are one such pair: so content and context are distinct and inseparable, and there is no content without a context in which it is content. At the end of the emptying, the black holes still hold the matter and light that fell into them. So there is still content. No large space is left around the matter and light to be their context, so a context must form again. Physics has two descriptions: Einstein's smooth description of gravity, and the quantum description of the very small. At the end of the inside of a black hole, space and time bend so sharply that both descriptions come to the limit of what they can describe. The descriptions stop at the end of the inside. Yet the matter is still there, and so is the shape of space and time. The content therefore remains at the end, together with the geometry of all ten dimen-

sions, the shape of space and time itself. So the new context forms from the geometry of the ten dimensions, the one remaining thing that can be a context. The seesaw of three and six tips back: the six close in, three directions of space open out, and a new large space begins.

The second ground is the Incommensuration Theorem, in the senses that the box at the head of this chapter recalls. As I said in Chapter One, the word "fundamentally" in the theorem means at the foundation of a comparison, exactly and not approximately: the things we find show symmetry and continuity together all the time, approximately, and never both perfect at once. The theorem holds wherever a comparison is made, and so it holds for every measurement, because every measurement is a comparison. Now picture the *heat death*: the end that popular writing on the universe foresees, in which everything has one temperature and nothing ever happens again. Take the heat death all the way: a final state of featureless emptiness, the same everywhere and at every moment, with no break anywhere. A final featureless emptiness would have perfect symmetry and perfect continuity, in the theorem's sense, at once. The emptiness would be the same in every place and at every moment, which is perfect symmetry. The emptiness would also have no break anywhere, which is perfect continuity. Perfect symmetry with perfect continuity is the one character no comparison ever finds, so the emptying cannot come to rest in a featureless emptiness.

The third ground is about *entropy*. The fear of a heat death depends on entropy rising without end. An entropy is a count of the arrangements of a thing's parts that leave the thing looking the same from where the thing is seen. Take the molecules in a cup of coffee, for example. The molecules can be arranged in a great many ways that all leave the cup looking the same to you. So an entropy is always a count made against a context: change the context, and you change what is counted. Within our epoch the count rises, as the laws of heat say it must: the cup cools, the ice melts, and neither goes back. An epoch's entropy tends toward a largest value. The largest value is counted against the epoch's own large space and the things in the large space. When the epoch's large space has emptied, the

count has nothing left to be counted against. The heat death is a final maximum of entropy that holds forever. So the heat death has no context in which to be counted, while the next epoch begins its own count against its own context.

Each of the three grounds shows on its own that the dark cannot be final, and the three grounds come from three different places: the first from the third axiom, the second from the Incommensuration Theorem, the third from what an entropy is. Kaku takes the faster expansion as the reason that all intelligent life must perish, but the faster expansion goes on carrying the galaxies apart in the space between the black holes. Black holes still form, and their insides still reach the one end, so the faster expansion does not stop the turn. I identify the opening of the new large space with the Big Bang of the new epoch. Each epoch begins its own count of entropy. In this way the epochs follow one another like the cars of one train, each car coupled to the car before it, in place of a single arc from a Big Bang to a heat death.

Every road stays in the country. The second thing Kaku's plan needs is a place to go. In the picture, a road is any path that a signal or a traveler can take. The country is the one world, everything any path can reach. Space is the pattern of which events a signal can join. So if a path from here can reach a region, through a wormhole, a warp drive or any engine at all, then the region belongs, by being reachable, to the same pattern as the place the path set out from. Every region a path from here can reach is therefore a region of our own epoch, in the one world, which is everything any path can reach. A journey to another universe can end in one of two ways: if the journey arrives, it arrives somewhere in our own epoch, and if no journey could ever arrive, there is nowhere to go.

Most of Kaku's steps are new ways of traveling in the road country. I answer each of the steps. In one step a traveler goes down through a black hole. I agree with Kaku that the edge of a black hole, its horizon, is crossed one way only, and that nothing returns across the horizon. The traveler reaches the end of the hole's inside. The turn begins at the end of the inside, and no body arrives at the end as a body. In other steps a civil-

ization builds new roads and faster cars: the wormhole, the baby universe, the warp drive. Wherever a new road or a faster car arrives, it arrives at a town of the same country, and in the same way, wherever a wormhole, a baby universe or a warp drive takes a traveler, the traveler arrives in our own one world. Kaku's baby universe begins from a state of empty space that could drop to a lower state. In this account empty space has one settled state, the one *vacuum*, and no second. So a baby universe that a civilization makes has no lower state of empty space to drop into. The baby universe stays a region of our own epoch. In one step a civilization waits by the roadside for a gateway to open, and the civilization waits until its epoch comes to an end. In his first step Kaku asks for a theory, the theory of everything, but a better theory describes more exactly every path there is, and a better theory describes no path that is not there.

The seesaw of three and six tips at the end of the inside of each black hole, where one epoch gives way to the next, and nothing passes from one epoch into the next through the trade of three and six. A comparer, anyone or anything that compares, travels through space from here to there, and never through the six dimensions of possibility: you can walk to the next room, and you cannot walk to the outcome that did not happen.

Over the longest time the one world itself, the whole road country, comes to the turn, and the next epoch begins at the turn. No road leads out of the road country into the next epoch. Two things join the next epoch to ours: the same law, which holds again in each epoch, and the form of everything that fell into our epoch's black holes, which crosses the turn averaged into one. The road country shows one reason that no journey runs from our epoch into the next: whatever a path can reach belongs to our own world. There are two more reasons, each on ground of its own. The first of the two further reasons is the turn itself. No signal ever gets out from the end of the inside of a black hole to the space outside the hole, so the end of the inside lies at no moment of our time, earlier, now or later. The next epoch begins at the end of the inside, so no path runs from any place in our epoch to any place in the next epoch. The second further reason is the argument that Chapter Six gave against an ocean of bubble uni-

verses, applied to the epochs, and the second reason does not depend on the turn at all. No single comparison can contain every epoch as one whole. Containing every epoch as one whole would require a comparison to do two things perfectly at once: count every epoch as belonging to the whole in exactly the same sense, and join every epoch to every other, with no epoch cut off. Symmetry made perfect, in the theorem's sense, is counting every epoch in exactly the same sense. Continuity made perfect is joining every epoch to every other. By the Incommensuration Theorem, symmetry and continuity cannot both be applied, simultaneously and fundamentally, to any comparison. So each epoch is whole and complete from inside, and no journey links any two epochs.

Every thing stays on this side of the turn, as the thing it was. The third thing Kaku's plan needs is something of us that crosses. Follow a traveler who sets out to cross. The traveler's path ends in one of two ways, as the thinker's did: at the end of the inside of a black hole, or in a drift into emptiness alone. At either end no large space is left around the traveler, so the six dimensions of possibility lose the shape that the forms of matter depend on, and the forms that make a body a body come to an end. Nothing of the old large space crosses the turn: no length, no shape and no field of matter. So no body crosses as a body, whether an astronaut in a shielded craft, a probe or the tiny machine of Kaku's last hope.

But, you may ask, what about the seed? In Kaku's last hope a civilization sends information in place of bodies. The word *information* needs a second look, because physics uses the word for two different things. Think of a handwritten letter in a post office. What the letter says belongs to the letter and goes wherever the letter goes: which words were chosen, and in which order. The office's sorting machine reads only the zip code. For each bin, the office can count how many letters lie in the bin looking alike to the machine. The count belongs to the office, and when the office closes, the office's counts have nothing left to be counts of. In the picture, the letter stands for the matter, and the office stands for the large space against which the matter is counted. In the first sense, information is the *form of*

the content: what the matter is, and which alternatives it has taken. In the second sense, information is a count made against a context, which is what an entropy is.

In the first sense, something of the seed does cross. If the seed falls into a black hole, the form of the seed's content is carried to the turn. The form is not destroyed. As a message, the seed does not cross. A message is a record: marks drawn in our epoch, made to be read by someone who can tell those marks apart. Every record and every mark of our epoch stays in our epoch, and every act of comparison lies on one side of the turn, so a finding made in our epoch is never set beside a finding of the next epoch. No identity crosses the turn either. Suppose someone wanted to find that something in the next epoch is the same person, the same civilization or the same message as something in ours. The person would have to compare the two things across the turn, and no one ever makes a comparison across the turn. The people of Kaku's last hope would not be in the seed in any case. A device can carry a description of a person, and the description is a map of the person: the person is not in the map. A person is not a very large file.

What Crosses, and What Returns

The form of the content crosses the turn: the form of the content of everything that ends inside the black holes of an epoch. Each black hole took in its own matter. Each black hole carries the form of its own content to the turn. At the turn the form of one hole cannot be told from the form of another by any comparison. So the forms cross as one form, with no mark of which black hole each 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 you cannot pick out any one voice in the roar. The form of the content crosses the turn in the same way. The share of every black hole goes in, averaged, and no share can be picked out.

Astronomers have measured an averaged pattern, like the stadium's roar, in our own sky. In 1992 George Smoot and his colleagues reported that the afterglow of the Big Bang is not perfectly even across the sky, working from the maps of the satellite called the Cosmic Background Explorer. Astronomers call the afterglow the *microwave background*: the oldest light that reaches us, the faint warmth from every direction left from our epoch's early years. The temperature of the microwave background differs from place to place by about one part in a hundred thousand, and every later map shows the same faint pattern in finer detail. The galaxies of our epoch grew by gravity from the small unevennesses of the microwave background. I identify the faint pattern of the microwave background with the form of the content of the epoch before ours, which was carried through the turn and averaged into one. So the faint pattern is how anyone can know that there was an epoch before ours, though no record crosses the turn, and Appendix A names the coming measurements that bear on the turn.

Kaku ends his last hope with a cosmic egg, and this account has a cosmic egg too. The cosmic egg of this account is the one averaged form of everything an epoch's black holes took in: the seed from which the next epoch's galaxies, its stars and in time its watchers grow. The cosmic egg of this account carries the form of the content of everything that fell into the black holes. The egg carries the instructions of no one.

The law returns as well, and no one carries the law across the turn. On the far side of every turn, the structure that I derive holds again: ten dimensions, the six of possibility with the same shape in every epoch, one vacuum, the same law.

What We Now Know

Go back to New York, to the autumn of 1978. Dyson wanted a universe in which thinking does not end. Krauss and Starkman answered that no thinker of ours goes on forever, and Kaku agreed and looked for a way out of the universe. I agree with Krauss, Starkman and Kaku about the

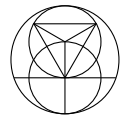
thinker, and I keep something of Dyson's hope by another route: thinking goes on. In each epoch that follows, comparison begins again, under the same law, but the thinking of the next epoch continues no thinker of this epoch.

In this account, we now know what the far future holds. The sky empties, and every thinker of our epoch comes to an end, just as Kaku says. The dark that follows the emptying ends in a turn, on three grounds. Content cannot be without a context, so a context forms again. A featureless emptiness has "the one character no comparison ever finds", so the emptying cannot come to rest. Every count of entropy belongs to the context it was made against, so no final count holds forever. Whatever a path from here reaches is a region of our own epoch, so no path leads to another universe. Nothing of us crosses as itself: no body, no message, no identity and no person.

Kaku asked how a civilization might be rescued from the dark. In this account the far future needs no rescue: what comes after our sky is the next epoch, under the same law, seeded by the form of the content of our own epoch.

The long emptying ends in a turn to a new epoch, and nothing escapes as itself. What crosses the turn is the form of the content, as one averaged form. The same law holds again on the far side, and the law is not carried across.

If nothing of us crosses as itself, and the far future needs no rescue from us, then what do we hold now, and what is ours to do?



Chapter Nine

Where Every Road Arrives

What do I hold now, and what is mine to do?

Through eight chapters you have walked with Michio Kaku to the far edges of physics: to time machines, to other universes, and out to the last of the stars. Now you may ask: what do I hold now, after the walk, and what is mine to do?

The Earth Comes Up

On 24 December 1968, three men were going around the Moon. The three men were Frank Borman, James Lovell and William Anders, the crew of Apollo 8. Apollo 8 was the first spacecraft with people aboard to travel around the Moon. The craft passed about one hundred and ten kilometers above the Moon's surface. On each pass the craft went behind the Moon, out of sight of the Earth. On the fourth pass, as the craft came out from behind the Moon, Borman began to turn the craft, and as the craft turned, the Earth rose into view over the Moon's edge. The Earth had risen on each of the three passes before. But on the first three passes no window of the craft had faced the Earth.

Anders was at the right side window, photographing the Moon below, when he saw the Earth. Anders's words are on NASA's transcript of the craft's onboard tape: "Oh my God, look at that picture over there! There's the Earth comin' up. Wow, is that pretty!" Anders took a photograph in black and white. Then he asked for color film. Lovell found a roll of color

film and handed the roll to Anders. Anders took the color photographs that people everywhere now know as *Earthrise*. In the best known of the color photographs, the gray surface of the Moon lies across the front of the picture, while beyond the Moon's surface the Earth, blue and white and partly in shadow, hangs in black space.

Later, Anders put what the crew had found into one sentence: "We came all this way to explore the Moon, and the most important thing is that we discovered the Earth". In his books Kaku takes his reader as far out as physics can imagine. I have followed Kaku's books the whole way, taking up his questions one at a time. At the end of this book, as at the end of Apollo 8's journey, we find the place we set out from, seen whole.

How Kaku Ends

Kaku ends his books by turning back to us, his readers. In *Hyperspace* (1994) Kaku takes his reader through the birth and the fate of the universe, and then, at the close of the book, he reminds his reader where the atoms in our bodies were made. The atoms in our bodies were made inside stars that exploded long before the solar system was born, and so, in Kaku's words, "We are literally made of star dust" (*Hyperspace*, ch. 15, "Our Role in Nature").

Parallel Worlds (2005) is a whole book on other universes and on the death of our own universe. At the close of the book, Kaku turns to the people now alive. He uses a ladder proposed by the Russian physicist Nikolai Kardashev. Kardashev's ladder ranks each civilization by how much energy the civilization can command. Kaku describes the first rung of the ladder: "A type I civilization is one that has harnessed planetary forms of energy" (*Parallel Worlds*, ch. 11, "Type I, II, and III Civilizations"). A type I civilization can use all the sunlight that falls on its planet. Kaku says that we are alive to witness the passage to the first rung, which he calls perhaps the most momentous, and also dangerous, transition in human history. He writes that we are passing "from being passive observers to the dance of nature to becoming choreographers of

the dance of nature" (ch. 12, "Transition to Type I Civilization"). He adds that with the power to shape nature comes a great responsibility. He says where he finds meaning: "For me, the real meaning in life is that we create our own meaning" (ch. 12, "Creating Our Own Meaning"). And he ends *Parallel Worlds* with three short sentences:

> The choice is ours. This is the legacy of the generation now alive. This is our destiny.

Kaku's three sentences are the last words on the last page of *Parallel Worlds* (ch. 12, "Transition to Type I Civilization"). Kaku's ending is a warm one. Kaku has spent a whole book among the stars and other universes. At the end he comes home: he speaks to his reader about the reader's own life.

What the Walk Has Given You

Everything in this book is worked out from one act, which you perform every waking moment: *comparison*, setting one thing beside another and telling the two apart. Every measurement is an act of comparison, and so is every look and every thought. On the walk through this book we took Kaku's questions one at a time, and we asked each question again, starting from comparison.

We began the walk with the word "impossible". In *Physics of the Impossible* (2008) Kaku sorts impossible things into three classes. Class I things might be possible in this century or perhaps the next. Class II things might be realized thousands to millions of years from now, "if they are possible at all". Class III things break the laws of physics as we know them. We found that the word "impossible" says two different things. In the first sense, the word "impossible" is a verdict that can change, because a thing not yet built waits on knowledge and power, and the laws as we know them can change. In the second sense, the word "impossible" is said of a request that names nothing, like a walk north of the North Pole. A re-

quest that names nothing is excluded by the shape of the thing the request asks about (on the globe, north ends at the Pole), and so the request is excluded in principle, and therefore in all future practice. We pictured a country where the only way to travel is by road, and we called the country the road country. A town that no road has reached yet is a place of the country that waits on a road, but a "town" that no road could ever reach is no place at all for the traveler. The first town is the picture of a thing not yet built. The second "town" is the picture of a request that names nothing. Kaku's three classes gave you a way to sort the impossible. I add the kind of impossible that no length of time can change: a request that names nothing. I also show you the reason that the request names nothing.

Next we took up Kaku's most famous wonders: a message sent faster than light, and a journey back into one's own past. The *light cone* of a happening is everything that the happening can affect: when a firework bursts, the light cone of the burst is every place and moment on or inside the growing sphere of the burst's light. We found that two of Kaku's wonders are requests that name nothing: a message that arrives outside the light cone of its sending, and a return to one's own past as the past was. "Time travel" names no concept, in the sense in which the phrase is used: a journey into one's own past, to an earlier occasion as it was. A *finding* is what one act of comparison yields: one outcome, laid down as a record. A loop in time brings the traveler to a later finding, not back to the earlier occasion. So the past as it was is not a place where a traveler can arrive. A *wormhole* is a tunnel through space joining two distant places. A *warp drive* is a region of space that carries a ship along inside the region. A wormhole or a warp drive would be a shortcut within the one shape of space and time. A traveler who takes a shortcut arrives sooner than by the long way around, but still inside the light cone of the traveler's departure. In the road country, a wormhole is a new road and a warp drive is a faster car, so each brings the traveler to a town of the same country, after the traveler set out. A wormhole or a warp drive still needs *negative energy*, an amount of energy below the energy of empty space, but I make no claim

either way on whether negative energy exists in the needed amount. Kaku placed the time machine in his Class II. In this book I have shown you the reason that the past is not a destination at all.

With *Hyperspace* Kaku made ten dimensions famous, and with them his word *hyperspace*: a space with more dimensions than the three we see. A *dimension* is an independent way in which two things can differ. This account also has ten dimensions: one of time, three of space, and six of possibility. The count of ten comes from what every act of comparison must contain. The six dimensions of possibility are the range of what can be found at each place. Nothing travels through the six dimensions of possibility. This account uses the six dimensions of possibility in two ways. When the six are taken as a pattern, with no size, the pattern is where we read the kinds of particle. When the six are present at every point of the four dimensions of time and space, and kept finite there, I call the six *held*. Taken as held, the six have a definite extent, and the strength of gravity is tied to that extent. The *dark matter* is the unseen matter whose weight holds the galaxies together. In this account the dark matter is a lasting vibration of the six dimensions of possibility. In *Hyperspace* Kaku offered the further dimensions as a possible refuge, a room that might one day open for intelligent life to flee into at the death of the universe. In this book I have shown you the six dimensions of possibility as present wherever you are.

In *The God Equation* (2021) Kaku tells the story of the search for one *equation* (a statement in symbols that two quantities are equal) from which every force would follow, an equation that Einstein hoped might be no more than an inch long. We found one world, which is everything any path can reach, and the one world is held together with no single equation. The *quantum* is the physics of the very small. Gravity and the quantum are two descriptions of one world, joined side by side and never merged. The three forces of the particles are inseparable and distinct: because the forces are inseparable, their strengths draw close, and because the forces are distinct, the forces never become one force. The particles themselves come from one structure: what every act of comparison must

contain. Kaku's books hope for one equation; the unity I have shown you is of another kind, in which each part keeps its own character: two descriptions joined side by side, three forces inseparable and distinct, and one structure for the particles.

Kaku's candidate for the one equation is *string theory*, in which every particle is a tiny vibrating string. Kaku wrote that if string theory could calculate the *constants* of nature from first principles, without any assumptions, then the calculation would, in his opinion, prove string theory correct. The constants are the fixed numbers, such as the mass of the electron, that the laws use and that physicists find by measurement. To calculate the constants *from first principles* is to calculate the constants from the theory's own starting points alone. The *Standard Model* is the theory of the particles of matter and of the forces among the particles. When the numbers of the *neutrinos*, the lightest particles of matter, are counted in, the Standard Model has twenty-six constants. A number's *standing* is the way the number stands toward the world: where the number's value comes from. We found that each of the twenty-six constants has its standing, or else has two answers carried side by side. There are four standings, and each rests on the *structure*, what every act of comparison must contain. The first standing is set by the structure. Some of the twenty-six constants are set by the structure in part. The *muon* is a heavier cousin of the electron. The structure sets the mass of the muon at the first, simplest level of the calculation of that mass. The second standing is set by the structure once a stated step is taken. In the step, I take something in the structure to be a quantity of the world. The third standing is measured. Four of the twenty-six constants are measured. I argue that no argument from the structure supplies two of the four measured constants: the electron's mass and the strength of light (how strongly light acts on electric charge). In the fourth standing, a number is measured, with its reason still a question. Many constants agree with their measured values while the reason for each value is still a question, like the masses of the *quarks* (the particles that make up the proton and the neutron). Each number of the fourth standing is written with its question beside the number. The seven num-

bers of the neutrinos stand at a *fork*: two arguments for each of the seven are carried side by side, until a measurement shows which of the two arguments is right. Kaku hoped that a derivation of the constants would prove string theory correct. We found instead that measurement validates the derived numbers strand by strand, because deriving the constants proves that the constants follow from a theory's premises, and measurement shows whether the constants hold of the world. A theory holds as a cable holds, strand by strand, and each strand is an argument from an independent source, so a mistake in one argument does not make the other arguments wrong. A number derived by the theory is one strand. In this book I have shown you a way to hold each number of nature at the number's own standing, or at the number's fork.

In *Parallel Worlds* Kaku writes that our universe may be one bubble among countless others. We found one world, with one *vacuum* (the one lowest state that empty space settles into), and so with no range of rival universes from which our universe could have been picked. In 1957 the physicist Hugh Everett proposed that every possibility of the quantum happens, each in its own branch of the world. The many worlds of Everett's account are real in one exact sense: for each *comparer* (anything that compares and registers what it finds), one outcome of each comparison is real. Our *epoch* is the long era that runs from our Big Bang, the hot, dense beginning that we find when we trace our history backward, to a *turn*, the passage into the next epoch. The epochs follow one another like the cars of one train, coupled at the turns, and not like the branches of a tree. So the epochs come one after another in a single line, and no epoch lies beside ours. In the road country, a bubble that no path could ever reach is no place at all for us, while a universe that a path could reach would be part of the one world. Kaku's books picture countless bubbles; I have shown you one world, and the same laws at the beginning of every epoch.

In *Quantum Supremacy* (2023) Kaku describes the *quantum computer* and its power on particular tasks. A quantum computer is a computer built from parts that follow the rules of the very small. We found that any machine, quantum or classical (that is, an ordinary computer), ap-

proaches what it *simulates* (imitates step by step in calculation) as closely as one wishes, and never contains the thing it simulates. Both kinds of machine share the same boundary between approaching a thing and containing the thing. A quantum computer's advantage is in time, on particular tasks. In the road country, every answer that a computer hands back is a town. A quantum computer is a faster car on the same roads. Given time enough, a classical computer can arrive at every town that a quantum computer arrives at. The quantum computer arrives at some of the towns sooner. In this book I have shown you the boundary that every machine shares. I have also shown you the advantage in time that is the quantum computer's own.

Last we took up Kaku's plan, in *Parallel Worlds*, for escape from a dying universe. In the long emptying of the sky, every galaxy beyond our own small family passes out of reach and the stars burn out. We found that the long emptying ends in the turn to a new epoch, and not in a final dark. What crosses the turn is the form of the content, as one averaged form. The form of the content is what the matter of our epoch is. The law that holds in our epoch holds again on the far side of the turn, and the law is not carried across. What stays on our side of the turn is every count, every length, every record, and every thing as the thing it was. So nothing escapes as itself. No traveler can reach another universe either, because whatever a path can reach belongs to the one world, and no path and no act joins the next epoch to our own epoch. In the road country, every road stays in the country, but over the longest time the country itself comes to the turn, and on the far side of the turn the next epoch begins. In this book I have shown you a far future that needs no rescue, in place of a plan of escape.

We found one answer in each of the eight chapters before this chapter, and all eight answers depend on one fact about comparison. 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. In every comparison, the comparer finds some *content*,

what is found, in some setting, such as a place or a moment. In the theorem's sense, *symmetry* is the same content in different settings, and *asymmetry* is a content that changes as the setting changes, a sense that differs from the physicists' sense, in which a symmetry is a change that leaves a thing the same. *Continuity* is the same content within one setting, with nothing jumping, and *discontinuity* is a content that jumps within one setting. Every act of knowing is an act of comparison, or is built from acts of comparison, so the theorem is inherent in every single act of knowing.

Kaku's books give you a universe full of wonders and the hope of reaching the wonders, and I add the ground under the wonders: an answer to each of Kaku's questions, and the reason for each answer.

The Choice Is Ours

Reasoning from comparison, I find that the first of Kaku's three closing sentences, "The choice is ours", holds word for word. I show that the world is *causal*: every change in the world can be understood as an effect that follows from causes. I also show that the world is not *determined*, that is, not fixed in every detail by what came before. Causes are real, and because the world is causal and not determined, the world has real choices in it.

I begin my account of choice with the picture of an evening, in which someone has a free evening and a list: a film, a dinner with a friend, an early night. When the person weighs the three and gives up two to have one, the person is making a decision. Then the friend calls with an idea that was on no list, a walk to watch the sun go down over the river, and so the evening becomes something that none of the three options was. The friend's walk is a choice. The difference: A decision selects within what is already laid out; a choice realizes what was open but not yet laid out. The world is causal and not determined, and so decision and choice are two different acts: decision and choice would be one act only if the world were fixed in every detail, because the list would then be all there is.

Just before his last three sentences, Kaku writes: "Decisions made by us will reverberate throughout this century" (*Parallel Worlds*, ch. 12, "Transition to Type I Civilization"). He names the matters that our decisions must settle: global wars, the spread of nuclear weapons, and strife between sects and peoples. A decision weighs what is on the list, but a choice can bring into being what was on no list. Decision and choice are both ours. Kaku's sentence "The choice is ours" uses the word "choice". In this book's sense of the word "choice", Kaku's sentence is true.

I give the order in which choice and cause run, an order that comes from the second of the three axioms of Chapter Four. The order has three steps: choices originate changes; changes can be understood causally; causal patterns create the conditions for new choices. Choice, change and cause follow one another in that one order, in a cycle that begins with choice and returns to choice. I also name the counterpart of choice: *creation*, which generates the range of what is open. Creation is cooperative: "the convergence of many agents, processes, and evaluations into one shared outcome". A language is a picture of creation. No one speaker made English, and the words of many speakers over many lifetimes have converged into one language, so English opens to every speaker more than any one speaker could have laid out. The many speakers are the many agents of the definition, and English is their one shared outcome. So Kaku's sentence "The choice is ours" holds for each person and for the generation together, because each choice is the act of one person, and the people of a generation create together what their generation brings into being.

Here, in the One World

In his ending Kaku also expresses a hope, and my answer to that hope differs from his. Kaku writes in his closing pages: "rather than be depressed by the sheer enormity of the universe, I am thrilled by the idea of entirely new worlds that exist next to ours" (*Parallel Worlds*, ch. 12, "Trans-

ition to Type I Civilization"). Kaku ends his eleventh chapter on the hope that intelligent life might one day escape a dying universe into another universe.

This account has a different result, for a reason we found earlier on the walk: whatever a path can reach belongs to the one world, and no path and no act joins the next epoch to ours. So the life that does the choosing is here, in the one world.

Kaku and this account agree again on how rare and precious life is. Kaku writes, of the rarity of liquid water and of minds like ours: "It should make us appreciate how delicate life is, and what a miracle it is that it flourishes on Earth" (*Parallel Worlds*, ch. 12, "Copernican Principle vs. Anthropic Principle"). I argue from comparison for the view of life that Kaku holds: that life is rare and precious. A living being is a place where choice is gathered and *known from inside*: known by the one who chooses, as that one's own. Meaning lives only where there is choice, and so meaning, known from inside, lives only where life is. The universe we can see is almost all stars, gas, dust and rock, matter that does not live. Life is rare in the universe, as a share of all its matter, and it is here. I hold that all life is sacred, and because life is rare and is here on the Earth, I can call the Earth a temple: a place where choosing is known from inside, and so a place where meaning lives at all. I use the word *sacred* to mean ultimately meaningful, and the word names nothing supernatural. Either everything is sacred, at every scale, or nothing is: to deny that any one life is meaningful is to deny that any life is.

Kaku says that we create our own meaning. In this account, meaning is made in the living: meaning is found where choice is known from inside, by the one who chooses. Kaku's star dust has its place in this account too: the stars that made the atoms of our bodies were made under one law, and the same law holds again in each epoch that follows.

What Is Yours to Do

What is yours to do? Kaku gives his own list, and his list is a good one: work, love, developing whatever talents you were born with, and leaving the world a better place than you found it (*Parallel Worlds*, ch. 12, "Creating Our Own Meaning"). I add the ground under Kaku's list: the reasons that your choices are real, your own, made in the one world, and made with others.

What is yours to do is to choose. Your choices are real, because the world is causal and not fixed in every detail. Your choices are your own, because a living being is where choice is gathered and known from inside. You make your choices here, in the one world, because every place you could ever reach is part of the one world. And you create what you bring into being together with others who choose, because creation is cooperative. Your choices matter here, in the one world, where you already are, and your choices need no escape to be real.

We now know what we hold: one world, everything any path can reach, known through comparison, a world with real choice and living choosers in it. On the ground of one world with real choice in it, Kaku's "The choice is ours" is a plain statement about the world.

The Last Picture

Look once more at Anders's photograph. The crew of Apollo 8 had traveled the farthest road that anyone had yet traveled, to the Moon, which in the road country is a town of the same country as the Earth. From the Moon the crew looked back, and they found the Earth.

Kaku's roads go farther still in imagination: through wormholes, past the speed of light, into hyperspace, out of a dying universe. Follow each of Kaku's roads as far as the road goes. The new road of a wormhole arrives at a town of the one country, and so does the faster car of a warp drive. Kaku imagines three other ends for his roads: a place reached by a message sent outside the light cone of its sending, a place reached through the

six further dimensions, which in this account are the six dimensions of possibility, and a place outside the country. Each of the three is a “town” that no road could ever reach, and so no place at all for the traveler. Every road that arrives anywhere arrives at a town of the one country, the country of everything any path can reach. The one country is the one world, and you are in the one world now, choosing. Every road arrives here, in the one world.

Appendix A

What the Coming Measurements Will Find

What will the measurements still to come find, where the measurements bear on the chapters of this book? In this appendix, as in every chapter, this account is the physics that my books work out from the act of comparison. To compare is to set one thing beside another and tell them apart. Each entry below names one measurement still to come, under the chapter that the measurement bears on. Each entry says what the measurement will measure and what this account says the measurement will find. Each chapter is complete in itself, so a reader who passes over this appendix can still follow every chapter.

On 1 November 2026 I wrote down forty-two predictions in one record. The title of the record is *The Registered Predictions of Physics from Comparison; A Dated Record, 1 November 2026*, and the record has its own DOI: https://doi.org/10.67291/RQQS3025. In this appendix I call the record of 1 November 2026 the dated record. The dated record is reproduced whole in my book *Side by Side*, Volume One. Most entries below state one of the dated record's predictions, with the prediction's number and the prediction's title, in the dated record's own words. Some entries state a claim from one of my books that is not among the forty-two predictions of the dated record, and each of these entries names the book.

The masses of particle physics are stated below in units of energy, since mass and energy are interchangeable. An *electron volt* is the energy that an electron gains in crossing one volt. A GeV is a billion electron volts, and a proton weighs a little less than one GeV. An MeV is a million electron volts, and an meV is a thousandth of one electron volt. "Give or take" states the range within which a stated value lies. A matter fraction of 0.311, give or take 0.001, lies between 0.310 and 0.312.

Chapter One: Two Kinds of Impossible

Antimatter in the sky. Detectors carried above the atmosphere count the particles that rain in from space, the *cosmic rays*. Among the cosmic rays the detectors look for nuclei of antihelium, the antimatter form of helium, which stars made of antimatter would produce. Kaku describes a search for antihelium by the satellite PAMELA, the Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (*Physics of the Impossible*, ch. 10, "Naturally Occurring Antimatter"). Astronomers also search the sky for stars, galaxies and regions made of antimatter. The *observable universe* is the part of the universe from which light has had time to reach us. This account says that matter is in excess over antimatter everywhere in the observable universe. This account also says that no region of antimatter will be found anywhere in the observable universe. This entry bears on the account as a whole, and on Kaku's search for antihelium, more than on any one chapter. The dated record states the claims about antimatter as Prediction 15, "The excess of matter has one sign everywhere".

Whether the future is already written. The physicists Sabine Hossenfelder and Tim Palmer have proposed an experiment to test *superdeterminism*: the idea that the outcome of every measurement, and the experimenter's choice of what to measure, were fixed together from the start. In the experiment of Hossenfelder and Palmer, measurements are made one after another, in quick succession, on systems prepared as nearly alike as possible. The measuring devices are as small and as cold as possible. Hossenfelder and Palmer look for patterns in time among the outcomes. *Quantum theory* is the physics of atoms, light and the particles. The *Born rule* is the rule of quantum theory that sets the weight of each possible outcome of a measurement. This account says the measurements in the experiment of Hossenfelder and Palmer will settle to the weights of the Born rule, at every sensitivity, with no pattern in time beyond those weights. The dated record states the claim as Prediction 25, "The statistics

of quantum theory hold". Prediction 25 names the tests proposed for superdeterminism. A second prediction of the dated record bears on whether the future is fixed in advance: Prediction 28, "No world is perfectly deterministic, and no process is perfectly reversible". Comparison is the act by which anything is known: setting one thing beside another and telling them apart. Prediction 28 rests on the structure of *comparison* alone, that is, on what every comparison must contain. Prediction 28 begins: "No superdeterministic completion of quantum mechanics will be found, and no world is purely and completely deterministic". In plain words, the dated record's "no world" covers our own one world and any other world whatever. Our own one world is everything any path can reach. No world has a future fixed in advance, ready, in principle, to be read before the future happens.

Chapter Two: Faster Than Light, and Back in Time

Entangled particles far apart. When the findings on two particles agree in a way that no separate description of each particle produces, physicists call the two particles *entangled*. Experiments will keep measuring pairs of entangled particles at ever greater distances, with the choice of measurement made ever faster. This account says that in every test of entangled particles, the statistics at each place will stay unchanged by whatever measurement is chosen far away. This account says news of a distant finding will enter a record only on or within the future *light cone* of the distant finding, the region of space and time that light leaving the finding can reach. This account says that whatever leaves a place, whether a signal or a body, will arrive only on or within the light cone of its departure. This account says the probabilities of the outcomes of a preparation (the way a system is set up before it is measured) will not depend on which test is chosen later. And this account says no later finding will come to precede an earlier finding. The claims about signals are Prediction 27, "No signal faster than light, and none backward in time". Prediction 27 permits travel within the light cone. Prediction 27 also permits distant

galaxies to recede faster than light, because the recession is a growth of the space between the galaxies, and no signal travels across that space. Chapter Two describes two shortcuts through space: a *wormhole*, a passage through space joining two distant places, and a *warp drive*, a region of space that carries a ship along with it. A wormhole and a warp drive would each carry a traveler within the light cone. The dated record makes no claim either way on whether anyone can engineer a journey within the light cone, by a shortcut or by an ordinary craft sent to the stars.

A wormhole on a chip. In 2022 the physicist Daniel Jafferis and colleagues ran a small quantum program on Google's quantum processor Sycamore, a computer built of quantum parts. The signals of the program on Sycamore had the features of a traversable wormhole, a wormhole that something could cross, as a traversable wormhole appears in a description in terms of gravity. In my book *The Quantum Bridge*, chapter 7, I read the run of Jafferis and colleagues as a quantum simulation of a model that has two descriptions, one of them in terms of gravity. On the reading of *The Quantum Bridge*, no wormhole is made. If anyone measures the pull of the processor on its surroundings while the processor runs, the measurement will show only the pull that the device and its contents produce by their ordinary mass and energy. The statement about the processor's pull is made in *The Quantum Bridge*. The statement is not one of the numbered predictions of the dated record.

Chapter Three: Ten Dimensions

The shape of a gravitational wave. Gravitational waves are ripples in the geometry of space and time. Gravitational waves are sent out when massive bodies such as *black holes* (bodies whose gravity lets no light escape) merge. There are detectors of gravitational waves in the United States, Europe and Japan. Working together, the detectors will measure how each passing wave stretches and squeezes space, which physicists call the *polarization* of the wave. The detectors will also time waves that arrive together with light from the same event. This account says the detect-

ors will find the two polarizations of Einstein's theory of gravity and no other. This account also says the waves will travel at exactly the speed of light. The claims about gravitational waves are Prediction 6, "Gravitational waves have two polarizations and travel at the speed of light". Prediction 6 rests on a claim that I argue in my book *The Gravitational Passage*: Einstein's form of the equations of gravity is the only form the equations of gravity can take.

Newton's law at short range. Experiments with delicate twisting balances measure the pull of gravity between small masses at ever shorter distances. In Newton's law the pull of gravity weakens as the square of the distance, and experiments with twisting balances have found Newton's law down to about a twentieth of a millimeter. The coming experiments will measure at shorter distances still. This account says Newton's law will hold in every test of gravity at short range. The physics of this account, like string theory, works in ten dimensions: the four of space and time, and six further dimensions beside them. On this account the six further dimensions are dimensions of possibility. Dimensions of possibility are dimensions of what can happen at each place, and not further directions of space. When the six dimensions of possibility are taken as held at every point of space and time, the six have a size and a shape. Two fields set the size and the shape of the six. Physicists call the two fields the *moduli* of the six. A vibration of either field would carry a pull between masses. The *Planck length* is the unit of length that the measured strength of gravity sets, and at the Planck length gravity and the quantum meet on equal terms: their effects are of the same size. The pull of either field has a range shorter than the Planck length, about thirty powers of ten shorter than the shortest distance at which any test of gravity at short range measures the pull. Some theories take the further dimensions to be dimensions of space, and the physicists who hold those theories expect Newton's law to change at short range, but this account says no change in Newton's law will be found. I make the statement that Newton's law holds at short

range in my books *The Compactification*, chapter 2, and *The Gravitational Passage*, chapter 11, but the statement is not one of the numbered predictions of the dated record.

The count of light species. The *microwave background* is the oldest light in the sky. The microwave background records how fast the young universe expanded. The rate of expansion depended on how much energy the young universe held, so the microwave background also records how much energy the young universe held in radiation other than light itself. Astronomers state the energy in radiation other than light as the *count of light species*, where "light" means of small mass. A *neutrino* is a particle with almost no mass and no electric charge, which passes through almost anything. The count of light species is the energy of all the radiation other than light itself, counted in units of the energy that one kind of neutrino carries, so the three known kinds of neutrino give a count of a little over three. The Simons Observatory is a set of telescopes in Chile. The Simons Observatory will measure the count of light species to within about five to seven hundredths. In this account our epoch is one of a series of *epochs*, long eras that follow one another like the cars of one train, and each epoch begins at a *turn* from the epoch before. At the turn the six dimensions of possibility settle into their shape, and the settling leaves a faint hum of gravitational waves, whose strongest frequency today lies above about five hundred billion vibrations a second. This account says the hum adds less than about nine hundredths of one kind of neutrino to the count of light species. No instrument now built or proposed can register waves at the frequency of the hum. So the count of light species is the measurement that bears on the hum. The claim about the hum is part of Prediction 14, "The gravitational waves of an epoch, and their absence where others expect them".

How much dark matter there is. The *dark matter* is matter that shows itself only by its pull of gravity: the dark matter holds galaxies and clusters of galaxies together, and no telescope sees the dark matter shine. This account says the dark matter is a lasting vibration of the six dimensions of possibility, made at the turn that begins each epoch. Maps of the

microwave background will measure the ratio of the density of the dark matter to the density of ordinary matter. Ordinary matter is the matter of atoms. The maps will measure the ratio to about six parts in a thousand, and among the maps will be the maps of the Simons Observatory combined with the maps of the Planck satellite. A second, independent kind of measurement will measure the same ratio of the dark matter to ordinary matter. The second kind will have the same precision, about six parts in a thousand. This account says both kinds of measurement will find the ratio to be six less two divided by pi, which is 5.3634, and the ratio has been the same at every time since helium was first formed. The two claims about the ratio are Prediction 16, "The ratio of the dark matter to the ordinary matter is $6 - 2/\pi$". The *curvature* of the six dimensions is how much their shape bends. The ratio of the two densities depends on the curvature of the six. The *matter fraction* is the share of the universe's energy carried by matter today. The matter fraction also depends on the curvature of the six. The measurement of the matter fraction is listed under Chapter Six. This account says the measurement of the ratio and the measurement of the matter fraction will both show the curvature of the six equal to one, in the unit that the strength of gravity sets. The claim about the curvature is Prediction 17, "The coefficient shared with the cosmological constant is 1". In the title of Prediction 17, the coefficient is the curvature of the six, and the cosmological constant is the energy of empty space.

Searches for the dark matter. Large detectors deep underground wait for a particle of dark matter to strike an atomic nucleus. Telescopes look for light or particles that dark matter might give off. *Colliders* are machines that smash particles together at high energy, and colliders look for dark matter made in the collisions. This account says no search will detect the dark matter by any means but the gravity of the dark matter, at any sensitivity. The claim about the searches is Prediction 19, "The dark matter acts only through gravity". Astronomers will observe the faintest small galaxies, and light bent by small clumps of matter, ever more finely. The finer observations will measure how finely the dark matter clumps. This ac-

count says the dark matter clumps on every small scale, with no smallest size set by the motion of the dark matter, and physicists call dark matter that clumps in that way cold. The claim about clumping is Prediction 21, "The dark matter is perfectly cold".

Chapter Four: One Equation?

How everything falls. Experiments will compare the free fall of different materials ever more finely. The Satellite Test of the Equivalence Principle is a proposed satellite designed to compare free fall to one part in a billion billion. Antihydrogen is the simplest atom of *antimatter*, matter whose particles carry the charges opposite to those of ordinary matter. CERN is the European laboratory for particle physics, near Geneva. Experiments at CERN have already seen antihydrogen fall downward. The experiments will time the fall of antihydrogen more precisely. Physicists also continue to search for any arrangement of matter that would screen gravity off, as a sheet of metal screens off a radio signal. This account says three things: every pair of materials will fall exactly alike, at every precision; antimatter will fall exactly as matter falls; and nothing will be found that shields gravity, or that gravity leaves untouched. The dated record states the three claims about falling as Prediction 4, "Free fall is universal and nothing shields gravity". The *arena* of physics is the geometry of space and time within which every piece of matter is found. Prediction 4 rests on a claim of this account: gravity is the arena of physics.

Two masses entangled by gravity. Several groups of physicists are working toward an experiment that the physicist Sougato Bose and colleagues proposed in 2017. In the experiment of Bose and colleagues, each of two tiny masses is held in a *superposition* of two places: both placements open together, in the sense of quantum theory, until a finding settles one of the two. The two masses are related to each other only through gravity. In the design of 2017, each mass weighs a hundred-billionth of a gram and is held in two places a quarter of a millimeter apart. The centers of the two masses are 0.45 millimeters apart. The masses are held in superposi-

tion for two and a half seconds. The entangling phase is the amount by which gravity shifts the quantum waves of the different placements against one another. For the design of 2017, this account says the two masses will become entangled. The entangling phase will be 0.314 radians, about a twentieth of a full circle. For any other design, this account says the phase is the phase that Newton's law of gravity predicts for the masses, distances and time of that design. The claims about the entangling phase are Prediction 1, "Gravitation entangles two masses". On this account each alternative placement of the matter carries a geometry of space and time that belongs to that placement alone. The entanglement comes from the separate geometries of the placements. Accounts of two kinds say no entanglement will be found: accounts in which there is one geometry for all the alternatives of the matter, and accounts in which gravity itself ends a superposition. So if the entanglement is found, the finding will set this account apart from both kinds of account. The *Planck scale* is the scale at which gravity and the quantum meet on equal terms: their effects are of the same size. Below the Planck scale, physicists can describe the small ripples of the geometry by quanta, indivisible units of the ripples, and that description predicts the same phase as this account. So a finding of the entanglement agrees with this account and does not show that gravity is quantized.

Whether gravity ends a superposition. The experiment of Bose and colleagues is also a test of whether gravity alone ends a superposition, and this account says no mass, however large, no separation, however wide, and no length of time ends a superposition of its own accord. On this account a superposition ends only through a finding: an interaction that registers which alternative is the case. The claims about ending a superposition are Prediction 2, "Gravitation alone ends no superposition". The physicists Lajos Diósi and Roger Penrose have proposed that gravity itself ends a superposition. For the masses in the experiment of Bose and colleagues, the proposal of Diósi and Penrose says the superposition lasts about a hundredth of a second, while the experiment needs the superposition to last two and a half seconds.

Quanta of gravity. In 2024 the physicist Germain Tobar and colleagues proposed to register a gravitational wave in single clicks, in a quantum sensor, as a light detector registers single *photons*, the quanta of light. This account says no effect will show the geometry of space and time holding quantum states of its own, beyond the geometries that go with the alternatives of the matter. Physicists can describe the small ripples of the geometry by quanta wherever the curvature of space and time is below the Planck scale (the scale of gravity and the quantum on equal terms). The curvature of space and time is below the Planck scale in every experiment now proposed. The quanta of the description by quanta belong to the description, and not to the geometry itself, so a detector that registers single clicks agrees with this account and does not show that gravity is quantized. The claims about quanta of gravity are Prediction 3, "Gravitation is not quantized".

Whether space has a smallest step. Telescopes will catch high-energy light from distant bursts and time the arrival of light of different energies from many sources, and detectors of gravitational waves will also study the waves that ring out after black holes merge, echoes included. This account says no step of space or time makes the speed of light in empty space depend on the energy of the light, and no area or volume will be found coming in steps, in the echoes or anywhere else. On this account the charges and the kinds of particle come in steps, and this account predicts those steps. The claims about steps are Prediction 5, "The arena has no least length, area or duration". The arena is the geometry of space and time. Some accounts make space out of tiny steps. Accounts that make space out of steps predict that light will arrive with its timing spread by its energy. The spread grows the farther the light has come. Accounts that make space out of steps also predict echoes that show areas or volumes coming in fixed steps, but this account says neither the spread of timing nor the stepped echoes will be found.

Whether the proton lasts. Two coming experiments will watch enormous numbers of protons for years, looking for a proton that breaks apart into lighter particles. The first experiment is Hyper-Kamiokande, a water

tank in Japan far larger than Super-Kamiokande. In the searches at Super-Kamiokande, no proton has so far been seen to decay. The second experiment is DUNE, the Deep Underground Neutrino Experiment, which will watch tanks of liquid argon in the United States. The decay most searched for gives a *positron*, the antiparticle of the electron, and a *neutral pion*, a short-lived particle made of a quark and an antiquark. *Quarks* are the particles of which protons and neutrons are made. An antiquark is the antiparticle of a quark. After ten years of watching with one tank, Hyper-Kamiokande will be able to see the decay to a positron and a neutral pion for lifetimes as long as seventy-eight million billion billion billion years. This account says Hyper-Kamiokande and DUNE will both find the proton stable, at every lifetime to which the two searches are sensitive. The *strong force* is the force that binds quarks together. Physicists call the charge of the strong force *color*. The *weak force* is the force behind some kinds of radioactive decay. In this account no carrier of force joins color to the charge of the weak force, at any energy. A change of a quark into a lepton would need a carrier of force that joins color to the charge of the weak force, so nothing turns a quark into a *lepton*, the electron or one of its kin. The three forces of the particles are the strong force, the weak force and the electromagnetic force. In the physicists' sense, a symmetry is a change that leaves a thing the same, and a unifying group would be one larger symmetry from which the three forces of the particles came as parts. This account also says no unifying group exists at any scale. This account says the measured strengths of the strong, weak and electromagnetic forces meet at no single energy. The three strengths are all equal at no energy. The claims about the proton are Prediction 33, "The proton does not decay".

New kinds of particle. The Large Hadron Collider near Geneva will search for new kinds of particle, and so will its upgrades and any larger collider after it. Physicists will also search with detectors deep underground and with observations of the sky. The *Standard Model* is the established theory of the particles and their forces. A *generation* is a family of matter particles, and three generations are known. This account says the

kinds of particle are a closed list: the kinds of the Standard Model, with a right-handed neutrino, the partner that each neutrino needs for its mass, in each generation. This account says no further kind will be found. No fourth generation will be found beside the three known generations. In the theory called supersymmetry (a symmetry in the physicists' sense), each known particle has a partner, called its supersymmetric partner. No supersymmetric partner will be found. The W and Z bosons are the carriers of the weak force. Physicists will find no heavier copy of the W or Z bosons. The *Higgs boson* is the particle of the field that gives many of the other particles their mass. No second Higgs boson will be found. An *axion* is a light particle proposed to settle a puzzle of the strong force. No axion will be found. A hidden sector would be a family of particles that feel none of the strong, weak and electromagnetic forces of the known particles. No particle of dark matter will be found, and no hidden sector will be found. This account says heavier composites, bound states of the known particles, exist at higher energies, and no new kind of particle exists there. The claims about new kinds of particle are Prediction 30, "No kind of particle beyond the closed list", and Prediction 31, "Exactly three generations".

New particles in the loops. Physicists also look for new particles indirectly. A particle too heavy to make can still appear for an instant inside a process and change the process slightly. Physicists draw the brief appearance of the particle as a *loop*. The *muon* is a heavier cousin of the electron. Physicists measure the magnetic strength of the muon to look for new particles in the loops, and physicists also look for the rare change of a muon into an electron with a flash of light. This account says the muon's magnetic strength receives nothing from any new particle. This account says a muon turns into an electron and a flash of light only about once in ten to the power fifty-five tries, a one followed by fifty-five zeros. So no change of a muon into an electron will be seen at any foreseeable experiment. The claims about loops are Prediction 35, "No new particle in any loop".

How the strengths of the forces change with energy. The strengths of the strong, weak and electromagnetic forces change slowly with the energy at which the strengths are measured, and with every measurement at a new energy, physicists measure the change more finely. This account says the closed list of kinds fixes the rates of the change, and the rates change only at the masses of the known particles and of the W and Z bosons. Physicists call the slow change of strength with energy the *running of the couplings*, and the claims about the running are Prediction 36, "The running of the couplings changes only at known masses".

Chapter Five: The Numbers of Nature

The entries below state masses, strengths of the forces and *mixings*. The mixings are the numbers that say how often the weak force turns one kind of particle into another. In my books *The Strengths of the Kinds* and *The Measures of the Kinds*, I compute the masses, strengths and mixings from a few measured inputs, among them the mass of the electron.

The strong force and the heaviest particles. Coming measurements will measure four numbers more precisely. The first number is the strength of the strong force, which physicists call the strength of color, read at the energy of the Z boson's mass. The other three numbers are the masses of the W boson, of the Higgs boson and of the top quark, the heaviest particle known. This account says the strength of color is 0.11888, give or take 0.00011. The value 0.11888 rests on one ratio among the strengths of the strong, weak and electromagnetic forces. To find the ratio, write each of the three strengths as one divided by its value. Then carry the three strengths up in energy to the Planck scale. The three strengths then have two gaps between them, and the ratio is the ratio of the two gaps. In my book *The Strengths of the Kinds* I carry two values of the ratio side by side, 5 and 21/4. The strength of color is 0.11888 when the ratio is 21/4. This account says the W mass is 80.3538 GeV, give or take 0.0045 GeV, and the Z mass is 91.1888 GeV. This account states the Higgs mass in four forms, from 125.1715 to 125.2245 GeV. This account states the top mass in

six readings, from 172.417 to 172.657 GeV. A *matching* is a calculation from measured quantities. The matching fixes the strengths of the strong, weak and electromagnetic forces at the energy of the top quark's mass. With a matching, physicists can carry the change of the strengths with energy upward from the energy of the top quark's mass. When the W mass is measured to about three thousandths of a GeV, the measured W mass will serve as an input of one matching. Physicists will use the measured W mass, and the matching computed with the measured W mass, to test the calculation in *The Strengths of the Kinds* that gives the strength of color. When the Higgs mass is measured to three hundredths of a GeV, or the top mass to two hundredths of a GeV, the measurement will show which of the six readings of the top holds. When the Higgs mass is measured to five thousandths of a GeV, the measurement will show which of the four forms of the Higgs mass holds. The values in this entry are Prediction 42, "The strength of color, the W and Z, the Higgs and the top".

A ceiling on the masses, and a balance among the leptons. This account says no particle of matter is heavier than 174.1036 GeV, which is the *vacuum value* of the Higgs field (the value the field holds in empty space) divided by the square root of two. A particle's *coupling* to the Higgs field is the strength with which the particle is tied to the field, and the mass of each particle of matter is its coupling times 174.1036 GeV. Every particle's coupling to the Higgs field lies between zero and one. So no particle of matter is heavier than the ceiling of 174.1036 GeV. The top quark, measured at 172.60 GeV, is just below the ceiling. The three charged leptons are the electron, the muon and the *tau*. This account says the three charged leptons satisfy *Koide's relation*, named for the physicist Yoshio Koide, who found it: the sum of their three masses is two thirds of the square of the sum of their square roots. This account says the neutrino masses come in the *normal order*. Each kind of neutrino, the electron's among them, is a blend of three neutrinos, each with its own mass, and in the normal order, the two of the three that make up most of the electron's neutrino are the lighter two. Three experiments will measure the order of the neutrino masses: the Jiangmen Underground Neutrino Observatory (JUNO) in

China, the Tokai to Kamioka experiment (T2K) in Japan and the NOvA experiment in the United States. The dated record states the ceiling, Koide's relation and the normal order as Prediction 37, "Ceilings and relations among the masses".

The mass of the tau. The tau is heavier than the electron and the muon. The Belle II experiment in Japan will measure the mass of the tau to within 0.045 MeV. This account has two readings of the mass of the tau, side by side. The measurement of Belle II will show which reading holds. Koide's relation, applied to the measured masses of the electron and the muon, sets the mass of the tau at 1776.969 MeV. In my book *The Measures of the Kinds* I build the masses of the charged leptons as the rungs of a ladder. The ladder starts from the electron alone, and on the ladder the mass of the tau is 1777.146 MeV. The dated record states the two readings, from Koide's relation and from the ladder, as Prediction 40, "The mass of the tau: two readings".

The triangle of quark mixing. The weak force changes one kind of quark into another, and the numbers that describe the changes close into a triangle, the *unitarity triangle*, whose angles physicists call alpha, beta and gamma. Physicists will measure the shape of the triangle by measuring alpha directly to about two degrees, or gamma to about one degree. This account says the triangle has a right angle: alpha is 90 degrees, beta 22.5 degrees and gamma 67.5 degrees. The phase of quark mixing is the one number in the mixing of quarks that tells matter from its mirror image (matter swapped for antimatter and reflected as in a mirror). If the triangle has a right angle, the phase of quark mixing is 67.15 degrees, give or take 0.70. In my book *The Measures of the Kinds* I carry two further readings of the triangle beside the right angle. The two further readings put alpha at 92.0 and at 94.0 degrees. The two further readings come from a family of patterns of the masses that I hold in *The Measures of the Kinds* as a hypothesis. The three readings are the right angle, alpha at 92.0 degrees, and alpha at 94.0 degrees. The direct measurements of alpha and gamma will show which of the three readings holds. The right angle is Prediction 41, "The quark unitarity triangle has a right angle".

How heavy the neutrinos are. Two kinds of map measure the sum of the masses of the three neutrinos of which every kind of neutrino is a blend: maps of the large-scale structure of the universe, and maps of the microwave background. *Beta decay* is the radioactive decay in which a nucleus gives off an electron. Experiments on beta decay measure the mass of the electron's neutrino directly, with no use of cosmology. This account has two readings of the three neutrino masses, side by side. Physicists will learn which reading holds from the measurements of the sum and of beta decay. On the first reading the three masses add to 84.95 meV, and on the second to 59.31 meV, give or take 0.25. The sum that tells the two readings apart is the sum measured when the matter fraction and the rate of expansion take the values of Prediction 7 (listed under Chapter Six) and the energy of empty space is constant. On the first reading the mass that beta decay measures is about 17.6 meV. On the second reading the mass is about 9 meV. So, if beta decay is measured with a give or take of about 3 meV, the measurement will tell the two readings apart. Both readings give the normal order, and three masses, none of which is zero. Both readings also give no neutrinoless double beta decay, a decay described two entries below. The two readings are Prediction 38, "The neutrino masses: two readings, decided by their sum".

How the neutrinos mix. A neutrino changes from one kind to another as the neutrino travels. The *lepton phase* is one number of the mixing of the neutrinos, and the lepton phase tells matter from its mirror image (matter swapped for antimatter and reflected as in a mirror) among the neutrinos. Hyper-Kamiokande and DUNE will measure the lepton phase closely enough to place the phase in its *quadrant*, its quarter of the full circle. Hyper-Kamiokande will need ten years of running for the measurement. This account has two families of mixing, side by side. The measurement of the quadrant will show which family holds. In the first family the phase is in the fourth quadrant, at 281.37 degrees, give or take 0.16, and in the second family the phase is in the third quadrant, at 203.88 degrees, give or take 1.43. The JUNO experiment measures one of the mixing angles directly: the solar angle, which sets the mixing of the neutrinos that come

from the Sun. Physicists state the solar angle as the square of its sine, a number that grows from zero to one as the angle grows from zero to a right angle. On the first family, this account states the square of the sine of the solar angle as 0.3185, give or take 0.0005. JUNO reported its first measurement of the solar angle in November 2025, and its later runs will measure the angle more finely. The first family and the second family are Prediction 39, "Lepton mixing: two families, decided by the quadrant of the lepton phase".

Whether a neutrino is its own antiparticle. Physicists search for *neutrinoless double beta decay*, a decay in which a nucleus gives off two electrons and no neutrino, because the decay can happen only if a neutrino is its own antiparticle. This account says every neutrino is a *Dirac particle*, a particle distinct from its own antiparticle. The *effective neutrino mass* is the combination of the three neutrino masses that neutrinoless double beta decay would measure. This account says the coming searches will not observe neutrinoless double beta decay at any sensitivity, at an effective neutrino mass from 15 to 50 meV or below that range. The range from 15 to 50 meV is the range that an inverted order of the masses (the reverse of the normal order) would give. This account says the mixing of the neutrinos has one phase. A neutrino that was its own antiparticle would bring two further phases, and on this account the mixing has neither of the two. So the Standard Model has twenty-six numbers to take from measurement, and not the twenty-eight that the two further phases would make. The claims about the neutrino and its antiparticle are Prediction 32, "The neutrinos are Dirac particles; no neutrinoless double beta decay".

Chapter Six: One Bubble Among Many?

How much of the universe is matter. Four surveys will map the expansion of the universe and the gathering of its galaxies. The four surveys are the Dark Energy Spectroscopic Instrument (DESI), the Euclid space telescope, the Vera C. Rubin Observatory and the Nancy Grace Roman Space Telescope. From the maps, the four surveys will measure the matter

fraction, the share of the universe's energy carried by matter today, and this account says the surveys will find the matter fraction at 0.311, give or take 0.001. The small spread of 0.001 comes from the measured amount of radiation. The energy of empty space, the *cosmological constant*, carries the rest of the universe's energy, 0.689. When the amount of matter is taken from the microwave background, the prediction of a matter fraction of 0.311 sets the rate of expansion today at 67.8 kilometers per second for every megaparsec, give or take 0.3. A megaparsec is about three and a quarter million light years. The number 0.311 comes from one exact equality between the *particle horizon*, the farthest distance from which light has had time to reach us, and the energy of empty space. In the equality, the strength of gravity cancels, and so does the rate of expansion. So the equality fixes a *pure number*, a number with no unit. The values in this entry are Prediction 7, "The matter fraction is 0.311".

Waves from the beginning. Physicists call gravitational waves present from the beginning of our epoch *primordial* waves, and primordial waves would leave a faint twisting pattern in the polarization of the microwave background, the direction in which the light of the microwave background vibrates. The Simons Observatory and the LiteBIRD satellite will look for the twisting pattern. Physicists state the strength of the primordial waves as a ratio to the strength of the first ripples in the density of the universe. The Simons Observatory is designed to measure the ratio to about three parts in a thousand. LiteBIRD is designed to measure the ratio to about one part in a thousand. This account says the ratio is far below one part in a million, so both instruments will find no primordial gravitational waves: on this account the young universe was at first uneven only in its density. The claim about primordial waves is Prediction 10, "No primordial gravitational waves". *Inflation* is a brief burst of expansion at the very start, which the standard account of cosmology uses, and many models of inflation predict primordial waves strong enough for the Simons Observatory and LiteBIRD to find. This account says no primordial waves strong enough for the two instruments to find will be found.

The flatness of space. Four surveys will measure the curvature of space on the largest scale: DESI, Euclid, the Rubin Observatory and the Roman Space Telescope. DESI and Euclid will lead the measurement. The surveys will show whether space curves like the surface of a ball, curves the other way like a saddle, or is flat. This account says the surveys will find space flat, curved only by its own small departures from uniformity, about one part in a hundred thousand, far below what the coming surveys can measure. The flatness of space is Prediction 9, "Space is flat to the size of the primordial departures", where the primordial departures are the first ripples in the density of the universe.

The pattern of the first ripples. Every finer map of the microwave background measures the first ripples of the universe more closely. This account says every component of the universe's content, the dark matter included, rippled together, with no separate pattern of its own. When every component ripples together, physicists call the ripples *adiabatic*. This account says the ripples form one pattern across the whole sky, of nearly the same strength at every length. The claims about the ripples are Prediction 11, "The primordial departures are adiabatic", and Prediction 12, "The departures are one pattern across the whole sky". Three kinds of measurement bear on Prediction 13, "No long inflationary phase": the maps of the ripples, the search for primordial waves, and the measurement of the flatness of space. This account says no long inflation took place. On this account the turn from the epoch before ours is the reason the sky is so even and space so flat. This account fixes the form of the pattern of ripples. In this account two things are taken from measurement: the overall strength of the pattern, and the pattern's slight tilt from large lengths to small.

Gravitational waves in space. The Laser Interferometer Space Antenna (LISA) is a planned set of three spacecraft millions of kilometers apart, and LISA will register slow gravitational waves, with periods from seconds to hours. Astronomers expect LISA to register waves from pairs of *white dwarfs* (the small dense remains of stars like the Sun) and from pairs of black holes. White dwarfs and black holes are bodies in space, so

the waves from their pairs do not come from the early universe. A *phase transition* is a sudden change of state, like water freezing to ice. This account says LISA will register no background of waves left by a phase transition in the early universe. *Cosmic strings* are long thin flaws that some theories expect changes of state to leave. On this account the early universe passed through its changes of state smoothly. On this account no stable network of cosmic strings formed in the history of the universe's content. The claims about LISA are part of Prediction 14, "The gravitational waves of an epoch, and their absence where others expect them".

Whether space loops back on itself. Astronomers search the microwave background for signs that space closes on itself, so that a path running straight out in one direction would come back from the other. This account says that, at every place in space, every path that runs straight out and comes back from the other direction is at least as long as the diameter of the horizon, which is twice the distance of the particle horizon. The claim about closed paths is Prediction 23, "No short loop exists anywhere in space".

Chapter Seven: The Quantum Machine

Error correction as quantum computers grow. A *qubit* is the unit of information of a quantum computer: a quantum system that can be held in a superposition of zero and one. A quantum computer protects its fragile states by spreading each working qubit, a *logical qubit*, over many physical qubits in a *code*. In a code, errors can be found and fixed. The larger the code, the more errors the code can fix. In 2024 Google's quantum team showed the error of a logical qubit falling each time the code grew. The coming processors will run larger codes still. This account says the error will keep falling as the codes grow. This account also says that if the error stops falling at some lowest level, the ordinary sources of error alone will set that level. *Decoherence* is the loss of a superposition through contact with the surroundings. The reason for the claims about the error is in Prediction 2, "Gravitation alone ends no superposition". Prediction 2 says

that no decoherence occurs beyond the ordinary kind. In my book *The Quantum Bridge*, chapter 4, I state that this account sets no ceiling of its own on how many errors a code can fix, for codes of every size. The statement about the ceiling is not one of the numbered predictions of the dated record. On this account the limits on how many errors a code can fix are the limits that quantum theory sets. Quantum theory sets the limits through three things: the number of physical qubits, how often errors occur, and how far the errors are tied to one another.

The statistics of quantum computers. Quantum processors prepare states of many qubits that have never been prepared before, and coming experiments will measure the outcomes on the new states. This account says that repeated measurements on systems prepared alike settle to the weights of the Born rule, whether or not the state of the systems has been prepared before. In my book *The Quantum Passage*, chapter 7, I say that the state before a measurement gives the weight of each outcome. Take many different states, each prepared for the first time and measured once: on the statement of *The Quantum Passage*, the first outcomes of the many states, taken together, will also follow the Born weights. The statement about first outcomes is not one of the numbered predictions of the dated record. The physicist Lee Smolin has proposed that a system prepared for the first time, with no earlier copies, need not follow the Born weights, but this account says neither the repeated measurements nor the pooled first outcomes will depart from the Born weights. *Interference* is the way the quantum waves of different paths add and cancel, and this account says interference among three paths will show nothing beyond what the pairs of paths give. There is a score for tests of entanglement between two places, devised by the physicists John Clauser, Michael Horne, Abner Shimony and Richard Holt: a number that measures how strongly the findings at the two places agree. This account says the score in the tests will rise to twice the square root of two, and no higher. Two measurements *commute* when either can be made first without changing the outcome of the other, and if, at either place, the two measurements chosen between

commute, the tests will stay at a score of two or below. Apart from the statement about first outcomes, the claims of this entry are Prediction 25, "The statistics of quantum theory hold".

Whether a computer's rule lies beneath the world. The physicist Gerard 't Hooft has proposed that a computation lies beneath quantum theory, a computation that follows one fixed rule in discrete steps, like a vast grid of cells, each updated by the same rule. Quantum information science is the study of how quantum systems store and process information. In precision measurement and in quantum information science, experiments are approaching the range of precision at which the statistics of a fixed rule in discrete steps can be tested very finely. For any one fixed discrete rule offered as the foundation of physics, this account says a fine enough measurement will tell the statistics of the rule from the statistics of the world. A measurement is fine enough when the measurement resolves differences smaller than the smallest step of the rule. The claim about a discrete rule is Prediction 29, "A discrete rule shows itself to a fine enough measurement".

Qubits at different heights. A processor can hold identical qubits at different heights and compare them. My book *The Quantum Bridge*, chapter 5, says qubits at different heights will differ in frequency by the slowing of time in gravity, about one part in ten million billion for each meter of height. Chapter 5 of *The Quantum Bridge* also says the qubits will differ in nothing else that depends on height. The *coherence times* of the qubits are how long each qubit keeps its superposition. So, when the ordinary surroundings of the qubits are matched, the coherence times will not depend on height. The statements about qubits at different heights come from *The Quantum Bridge* and are not among the numbered predictions of the dated record.

Chapter Eight: When the Stars Go Out

The energy of empty space at every era. Four surveys will map the history of the expansion: the Euclid space telescope, the Vera C. Rubin Observatory and the Nancy Grace Roman Space Telescope, with the continuing survey of DESI. The four surveys will map the history of the expansion in four ways: the distances to exploding stars of known brightness, the spacing of galaxies, the bending of light by matter, and the pattern of the microwave background. The energy that drives the accelerating expansion has an *equation of state*. The equation of state is the ratio of the energy's pressure to its energy in each cubic meter. From the history of the expansion, the four surveys will measure the equation of state, and this account says the surveys will find the equation of state exactly minus one, at every era. On this account the energy of empty space is one constant, fixed once, and neither grows nor fades. The team of the Dark Energy Survey combines the survey's final data with DESI and the microwave background, and in that final analysis the team reports a departure from minus one (Abbott and others 2026). On the reported departure, the dated record says: "The reported departure from -1 will not be confirmed". The claims about the equation of state are Prediction 8, "The equation of state of the vacuum energy is exactly -1".

How long the dark matter lasts. Two kinds of coming measurement will measure the history of the expansion closely enough to show whether any of the dark matter has been decaying away. The first kind is the coming maps of the microwave background, among them the maps of the Simons Observatory, and the second kind is the coming surveys of galaxies, among them DESI and Euclid. This account says the dark matter does not decay. On this account, as space grows, the density of the dark matter falls exactly as the density of matter falls. So the dark matter keeps the same ratio to ordinary matter today as when the microwave background was released. Each epoch's dark matter is made at its own turn, and none passes from one epoch into the next. In the conformal cyclic cosmology of Roger

Penrose, one epoch also follows another, and the measurement of whether the dark matter decays sets this account apart from the cosmology of Penrose. In Penrose's account the dark matter must decay within each epoch, with a lifetime that he puts at perhaps about a hundred billion years. The claims about the lasting of the dark matter are Prediction 20, "The dark matter does not decay".

Entries listed under earlier chapters. The searches for the decay of the proton are listed under Chapter Four. The searches bear on whether ordinary matter lasts through the long emptying of the universe, in which the stars burn out. This account says the proton lasts. Two measurements listed under Chapter Six also bear on the turn to a new epoch: the measurement of the flatness of space and the search for waves from the beginning. This account says space will be found flat and no primordial waves will be found, since each epoch begins at a turn, with no long inflation.

Appendix B

For the Specialist

This appendix gives, for every claim of the chapters that rests on my collection, the book, the chapter and the section of the collection that carries it. Beside the locations it gives the mathematics and the exact values that the chapters leave out of the main line, with each symbol read in words where it first appears. It also names primary papers by author and year, and their full entries are in the References. The entries follow the chapters, and within each chapter they follow the order in which its claims occur, each stating the claim in the chapter's own words where it can. The last entries locate, in the books of the collection that carry them, four statements of the appendix "What the Coming Measurements Will Find". The word *symmetry* has two senses here, and each entry says which one it uses. The two senses differ in what the word is said of. In the theorem's sense, the word is said of what a comparison finds, and it names a sameness: in the words of *Incommensuration; The Theorem and the Three Axioms*, "*Symmetry* is a sameness of content where there is a difference of context". In the physicists' sense, which Kaku uses, the word is said of a thing or of the equations of a law, and it names a change after which the thing is as it was, as a sphere looks the same however it is turned. The same book keeps the two senses apart in chapter 5, "The Ground as Premises", section VII, "Two Vocabularies": "Physics uses the words 'symmetry' and 'continuity' of mathematical objects, while this book uses them of what a comparison finds". Each chapter is complete without this appendix.

Preface: Kaku's Promise

The Immanent Metaphysics works from inside the act of knowing, here and now, while that act takes place, and never from a place outside the world. The ground it starts from takes nothing from physics: no measurement, no law and no result of any experiment. Location: *Home in the World; The Immanent Metaphysics for Readers of Carlo Rovelli*, Prelude, "Two Crews, One Tunnel", section "The Crew from Knowing". The same passage defines metaphysics as "the study of what must be so for anything at all to be known" and immanent as "within". It names the question from which the account is worked out: "what must every comparison contain, whatever is compared, and whoever or whatever does the comparing?"

Every measurement is an act of comparison, and every result of physics stands on comparisons. Location: *Comparison; The Necessary Basis*, chapter 2, "Comparison as the Ground of Science", in the opening paragraphs before the chapter's first section. The definition of comparison is given in *The Last Turtle*, Glossary, entry "Comparison": "the act of finding whether two things are the same or different, in some respect". The same entry states that comparison, interaction and relation are one act, named three ways, and that every act of knowing is a comparison or is built from comparisons.

The road country, a country where the only way to travel is by road, stands for the one world: everything any path can reach. Location: *What Comes After the Dark; The Far Future of the Universe, in Plain Words*, chapter 10, "Could Anyone Escape?", section "No Other Sky Along Any Path". The physics the picture carries is stated in that section in one sentence: "In this physics, space is the pattern of which events a signal can join". In its chapter 12, "What Comes After the Dark?", section "What Crosses", the same book says: "The next epoch is joined to ours by no path and no act, and whatever a path can reach belongs to our own one world".

Chapter One: Two Kinds of Impossible

The resolution of the Royal Academy of Sciences of 3 May 1775, with the session at which it was voted, is printed in the Academy's *Histoire* for the year 1775 (Académie royale des sciences, 1775). Its history, and the paper of M. de la Frainaye that was before the members, are set out by Jacob (2005).

The editorial of the *New York Times* that mocked Robert Goddard, "A Severe Strain on Credulity", appeared on 13 January 1920. Kaku gives the year as 1921 (*Physics of the Impossible*, Preface, "Studying the Impossible").

The laws of physics, as we know them, can change: a law is a regularity of what is found within one domain, our universe, and if an experiment contradicts a law, the law must be revised. Location: *Comparison; The Necessary Basis*, chapter 10, "Reasoning", section VIII, "Axioms, Laws, and Principles", under "Three Levels" and "Worked Example: Physics". In chapter 10, section VIII, of *Comparison; The Necessary Basis*, I sort descriptions into three levels by the reach of each description, counted in domains. A domain is the whole range of places, or of things, that can be joined to one another. Laws apply within one domain, our universe with its particular constants and particles. Principles apply across many domains. The axioms of comparison apply between all domains, and would hold "in any universe with any physics". Falsification applies to laws, within one domain, and the same section says that "To demand that the axioms be falsified as a law is falsified is a category error".

In inquiry, a gap is the place where the next question is asked. A gap of that kind marks the frontier, where the next work is done. Location: *Physics Is Not Math*, chapter 12, "Chains and Cables", section IV, "An Argument About the World Has Four Features of Its Own".

An engineer who knows that energy is conserved can judge a design for a perpetual motion machine from its drawings, and can point to where its trouble will show. Location: *Two Theories, One World*, chapter 21, "Four

Questions for Any Theory", section "Judging a Design Before It Is Built". In that section's words, her judgment "depends on a law that every machine must meet, and that this design does not meet".

The perpetual motion machine is excluded by the conservation of energy, a law of our universe that was learned from measurement. An exclusion by such a law is of the kind the collection calls empirical: it rests on what measurement has found, and it stands as long as the law stands. So the machine keeps the place Kaku gave it, in his Class III, and it is not among the requests that name nothing. Locations: *Two Theories, One World*, chapter 21, section "Judging a Design Before It Is Built", for the law the machine fails; *What Cannot Be*, chapter 12, section "What Kind of Impossible", for the empirical kind, an impossibility shown by experiment; and *What Cannot Be*, chapter 2, for the reason, given in the next entry, that the account adds to the law.

Conservation has a reason that comes before the measurements: the conservation law is the symmetry itself, in the theorem's sense (a sameness of content where there is a difference of context), said in the form of a number that does not change. Location: *What Cannot Be*, chapter 2, "Two Kinds of Law", section "Conservation: Symmetry Said as a Number". The section's picture is a corked bottle of water: "The amount of water is the content, and it is the same; the moment at which we look is the context, and it is different". The same section adds: "Vary the context in time, and the content that does not vary is energy". Emmy Noether's theorem (Noether, 1918) is kept there as the exact mathematics it is. Its statement holds for every system whose laws can be written in the *Lagrangian form* (all of a system's laws written through one quantity, from which the laws follow). For such a system, to every smooth symmetry in the physicists' sense, a continuous family of changes that leaves the laws the same, there corresponds a *conserved current*: a quantity that can flow from place to place and is never made or lost. On the account, conservation holds of every domain that has symmetry in the theorem's sense. It holds whether or not the domain can be written in the Lagrangian form, and whether or not its sym-

metry can be written as a smooth family of transformations (a Lie group). Noether's theorem tells the physicist exactly which conserved quantity goes with which symmetry, and how to compute it, and the account tells the physicist why there was going to be one. The physicist's statement of this is in the same book, Appendix, "For the Physicist", section "For Chapter 2: Conservation and the Group", under "Conservation beyond the Lagrangian form".

A conservation law holds within a range of settings, and no conservation law holds perfectly across all conditions. At the end of its range, in the words of *What Cannot Be*, there are "conditions under which the conservation fails, or under which the quantity it conserves stops being well defined". That bound on conservation lies at the edges of domains, so it forecasts no loss of energy in a laboratory, which lies well inside the range of the conservation of energy. Location: *What Cannot Be*, chapter 2, "Two Kinds of Law", section "Where Conservation Ends"; and *The Last Turtle*, chapter 23, "Conservation and Its Bound", section II, "The Bound on Conservation". *What Cannot Be* reads the known difficulty of defining a conserved total energy for a universe that is curved and expanding as an instance of the bound.

In the road country, a town is a place because a road can join it to the other towns. A town not yet reached by any road is a place of the country that waits on a road, and a "town" that no road could ever reach is no place at all for a traveler there. Location: *What Comes After the Dark*, chapter 10, "Could Anyone Escape?", section "No Other Sky Along Any Path".

A request to go north of the North Pole defeats itself in its statement. A constraint could in principle be otherwise, and the edge of a domain is what makes the domain the domain it is. Location: *What Cannot Be*, chapter 12, "The Shape of What Can Reach What", section "Beyond the Farthest Point".

Kaku names, among the things "impossible to explore", "the world existing beyond the reach of the speed of light" (*Physics of the Impossible*, Epilogue, "Is Physics Incomplete?"), and this account agrees. Happenings beyond that reach "are not places at all, in the sense that matters here, because a place is a position in the pattern of connection". Location: *What Cannot Be*, chapter 12, section "Beyond the Farthest Point".

When this account says that something cannot be, it means that the request names nothing. No future machine can satisfy a request that names nothing, so what is excluded in principle is excluded, for that reason, in all future practice. Location: *What Cannot Be*, Preface, "Before We Begin", section "What 'Cannot Be' Means Here".

On the surface of a sphere, a point farther away than the antipode is no place to travel to, "but not because there is a rule forbidding travel beyond the antipode": the antipode is the farthest point there is. Signaling faster than light is the causal counterpart of that request, and of it the same section says: "It is not forbidden by a rule. It is precluded by the structure of the domain". Location: *The Basis of Physics*, essay 10, "Causation, Connectivity, and the Domain Boundary of Comparison", section VI, "The Category Error: Beyond the Antipode". The collection names three kinds of impossibility: logical (a contradiction in a formalism), empirical (a finding against a law of our world) and structural (a request the structure of the domain has no place for). Locations of the three kinds: *What Cannot Be*, chapter 12, section "What Kind of Impossible"; and *The Basis of Physics*, essay 10, section IX, "The Fermi Paradox and the Wrong Channel", method note "On the Kind of Impossibility Claimed". I place Kaku's Class III in the empirical kind, since he defines it as "technologies that violate the known laws of physics" (*Physics of the Impossible*, Preface, "Predicting the Future"). The first kind of "impossible" in Chapter One, the kind that can change, holds things not yet built and empirical verdicts. The second kind of "impossible" in Chapter One is the structural kind.

The Incommensuration Theorem, in its own words: “Symmetry and continuity cannot both be applied, simultaneously and fundamentally, to any event or comparison; and neither can asymmetry and discontinuity”. Location: *Incommensuration; The Theorem and the Three Axioms*, chapter 2, “Symmetry and Continuity Cannot Both Be Perfected”, section VI, “The Theorem”. The same chapter, in section I, “Four Characters”, defines the four characters by two verdicts of a comparison, one on the content and one on the context. “*Symmetry* is a sameness of content where there is a difference of context”, and “*Continuity* is a sameness of content where there is a sameness of context”. *Asymmetry* is a difference of content where there is a difference of context, and *discontinuity* a difference of content where there is a sameness of context. The plain gloss of symmetry that the chapters use, the same content in different settings, is that of *What Cannot Be*, Preface, section “What This Book Offers”. The plain gloss of continuity is that of *Incommensuration*, chapter 2, section I: “Within one unbroken stretch of context, the content does not jump”.

The Incommensuration Theorem is a structural fact about the nature of knowing. Every act of knowing is an act of comparison, or is built from acts of comparison, so the theorem is inherent in every single act of knowing. Location: *Incommensuration; The Theorem and the Three Axioms*, Preface, and its section “The Incommensuration Theorem, as a Prohibition”; and *What Cannot Be*, Preface, section “What This Book Offers”, and chapter 3, “Why One Description Cannot Be Perfect Both Ways”, section “What Kind of Claim This Is”. *What Cannot Be* states the standing in full: the theorem, “together with the intrinsics of comparison from which it is built, is inherent in every single act of knowing”.

No experiment, no physical theory and no particular kind of mathematics enters the theorem, and it was not learned from measurement. Location: *What Cannot Be*, chapter 3, “Why One Description Cannot Be Perfect Both Ways”, section “What Kind of Claim This Is”.

The theorem's result is a claim about what holds permanently, whatever is later learned and whatever theory is later found. Location: *Incommensuration; The Theorem and the Three Axioms*, chapter 6, "The Incommensuration Theorem: Statement and Proof", section XI, "The Two Surviving Modes". Of the pairings of the four characters, two hold together when both members are applied absolutely, that is, held exactly, at the foundation of a description, with no exception at any scale. The two are continuity with asymmetry (smooth and going somewhere) and symmetry with discontinuity (the same everywhere and countable), each in the theorem's sense. *What Cannot Be* calls them the *survivors* of the theorem (Preface, section "What This Book Offers").

My book *Incommensuration* reads a family of limits already known in physics and mathematics as instances of the theorem, and Gödel's proof that arithmetic is incomplete is one of those limits. Location: *Incommensuration; The Theorem and the Three Axioms*, chapter 15, "The Theorem Among Other Results", section III, "A Family of Limits, and the Ubiquity of the Duality"; the instance is worked in section II, "Four Instances", under "Instance: Gödel's Incompleteness". The same section names Bohr's complementarity, Heisenberg's uncertainty relations, Gödel's incompleteness theorems and Arrow's impossibility theorem as domain-specific instances of the theorem's two forbidden pairings, and says the theorem explains "why no future theory will remove them". Primary paper: Gödel, 1931.

The exclusions of the second kind are few, and each is named and shown in full in its own chapter of *What Cannot Be*. Location: *What Cannot Be*, Preface, section "What 'Cannot Be' Means Here"; the list is gathered in its Afterword, "What Cannot Be, and What Can", section "The Eight Exclusions". The Preface names four of them, in its section "Four Things We Are Told Might Be Possible". They are "a message sent faster than light", "a trip back to last Thursday", "a world that is someone's program, running on a computer in some other world, with us inside it", and "a uni-

verse that runs like clockwork". The Afterword says of every one of the exclusions that it names nothing and that each "is excluded in principle, and therefore in all future practice".

Kaku counts robots and other thinking machines in his Class I (*Physics of the Impossible*, ch. 7, "Robots", closing paragraph), and this account agrees: "Artificial intelligence is possible". Location: *What Cannot Be*, chapter 22, "Why No Computation Is Everything", section "What Computation Can Do".

What can be had in place of a request that names nothing is a coherent request that does name something. Location: *The Basis of Physics*, essay 12, "Cross-Modal Reach: Why General Relativity and Quantum Mechanics Cannot Be Unified", section VI, "What a Unification Would Have to Be": "To an impossibility, one responds by asking what the coherent version of the request is, and pursuing that instead".

Chapter Two: Faster Than Light, and Back in Time

Einstein and Rosen meant the bridge as a model of a particle, and not as a passage to travel through. The wormholes found later each need a throat held open by a material whose tension is greater than its energy, which physicists call negative energy. Location: *What Comes After the Dark*, chapter 10, "Could Anyone Escape?", section "A Bridge Between Two Sheets"; the gloss of negative energy, "a state of a field with less energy than empty space", is in the section "Kaku's Plan of Escape" of the same chapter. Primary papers: Einstein and Rosen, 1935; Morris and Thorne, 1988.

Every measurement is an act of comparison, and so is every interaction, every case of one thing acting on another. Location: *What Cannot Be*, chapter 12, "The Shape of What Can Reach What", section "Every Cause Is a Comparison".

The forward light cone of an event is everything the event can affect, and the backward light cone is everything that can affect it. Location: *What Cannot Be*, chapter 12, section "The Cone Comes First". The same section places the cone in the terms of the Incommensuration Theorem. Causality taken as a reach, the connection from one event to every event it can affect, unbroken and one-way, has the character of continuity with asymmetry, in the theorem's sense. Continuity with asymmetry is one of the two pairings that the Incommensuration Theorem allows to be carried all the way, and general relativity carries continuity with asymmetry all the way.

Space is the pattern of which events are causally connected with which. Location: *What Cannot Be*, chapter 12, section "What Space Is". In the section "What Space Is" of *What Cannot Be*, I cite the results of general relativity in which the causal structure alone, the bare list of which events can reach which, already fixes the topology of space and time (Malament, 1977; Hawking and Ellis, 1973).

The speed of light marks the outer edge of the domain of comparison, the whole range within which comparisons can be made. No rule is needed to keep anything within it. Location: *What Cannot Be*, chapter 12, section "The Two Edges of Comparison"; the sentence "There is no rule" is in the section "A Rule on a Stage"; the picture of the horizon made by the curve of the ground is in the section "Beyond the Farthest Point". In the section "An Exchange Rate Between Time and Space", the speed of light, written c, is the conversion factor between the time side and the space side of the pattern of causal connection. It is the one ratio by which that connection is shared between time and space, as a light-year is a distance named by a time.

The no-communication theorem of quantum theory is correct, and this account reaches the same result on deeper ground. The argument uses only three things: that interaction is comparison, that comparison has edges built into it, and that the speed of light marks the outer edge. So "the edge of the domain would remain if quantum theory were modified or re-

placed". Location: *What Cannot Be*, chapter 12, section "The Edge Rests on Comparison Alone". Primary paper for the no-communication theorem: Ghirardi, Rimini and Weber, 1980. The same result is argued from the geometry of each alternative in *The Unquantized Arena*, chapter 7, "One Geometry for Each Alternative", section IV, "No Signal Faster Than Light", Proposition 7.2. A finding changes no geometry, here or anywhere, and news of a distant finding enters a comparer's record only at an event on or within the future light cone of the finding.

Nothing crosses the distance between entangled particles: each record, taken alone, is a random list, and the agreement appears only when the records are brought together "by ordinary means and at ordinary speed". Location: *What Cannot Be*, chapter 10, "What Bell Found", section "What the Correlations Are".

In 2015 at Delft, Hensen and colleagues set two entangled electrons one point three kilometers apart and found an agreement stronger than any account built from local causes allows. Location: *What Cannot Be*, chapter 10, "What Bell Found", section "Bell's Question". The exact values are given in the same section, in the form of the test due to Clauser, Horne, Shimony and Holt. Four pairs of detector settings give four correlations, combined into one score. Any account that is both local and realistic (each result fixed in advance at its own place) scores at most 2, and quantum theory predicts that the score can reach $2\sqrt{2}$ (twice the square root of two), a little more than 2.8. The measured scores are above 2. Primary papers: Clauser, Horne, Shimony and Holt, 1969; Aspect and colleagues, 1982; Hensen and colleagues, 2015.

Every comparison has one order, first the range of what is possible, then the act, then the record of the act. A finding, once laid down as a record, is not undone as a finding. Location: *What Cannot Be*, chapter 12, section "A Signal That Would Arrive Before It Was Sent"; and chapter 16, "Why Time Travel Names Nothing", section "The One-Way Order of Findings", where the order is called "a precedence and not a clock reading, and it cannot be reversed". The same book places this order under Axiom II of the Imman-

ent Metaphysics (chapter 16, section "The Four Barriers"). It says the order plainly in chapter 16, section "The Four Premises": "A range of possibility comes before an act, an act comes before its record, and a record comes before the next range of possibility".

"A law exists; a measurement is real". To exist is to stand as structure, timeless, the same in every instance. To be real is to be given in an actual act of comparison, occurring now, with the future still open. Location: *Why Time Travel Is Not a Concept*, chapter 1, "The Question", section III, "What Exists and What Is Real", quoting *The Unquantized Arena*, premise P14; the same distinction is Definition 4.4 of chapter 4 of that book. *What Cannot Be* applies the distinction to the past in chapter 16, section "The Conclusion": an occasion of event time "is real, given once in an act of comparison", and "The region of the geometry in which last Thursday lies exists, as structure".

Travel into the future stands untouched: a body can go anywhere its forward cone reaches, and its forward cone, given time, reaches a great deal. Location: *The Basis of Physics*, essay 10, "Causation, Connectivity, and the Domain Boundary of Comparison", section VIII, "What Is Not Excluded".

A wormhole needs negative energy to hold its throat open; on whether such energy exists in the needed amount, my books make no claim either way. Location: *Side by Side; Twenty-Four Models of the Universe*, Volume Two, the chapter on Stephen Wolfram, "The Rule and the World", section VIII, "Where the Predictions Part, and Why", under "Travel faster than light".

Asking whether one can signal faster than light is a category error. A happening outside an event's light cone has no position in the pattern of what can affect what, as seen from that event, and such happenings "are not places at all, in the sense that matters here". Location: *What Cannot Be*, chapter 12, section "Beyond the Farthest Point"; the gloss of a category error, a concept applied where it does not belong, is in the Preface, section "What 'Cannot Be' Means Here".

Two happenings outside each other's light cones have no order that every observer shares, so a signal between them would, for some observer, arrive before it was sent. In the book's words, "such a signal is no signal". Location: *What Cannot Be*, chapter 12, section "A Signal That Would Arrive Before It Was Sent".

No civilization communicates faster than light, because no civilization can. Location: *What Cannot Be*, chapter 12, section "The Silent Sky".

"Faster than light" carries two meanings. The first meaning is arrival outside the light cone of one's own departure, and that meaning names nothing. The second meaning is arrival sooner than the long way around would allow, by a shortcut that still arrives within the light cone of the geometry that has the shortcut. Location: *Side by Side*, Volume Two, the chapter on Stephen Wolfram, section VIII, under "Travel faster than light". On the second meaning the collection makes no claim either way about whether such travel can be engineered.

A wormhole held open by negative energy would be a new road, and a warp drive a faster car, and each arrives at a town of the same country. Location: *What Comes After the Dark*, chapter 10, section "The Plan, Step by Step".

"Time travel", in the sense in which the phrase is used, names no concept. Location: *What Cannot Be*, chapter 16, "Why Time Travel Names Nothing", section "Very Hard, or Nothing There?". In the section "The Conclusion" of *What Cannot Be*, I define the phrase 'names no concept'. A phrase names no concept when every account of what would satisfy it either describes something other than what the phrase is used to mean, or asks for a set of conditions, all at once, that nothing satisfies. "The largest prime number" names no number in the second way, and "time travel" fails in both ways, reading by reading.

Taken as a path on the map of space and time, a journey around a time loop ends in a later finding of the traveler, and not in an arrival at last Thursday as it was. Location: *What Cannot Be*, chapter 16, section "The

Geometric Reading": "So the arrival at the departure is a later finding of the traveler". Primary paper for the principle of self-consistency: Friedman, Morris, Novikov, Echeverria, Klinkhammer, Thorne and Yurtsever, 1990. The argument is set out as numbered propositions in *Why Time Travel Is Not a Concept*, chapter 4, "The Chain", section VI, "The Three Readings". Proposition 4.8 (the geometric reading) takes p as the event of departure and C as the traveler, and states four things about the paths a signal or a clock can follow forward in time (future-directed causal curves). First, no future-directed causal curve from p reaches an event that lies in the causal past of p (the events that can affect p) and not in its causal future (the events p can affect). Second, an arrival at an event in both the causal past and the causal future of p, which can happen only where closed causal curves pass through both, is a later finding of C. Third, a return to p along a closed timelike curve (a time loop) is a later finding of C, and not the occasion of the departure given again. Fourth, where a spacetime is extended beyond a *Cauchy horizon* (the boundary past which the state of the world is no longer fixed by its state on one slice of space at one moment), the same holds of the region beyond.

The order of findings runs one way, so a request that a later finding come before an earlier one asks for the one reversal that this order excludes. Location: *What Cannot Be*, chapter 16, section "The Event Reading and the Joint Reading"; in *Why Time Travel Is Not a Concept*, chapter 4, these are Proposition 4.6 (the order of findings is not reversed) and Proposition 4.9 (the event reading).

Being at last Thursday as it was asks one time to be found both as the map's time (continuous and asymmetric, in the theorem's sense) and as the notebook's time (discontinuous and symmetric), each exactly. The Incommensuration Theorem forbids both pairings that this would carry, so nothing satisfies the request, and "You cannot go back". Location: *What Cannot Be*, chapter 16, sections "No Unified Time" and "The Event Reading and the Joint Reading"; "You cannot go back" is in the section "The Reach of the Argument". The theorem is proved from comparison alone,

with no added assumption, in *Incommensuration; The Theorem and the Three Axioms* (cited in *What Cannot Be*, chapter 16, section "The Four Premises"); its statement is in chapter 2, section VI, "The Theorem", of that book. The Incommensuration Theorem is a structural fact about the nature of knowing. In *Why Time Travel Is Not a Concept*, chapter 4, the steps are Proposition 4.5 (no unified time) and Proposition 4.10 (the joint reading).

The account sets four barriers in the way of the phrase "time travel". There is no unified time. The order of findings runs one way. The record is not undone. And physics guards its own Cauchy horizons. Location: *What Cannot Be*, chapter 16, section "The Four Barriers", with the results of general relativity set out in chapter 15, "Time Machines on Paper", section "What Physicists Mean by a Time Machine". The first three barriers are structural, and the chain rests on them. The fourth is made of results reported from general relativity, and it is a check on the conclusion, not a premise of the chain. Hawking proved that a time machine built in a limited region cannot form from a slice of space that runs on without end if the *weak energy condition* holds (Hawking, 1992). A limited region here is a spacetime whose Cauchy horizon is compactly generated: its light paths, followed back into the past, stay within a bounded region. The weak energy condition is the rule that the energy any observer measures is never negative. Kay, Radzikowski and Wald proved that every well-behaved (Hadamard) state of the free scalar field breaks down at every point of a core part of such a horizon (Kay, Radzikowski and Wald, 1997).

A traveler who drives back to the town where she was born finds the town as it is on the day she arrives, not the morning of her birth. Location: *What Comes After the Dark*, chapter 10, section "The Plan, Step by Step".

Deutsch's result, that quantum theory near a time loop admits consistent histories in which a traveler arrives in the past of another branch, agrees with this account on the main point: no traveler arrives at an earlier occasion as the occasion it was. Location: *Side by Side; Twenty-Four Models of the Universe*, Volume One, Appendix D, "The Registered Predictions Beside

David Deutsch", section V, "Where No Measurement Decides", under "Travel into the past"; with *Why Time Travel Is Not a Concept*, chapter 4, Proposition 4.8. Primary paper: Deutsch, 1991.

Chapter Three: Ten Dimensions

The English wording of Einstein's reply to Kaluza, of 21 April 1919, is that of O'Raifeartaigh and Straumann (2000).

The dimension of a setting is the number of its independent ways of differing. Location: *Measurement; The Steps from Comparison to Physics*, chapter 11, "The Ten-Dimensional Context", section I, "What a Dimension Is".

The numbers that the structure of comparison supplies are one, two, three, four and six. One is for the single point of view, and two for the members of any pair. Three is for the three pairs of ideas, four for the four ideas that can be followed apart from the one who compares, and six for all six ideas together. Only the sizes of these sets of parts count, and not the numbers of their combinations, because a combination is made from parts already counted and brings no new part. Location: *Measurement*, chapter 11, section III, "The Numbers Comparison Supplies", where the same section says: "So only the sizes of the sets of elements count, and not the numbers of their combinations"; the three pairs and the four ideas that can be followed are set out in section II, "What the Count Can Use".

Time has one dimension, because the comparing is one point of view, and from one point of view any two findings stand simply as earlier and later. Location: *Measurement*, chapter 11, section V, "Time Has One".

Space has three dimensions: one would not tell space from time, two cannot mark the difference between themselves, and three is the least number in which every difference between two directions is marked by the third. Location: *Measurement*, chapter 11, section VI, "Space Has Three": "So the dimension of space is three". The exact statements of the rule for placing a difference, the doubling and the minimality principle are in sections II to X of the same chapter.

The count of space stops at three by the principle that "a difference that no comparison can register is no difference". A fourth way of space would place only distinctions already placed. Location: *Measurement*, chapter 11, section IV, "The Minimality Principle, and the Principle Beneath It".

Possibility has six dimensions, because each possible finding is fixed in all six ideas of comparison. Location: *Measurement*, chapter 11, section VII, "Possibility Has Six".

"Time has one dimension, space has three, and possibility has six: one and three and six make ten". Location: *Measurement*, chapter 11, section XI, "The Structure Without a Shape".

The Gravitational Passage reaches the counts of time and space by a second route, which shares no step with the first. Location: *At the Edge of Reality; From Black Holes to the Big Bang in Ten Dimensions*, chapter 7, "Six Dimensions of Possibility", section "Why We Never See Them", and the same chapter's sidebar "A Second Road to Ten", where the route is stated; and *Measurement*, chapter 11, Summary. The second route is the cycle of Axiom II (the order in which possibility, act and record follow one another): its three passages are identified with the three directions of space, and its one way of running with the one direction of time.

String theory's ten and this account's ten agree in number and differ in kind. String theory has nine dimensions of space and one of time, all of one kind. This account's ten are of three kinds, and its six are dimensions of possibility, which are never traversed. Location: *Measurement*, chapter 11, section XII, "Questions".

The six dimensions of possibility are met only as what could be found, the range from which each finding is one selection, and no located comparer travels through them as it travels through space. Location: *Measurement*, chapter 11, section VIII, "Why the Six Are Not Traversed".

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. Location: *At the Edge of Reality*, chapter 7, section "What This Means for You".

A measurement of how the pull of a mass weakens with distance would show a fourth way of space if space had one, and every such measurement made so far finds three. Location: *Measurement*, chapter 11, section IV, "The Minimality Principle, and the Principle Beneath It". The chapter's lamp stands for one relation. In a space of N directions the pull of a mass falls off as one over the distance raised to the power $N - 1$: as the square of the distance for three directions, and as the cube for four (Kaku, *The God Equation*, ch. 6). Primary papers for the tests of the inverse square law: Long and colleagues, 2003; Kapner and colleagues, 2007.

A vibration of either of the two moduli of the six would carry a pull between masses. The reach of each of the two pulls is shorter than a twentieth of a millimeter, the shortest distance the tests have reached, by about thirty orders of magnitude. Location: *The Compactification; Initial Conditions, the Perturbation Spectrum, and the Gravitational Wave Signature*, chapter 2, "One Vacuum", section V, "The Floor". The exact values follow. The two *moduli* of the six (the fields that set their size and their shape) have masses of 2.25 M_{Pl} (mostly size) and 3.09 M_{Pl} (mostly shape). They are two fields of the geometry apart from the joining fields, the mixed components that join the six to the four. *The Gravitational Passage* derives them, in the opening of its chapter 11, "The Kaluza–Klein Reduction", as the fields that describe the size and the shape of the six. Here M_{Pl}, the Planck mass, is the full Planck mass, 1.221×10^{19} GeV, and a GeV is a billion electron volts. A mass of two to three Planck masses gives each pull a range shorter than the Planck length, the length formed from the measured Newton constant. A modulus of small mass would carry a long-range force of the kind the Cassini measurement of the bending of radio waves by the Sun excludes (Bertotti, Iess and Tortora, 2003). The same val-

ues are given in *The Gravitational Passage*, Appendix D, section III, and in *What the Beginning Left Behind*, Appendix B, section "Measured Agreements Beneath the Account".

The six dimensions of possibility have one shape: the space of all the states of a three-way choice, of four dimensions, taken together with the space of all the states of a two-way choice, of two. Location: *At the Edge of Reality*, chapter 7, sections "The Shape of the Six" and "A Space of Possibilities"; and chapter 3, "Why Ten Dimensions?", section "The Answer of This Book". The shape is derived from the grid of the six *measures*, six independent respects in which what is found can vary, one from each of the six ideas of comparison (chapter 7, section "The Shape of the Six"). The space of the six gives each measure its own direction, and the grid has two rows, content and context, and three columns, the three roles. In symbols the space of the six, which physicists call the *internal space*, is $\mathbb{C}P^2 \times S^2$. Here $\mathbb{C}P^2$ (read "the complex projective plane") is the space of states of a three-way choice, of four real dimensions, and S^2 (read "the two-sphere") is the space of states of a two-way choice, of two. The sign $\times$ (read "times") joins them as a product, of dimension four plus two, which is six. $\mathbb{C}P^2$ has four real dimensions because a state of a three-way choice has three complex amplitudes, six real numbers, less one for the overall size and one for the overall phase. S^2 has two by the same count: two complex amplitudes, four real numbers, less the same two. The shape is fixed by the *Euler characteristic*, a number fixed by a shape's basic pieces, written χ (chi). The piece that carries the three roles has $\chi = 3$, and the piece that carries the two rows has $\chi = 2$. Take each piece to be homogeneous (every point like every other) and compact (closed, and of finite extent). Then the only such surface with $\chi = 2$ is the sphere, and the only such four-dimensional shape with $\chi = 3$ is the complex projective plane. So $\mathbb{C}P^2 \times S^2$ is the only compact homogeneous product that meets the conditions. The classification on which this rests is given in *The Gravitational Passage*, chapter 9, "The Internal Space and Its Uniqueness", sections IV, "Cells and the Euler Characteristic", and VI, "The Classification". It is given also in

The Compactification, chapter 1, “The Re-Forming of the Internal Space”, section III, “The Internal Space on the Context Instance”. For a compact homogeneous space, χ is positive exactly when the subgroup that fixes a point has the same rank as the whole group (Hopf and Samelson, 1941). The four-dimensional cases are classified by Ishihara (1955). The natural distance on a space of states measures how well one state can be told apart from another (Wootters, 1981; cited in *At the Edge of Reality*, chapter 7, section “A Space of Possibilities”).

I identify the six of possibility with the six further dimensions of this account’s physics: both are counted by the same six ideas of comparison, one dimension for each, and by nothing else, so no comparison could register a difference between them. Location: *At the Edge of Reality*, chapter 7, section “A Space of Possibilities”: “I identify the two sixes as one set”.

The same six serve in two ways, as the face of a clock is both the pattern of twelve hours, with no size, and a particular clock, with a width. Neither way of taking the six is a place, and nothing travels through either. Location: *What the Beginning Left Behind; The First Ripples, the First Waves and the One Vacuum, in Plain Words*, chapter 1, “Where the Last Book Left Us”, section “One Space, Taken Two Ways”. In the specialist’s terms the two are the content instance and the context instance. The content instance is the space of states, with no size and no fields, where the kinds and values of the particles are read. The context instance is the space with radii, on which gravitation, the cosmological constant and dark matter rest. Locations: *The Compactification*, Preface, section II, “The Two Instances of the Internal Space”; *The Gravitational Passage*, chapter 8, “The Product Structure $M^4 \times \mathbb{C}P^2 \times S^2$”, section IV, “The Kaluza–Klein Reading”.

Taken as a pattern, the six settle which kinds of matter there can be, and how those kinds can join into atoms and bodies. Location: *What Comes After the Dark*, chapter 4, “Could Empty Space Change Its Nature?”, section “The Six Small Dimensions”.

Taken as held, the six are present at every point of the four dimensions of space and time and kept finite there, with those four as their setting. The word *compactification*, in my books, means only that holding, since the six were never directions of space. A *field* is something spread through space with a value at every point, as the temperature of a room has a value at every point in it. Location: *What the Beginning Left Behind*, chapter 1, "Where the Last Book Left Us", section "One Space, Taken Two Ways", where all three are stated.

Taken as held at every point of the four dimensions of space and time, the six have a definite extent, and the strength of gravity is tied to that extent. Location: *At the Edge of Reality*, chapter 7, section "Why We Never See Them": "Their extent shows only through its effects, among them the strength of gravity, which is tied to the volume of the internal space". The radii are fixed by one identification, made in the first person: every internal direction reaches one curvature, the Planck curvature $1/l_{\mathrm{Pl}}{}^2$ (one over the square of the Planck length l_{Pl}, the length formed from the measured Newton constant). That makes the internal metric an *Einstein metric* (one whose curvature, averaged over directions, is a fixed multiple of the metric itself), and gives $R_{\mathrm{T}} = l_{\mathrm{Pl}}$ and $R_{\mathrm{O}} = \sqrt{6}\, l_{\mathrm{Pl}}$. Here R_{T} is the radius of the sphere S^2, and R_{O} the radius of the round five-sphere whose quotient by the circle of phases is $\mathbb{C}\mathrm{P}^2$. The internal space is a few Planck lengths across. Locations: *The Compactification*, chapter 1, section III, under "The radii", equation (1.1); *The Gravitational Passage*, chapter 9, section IX, equation (9.2).

Kaluza's own method, used in ten dimensions on a geometry with nothing in it but the shape itself, gives Einstein's gravity in the four dimensions we live in: "That is a unification in the sense of a common source". Location: *The Gravitational Passage*, chapter 8, "The Product Structure $\mathrm{M}^4 \times \mathbb{C}\mathrm{P}^2 \times \mathrm{S}^2$", section IV, "The Kaluza–Klein Reading". The whole space is $\mathrm{M}^4 \times \mathbb{C}\mathrm{P}^2 \times \mathrm{S}^2$, of $4 + 4 + 2 = 10$ dimensions, where M^4 is the four-dimensional space and time we observe. The ten-dimensional Einstein–Hilbert action (the quantity from which Einstein's equations fol-

low), integrated over the internal space with its moduli held, gives the four-dimensional Einstein equations. The reduction also gives the Planck mass from the internal volume, the two moduli (volume and shape), and a bare curvature term. Location of the reduction: *The Gravitational Passage*, chapter 11, "The Kaluza–Klein Reduction", sections II, "The Decomposition of Metric Fluctuations", and V, "What the Reduction Achieves". Primary papers: Kaluza, 1921; Klein, 1926.

A program that merges the four and the six, treating all ten dimensions as of one character, meets the Incommensuration Theorem as a no-go result. In the theorem's sense the arena is continuous and asymmetric, and what is found in it is discontinuous and symmetric. One geometry that carried both characters in the same directions would carry a pairing the theorem excludes. Location: *The Gravitational Passage*, chapter 8, section III, "The Incommensuration Theorem Forbids a Merger". The theorem's statement is quoted from *Incommensuration; The Theorem and the Three Axioms*, chapter 2, section VI, "The 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.

The extra components of the geometry belong to the six taken as held, with their extent, and their vibrations reach ordinary matter only through gravity. The symmetries of light and of the two nuclear forces, in the physicists' sense, are read from the same six taken as the pattern where the kinds of particle are read. Location: *The Gravitational Passage*, chapter 8, section IV, "The Kaluza–Klein Reading": the mixed components "couple to the matter and the gauge forces only through gravity", and "The gauge symmetry of the content is read from the isometries of the internal space read as a space of states". The same section names three facts at the boundary of what that book derives. First, the *isometry group* of $\mathbb{C}\mathrm{P}^2 \times \mathrm{S}^2$ (the group of its symmetries, in the physicists' sense, that keep all distances) is locally $\mathrm{SU}(3) \times \mathrm{SU}(2)$, with no $\mathrm{U}(1)$ factor. Here $\mathrm{SU}(3)$ is the group of symmetries of a three-way choice, the group of the strong nucle-

ar force. SU(2) is the group of symmetries of a two-way choice, the group of the weak nuclear force. And U(1) is the group of phases, the rotations of a single setting on a circle. Second, $\mathbb{C}P^2$ is spin^c (a space on which a field of half-integer spin can be written once a field of phase is joined to it), and it is not a spin manifold. A spin manifold is a space on which a field of half-integer spin, such as the electron's, can be written with no further field. So a spinor field on it, a field of half-integer spin, needs a U(1) connection, a field of phase. Third, the first of these is a stated difference from Witten's seven-dimensional internal spaces, which are circle bundles over $\mathbb{C}P^2 \times S^2$ with isometry group $SU(3) \times SU(2) \times U(1)$ (Witten, 1981).

I identify gravity with the arena itself, the setting in which everything is found: "I identify gravity as the context-modal phenomenon of physics". Location: *Measurement*, chapter 10, "Context and Its Markers", section VII, "Gravity Is the Context".

"The arena is the setting in which every content is found, and the content is what curves the arena". The two descriptions are composed side by side and not merged. Location: *Measurement*, chapter 10, section IX, "The Two Characters Cannot Be Merged into One Geometry".

The four and the six belong to one structure, joined at every root: each gauge field joins the two factors while each keeps its own pairing, which is the inseparability of the content factor and the context factor that Axiom III requires. Location: *The Gravitational Passage*, chapter 8, section IV, "The Kaluza–Klein Reading".

No single larger symmetry, in the physicists' sense, joins the forces of the particles into one at any energy. Location: *The Kinds of Particle*, chapter 4, "The Gauge Factors", section I, "The Gauge Group": "No simple Lie group is the gauge group of the theory at any scale; no set of gauge bosons beyond the twelve of the three factors exists".

Chapter Four: One Equation?

The three axioms, in the exact wording of *An Immanent Metaphysics*, aphorism 1.3-1. Axiom I. The immanent is more fundamental than the omniscient and/or the transcendent. The omniscient and the transcendent are in conjugate relationship to one another. Axiom II. 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. Axiom III. The (classes/instances) of the immanent, omniscient, and transcendent are distinct, inseparable, and non-interchangeable. In the first axiom, "and/or" means of either one and of both together; in the third, the bracket means that the statement holds both of the classes and of the instances. In the frame of Chapter Four, where the three positions are the parts of one act of comparing, the immanent is the act of comparing, the omniscient is the thing compared, which the one comparing has fully in view, and the transcendent is the thing it is compared against, which the one comparing reaches toward and never contains. The third axiom holds as well of the pairs of ideas that fill the positions, and content and context are one such pair, as Chapter Eight uses it.

David Scott's drop of the hammer and the feather, on 2 August 1971, is recorded in the Apollo 15 Lunar Surface Journal, "EVA-3 Closeout". The Apollo 15 Preliminary Science Report gives the height of the drop as about 1.6 meters, and the Journal's annotation estimates it at a little over a meter. It finds about 120 centimeters from Scott's posture, about 113 from the photograph, and about 117 from the measured time of the fall, 1.2 seconds, under the Moon's gravity. The drop is also described by NASA's Space Science Data Coordinated Archive, on its page "Apollo 15 Hammer-Feather Drop", which gives the Preliminary Science Report's height.

The agreement of every falling body, from the hammer and the feather on the Moon onward, pointed "to something that does not depend on what a body is made of, which in the end was the arena of space and time itself". Location: *Physics Is Not Math*, chapter 13, "A Value That Lands", sections I, "Two Kinds of Mass", and II, "Why Does It Land?".

In 2022 the MICROSCOPE satellite reported that titanium and platinum, falling together around the Earth, fall alike to within a few parts in a million billion. Location: *Two Theories, One World*, chapter 27, "What the World Will Show", section "Every Material Will Fall Alike". Primary paper: Touboul and colleagues, 2022.

There is one account of everything, and it is made of two descriptions joined together. Location: *Two Theories, One World*, chapter 24, "Joined, Not Merged", section "One World, One Account, Two Descriptions".

Gravity carries four marks that any arena must carry. It couples to everything, and nothing shields it. The mass it pulls on is the mass that resists being moved, and it has no charge of its own that comes in steps. So gravity is the shape of the arena, and not one more force acting within it. Location: *Two Theories, One World*, chapter 9, "Four Marks of the Arena", which derives each mark for any arena and then finds it in gravity, with the four set side by side in its section "The Four Together"; the same marks are summed up in the Preface, "The Argument in Brief", section "The Answer in a Page".

A comparison perfected at its foundation has one of two characters, by the Incommensuration Theorem: smooth and changing from place to place (continuous and asymmetric, in the theorem's sense), or exactly repeating and coming in countable steps (symmetric and discontinuous). Location: *Two Theories, One World*, Preface, section "The Answer in a Page"; the theorem's statement is in *Incommensuration; The Theorem and the Three Axioms*, chapter 2, section VI, "The Theorem". The same section of *Incommensuration* defines the word: "To be perfected is to hold exactly, at the foundation of a description". It also states what follows from the theorem: "Any com-

parison, perfected at its foundation, is either continuously asymmetric or discontinuously symmetric". A comparison held exactly is either symmetric or asymmetric, and either continuous or discontinuous, so four joinings of its characters are possible, and the theorem excludes two of them; the four are set out in chapter 2, section I, "Four Characters", of the same book. The Incommensuration Theorem is a structural fact about the nature of knowing.

I identify quantum theory as the description of the content of physics, and general relativity as the description of its context, the arena. Location: *Two Theories, One World*, Preface, section "The Answer in a Page".

Each of the two theories is perfected in one of the two remaining joinings: each holds its joining exactly, at its foundation. Each captures what the other leaves out, and every comparison uses both. They are two descriptions of one world, joined side by side and never merged. Location: *Two Theories, One World*, chapter 24, "Joined, Not Merged", sections "What the Theorem Permits" and "What Follows for the Search"; the same sentence closes the Preface's section "The Answer in a Page".

"Theory of everything" has two meanings, an account that leaves nothing out and an account written as one description with one character throughout, and "The theorem allows the first and forbids the second". Location: *Two Theories, One World*, chapter 24, section "One World, One Account, Two Descriptions". In the section "What the Theorem Forbids" the merger is stated exactly: one description in which the directions of space and time themselves carry both characters. A quantized arena would carry at least one of the two forbidden pairings, and, where all four characters are asked of the same directions, both. The general form of the distinction among a merger, a common source, a correspondence and a union within one character is in *The Unquantized Arena*, chapter 16, "Common Source, Not Merger", section III, "What the Theorem Permits". The theorem itself is silent on joining one content to another (*Two Theories, One World*,

chapter 24, section "What the Theorem Permits"). The claim that the three forces of the particles stay three rests on Axiom III, as the entries on the three forces below give it.

To quantize the arena is to apply a concept where the concept does not belong: a category error, and the error behind the search for one theory. Location: *Two Theories, One World*, Preface, section "The Answer in a Page".

Gravity is the arena, and not a fourth force with a carrier. Location: *The Story of the Particles*, Level 7, "The Three Forces", section VI, "What about Gravity?".

Three positions, three forces: the act of comparing, the thing compared and the thing it is compared against each carry one force, and there is no fourth way, because comparison has no fourth position. Location: *The Story of the Particles*, Level 7, section I, "Three Ways, One Per Position"; the three positions are set out in Level 0, "The Three Carriers", section I, "Why Three?".

The content of a comparison, once it has parts, carries three marks that a comparison can act on, and each is the mark of one position. The act of comparing reads the content by its phase, a setting on a circle, and the force on the phase is electromagnetism. The two sides of each pair are the mark of the thing compared against, and the force between the two sides is the weak force. The three colors held inside the content are the mark of the thing compared, and the force among the colors is the strong force. Location: *The Story of the Particles*, Level 7, section I, "Three Ways, One Per Position", in the words "structured content carries three things a comparison can act upon"; section II, "The Strong Force: Eight Gluons", where the strong force is "the omniscient force", the force of the thing compared; section III, "The Weak Force: Three Bosons", where "The transcendent is the thing compared against"; and section IV, "The Force on the Phase: One Boson", where "the force on the phase is the immanent force", the force of the comparing act. Level 9, section III, "The Algebra Is Finite", gives one

summand of the algebra to each position: “one complex dimension for the phase of the unit, two for the two sides of a doublet, three for the three colors”.

The three measured strengths of the forces of the particles draw close as the energy rises, cross in pairs at three different energies, and never meet at one. Location: *Why These Numbers; The Strengths, Masses and Mixings of the Particles, in Plain Words*, chapter 5, “Where the Strengths Cross”, section “One Force, or Three?”; and *The Strengths of the Kinds*, chapter 3, “Where the Couplings Cross”, section III, “Where the Crossings Are”. The exact values are those of *The Strengths of the Kinds*, chapter 3, section III. The strength of each force is written α (alpha), with α_1 for the phase force, α_2 for the weak force and α_3 for color. Its *inverse strength* is one over α. The first values come from the calculation at one loop (its first order), with inverse strengths at the mass of the Z particle of 59.0 for the phase force (in the normalization used by unified theories), 29.6 for the weak force and 8.5 for color. With α_s, the strength of color at that mass, equal to 0.1180, the three crossings lie near $10^{13.0}$, $10^{14.4}$ and $10^{17.0}$ GeV. They come in the order $\mu_{12} < \mu_{13} < \mu_{23}$, where μ_{ij} is the energy at which forces i and j cross. Places are counted in *halvings*: an energy μ stands at $\log_2(\mu/m_e)$ halvings above the electron’s mass m_e, so that one halving is one doubling of the energy (chapter 2 of the same book). The middle crossing is fixed by the content alone: with X_{ij} the place of the crossing of forces i and j in halvings, $X_{13} = (218\ X_{12} + 115\ X_{23})/333$, a weighted mean of the other two (Box III-1). Run at three loops from the measured couplings, the crossings lie at 54.259, 58.200 and 65.521 halvings above the electron’s mass. Run upward to 5.3×10^{18} GeV, the three inverse strengths are about 34, 49 and 51. In the book’s words, “the gauge group has no unifying group, and the measured couplings meet at no scale”.

Because the three forces are inseparable, their strengths draw close, and because they are distinct, they never become one force. Location: *The Strengths of the Kinds*, chapter 3, section III, under “The measured couplings draw close and stay apart”, which reads the measured running

through two clauses of Axiom III; the axiom's statement, that the three positions of comparison are distinct, inseparable and non-interchangeable, is quoted in *The Story of the Particles*, Level 9, "The Composites and the Boundary", section III, "The Algebra Is Finite".

The Large Hadron Collider has searched for the heavier partners that supersymmetry calls for, and it has found none. Location: *Side by Side*, Volume One, Appendix B, the record "The Registered Predictions of Physics from Comparison", section VII, "The Kinds of Particle", Prediction 30. The values recorded there: the collider excludes gluinos below about 2300 GeV, a W′ with the couplings of the W below about 6000 GeV and a Z′ below about 5150 GeV, among others.

In this account the forces were never one larger force, and each of the three symmetries of the forces, in the physicists' sense, is its own from the start, and not what is left of a larger symmetry that broke. Location: *What the Beginning Left Behind*, chapter 13, "No Inflation Needed", section "No Monopoles, No Strings, No Walls". The same book gives the settling of the Higgs field at its value, the change that switches on the masses of the kinds, as a *crossover*: a smooth change, with no bubbles. For the measured Higgs mass of about 125 GeV the crossover is centered near 159.5 GeV (chapter 10, "The Counts of an Epoch", section "Smooth Changes, With No Bubbles"). That the settling of the Higgs field then leaves no strings, no walls and no monopoles rests on which kinds of trapped energy can last, which Tom Kibble showed in 1976 (chapter 13, section "No Monopoles, No Strings, No Walls"). Primary paper: Kibble, 1976.

There is no force that turns a quark into a lepton, and no single force of which the three are parts. Location: *The Story of the Particles*, Level 9, "The Composites and the Boundary", section IV, "What the Zoo Does Not Contain".

The rulebook of comparison has three chapters, one for each position of comparison: one governing a phase, one governing two sides, and one governing three colors. Location: *The Story of the Particles*, Level 9, section

III, "The Algebra Is Finite". In symbols the algebra is $\mathbb{C} \oplus \mathbb{H} \oplus M_3(\mathbb{C})$: $\mathbb{C}$ is the complex numbers, $\mathbb{H}$ the quaternions, and $M_3(\mathbb{C})$ the three-by-three complex matrices, and $\oplus$ (read "plus", the direct sum) sets them side by side. The three summands give the three factors of the gauge group: U(1) from $\mathbb{C}$, SU(2) from $\mathbb{H}$, and SU(3) from $M_3(\mathbb{C})$. In that book's words, "There are exactly three summands because there are exactly three modalities, one carrier for each". Location of the derivation: *The Grand Synthesis; One Theorem from Comparison to the Particles and the Cosmos*, chapter 7, "The Unique Algebra", section IV, "What Uniqueness Establishes"; the foundation is *Non-Commutative Geometry and the Immanent Metaphysics*.

The rules were derived from starting statements about the structure of comparison that "make no reference to particles", and "The Standard Model fell out". Chamseddine and Connes reached the same algebra from a classification of finite geometries. Location: *The Grand Synthesis*, chapter 7, section IV, "What Uniqueness Establishes", which quotes the words "make no reference to particles" from *Non-Commutative Geometry and the Immanent Metaphysics*, Preface. Chamseddine and Connes singled out the algebra "by classifying the irreducible finite geometries of KO-dimension 6 under a short list of hypotheses", one of which is a Majorana coupling of the right-handed neutrino (*The Connes Correspondence*, Preface, which reports their work). The algebra is the same on both routes: the hypothesis of a Majorana coupling belongs to the route of Chamseddine and Connes and not to the algebra, and this account reaches the same algebra with neutrinos whose mass is of the electron's kind (Prediction 32 of Appendix A). The *KO-dimension* of such a geometry is, by definition, a number counted modulo eight: only its remainder on division by eight counts. It is fixed by the signs of three relations among three parts of the geometry. They are its real structure (the operation that takes each state to its antiparticle), its grading (the sorting of states into left-handed and right-handed) and its Dirac operator (the operator from which its distances are read). Left-handed and right-handed are the two mirror-image kinds of state in which a particle of half-integer spin, such as the electron, can be

found. For the finite geometry of the Standard Model it is 6, a class of sign relations and not a count of directions (*The Connes Correspondence*, chapter 1, section 8, "The Two Instances of the Internal Space, and the Count of Ten"). Primary papers: Chamseddine and Connes, 2007 and 2008.

"The comparison route therefore has no single action principle": the form of the physics of the particles comes from their algebra, and the equations of the arena come from the ten dimensions together with a theorem showing they can take only one form. The numbers come each from its own route or from measurement. The description of the arena and the description of its content "are composed side by side and not merged". Location: *The Connes Correspondence; A Comparative Study of Non-Commutative Geometry and the Immanent Metaphysics*, chapter 6, "The Spectral Action and the Comparison Route", section II, "The Comparison Route Has No Single Action", subsections 2.2, "The side of context", and 2.3, "The action principle of the comparison route". The words "are composed side by side and not merged" are those of *Measurement*, chapter 10, section IX, which *The Connes Correspondence* quotes there. In the specialist's terms, the form of the physics of the particles comes from the *spectral action* (the action built from the spectrum of one operator on the product of space and time with a finite geometry) with the finite triple of the derived algebra. Primary paper for the spectral action: Chamseddine and Connes, 1997. The field equations of the arena come from the Kaluza–Klein reduction of the ten-dimensional action on $\mathbb{C}P^2 \times S^2$ (radii $\sqrt{6}\ l_{Pl}$ and l_{Pl}) and from Lovelock's theorem, which "gives their form as the only one" (Lovelock, 1971). *The Grand Synthesis*, chapter 10, "From Algebra to the Standard Model", section VI, "Gravity, the Arena", reads the single trace of the spectral action, from which gauge and gravitational terms both come, as a common source and not a merger.

Chapter Five: The Numbers of Nature

Balmer's rule for the four visible lines of hydrogen landed for twenty-eight years before anything explained it, and then it became one of the doors into quantum theory. Location: *Physics Is Not Math*, chapter 13, "A Value That Lands", section III, "A Formula Waiting for Its Reason". The rule, in the section's words: take a whole number n, starting from three, and multiply 364.56 by n^2 divided by $(n^2 - 4)$. The result is the wavelength in nanometers (billionths of a meter). For $n = 3$, 4, 5 and 6 it gives 656.2, 486.1, 434.0 and 410.1, and for $n = 7$ it gives 397.0, a line already observed. Bohr worked out the number in the formula from the charge and the mass of the electron, the speed of light and Planck's constant. Primary papers: Balmer, 1885; Bohr, 1913.

A value that lands is a value that agrees with what is measured. Location: *Physics Is Not Math*, chapter 13, "A Value That Lands", in the chapter's opening paragraphs before section I.

The Standard Model is a recipe card with its numbers left blank. Location: *Why These Numbers; The Strengths, Masses and Mixings of the Particles, in Plain Words*, chapter 1, "Numbers Physics Cannot Explain", section "A Recipe with Blanks".

The Standard Model as first written has nineteen adjustable numbers, and the neutrinos add seven: nineteen and seven make twenty-six. Location: *Why These Numbers*, chapter 1, section "Counting the Numbers"; the table of all twenty-six, each with its standing, is in chapter 18, "The Higgs Mass, the Top's Readings, and What Measurement Supplies", section "The Twenty-Six Numbers". The neutrinos add seven, and not nine, because the neutrino's mass is a *Dirac mass*, of the same kind as the electron's, which joins the left-handed and right-handed states of one particle. "Majorana neutrinos would have added two more" (chapter 2, "What There Is, and Why It Is Built So", section "The Neutrino's Mass, and No Seesaw").

Every number is said with its standing, the way it stands toward the world, and there are four standings, each with its own picture. A number may be set by the structure. It may be set by the structure once a stated step is taken. It may be measured. Or it may be measured, with its reason still a question. Location: *Why These Numbers*, Preface, "To the Reader", section "What This Book Is For"; and chapter 1, section "Four Ways a Number Can Stand". The same section adds a further word for the numbers still to be decided: a number stands *at a fork* when two arguments for it are carried side by side until a measurement decides between them. The seven numbers of the neutrinos, their three masses and the mixing of the leptons, stand at forks: "Seven belong to the neutrinos, and all seven stand at a fork" (chapter 18, section "The Twenty-Six Numbers"). The same section names each fork. The three masses stand at a fork between the count route and the Koide route, which the sum of the masses will decide. The three mixing angles of the leptons stand at a fork between the carry family and the segment family of readings. And the phase of the leptons stands at a fork that the quadrant of the phase will decide.

Some numbers are set by the structure: every charge in the world is a whole number of thirds of the electron's charge, and there are three generations of matter. Location: *Why These Numbers*, chapter 1, section "Four Ways a Number Can Stand"; and chapter 2, "What There Is, and Why It Is Built So", sections "Charges in Thirds" and "Three Generations, and No Fourth". Among the twenty-six, three numbers stand partly in this way, and none stands wholly in it. The first of the three numbers is the angle of the strong force: the structure sets the strong force's own part of that angle to zero. The phase that comes from the quark masses is carried as zero, and measurement places the whole angle below about one part in ten billion. That this phase lands on zero is measured, with its reason still a question (chapter 1, section "Four Ways a Number Can Stand"; chapter 18, section "The Twenty-Six Numbers", which asks "why do the quark masses add no angle to the strong force's own?"). The second of the three numbers is the *weak angle*, the number by which physicists, and I in my

books, write the strength of the weak force. The structure sets its measure, the square of its sine (a number that runs from zero for no angle to one for a right angle), at three eighths at the equal traces, the equal weights the structure gives the three forces. Its value at the mass of the Z particle, 0.23122, give or take 0.00006, is measured, with its reason still a question. The third of the three numbers is the muon's mass, which the structure sets on the ladder of masses to first order. Location of the three: *Why These Numbers*, chapter 1, section "Four Ways a Number Can Stand", and chapter 18, section "The Twenty-Six Numbers".

Some numbers are set by the structure once a stated step is taken, as a surveyor's deed names its stake. The mass of the tau follows from the masses of the electron and the muon once the step is taken, and it lands within less than half a *margin*, a margin being the give or take of the measurement. Location: *Why These Numbers*, chapter 1, section "Four Ways a Number Can Stand"; and chapter 18, section "Two Accounts of What Measurement Supplies". The step and Koide's relation are worked in chapter 11, "The Electron, the Muon and the Tau", sections "Koide's Number, Worked by Hand" and "Why Half and Half: the First Route". There the stated step gives the part the three masses share and the part by which they differ equal squared size, and that sets the relation's number at two thirds (Koide, 1982 and 1983). The exact values: the tau, from the electron and the muon by Koide's balance, is 1776.969 MeV (millions of electron volts) against the measured 1776.93, give or take 0.09. The two are less than half a margin apart, which the book counts as 14.3 bits of agreement.

The electron's mass is the unit in which every other mass is read. A unit is bookkeeping, and no verdict depends on a unit alone. Location: *Why These Numbers*, chapter 1, section "Units and Pure Numbers": "The same reason shows why no unit is derived: a derivation ends in a verdict, and no verdict depends on a unit alone". The measured value: 0.51099895069 MeV, give or take 0.00000000016 (chapter 1, section "Give or Take").

Some numbers land, with their reason still a question and its clues kept beside it, as two clocks in different rooms keep the same time. The muon's mass is set by the structure to a first approximation, and its full value agrees with measurement to eight figures. Location: *Why These Numbers*, chapter 1, section "Four Ways a Number Can Stand"; and chapter 18, sections "Two Accounts of What Measurement Supplies" and "The Twenty-Six Numbers". The exact values: the muon's mass over the electron's, from the ladder of masses and its dressing, is 206.7682862 against the measured 206.7682827, three quarters of a margin, 25.4 bits. The value uses one more number at the second order of the calculation, the constant seven ninths. Of all fractions whose bottom number is forty or less, seven ninths alone puts the muon's mass within twice the measurement's give or take. The muon's window for the constant, two margins on each side of the measured mass, runs from 0.77623 to 0.78119. That landing is measured, with its reason still a question, and the question is written beside it: why does the muon's constant land on seven ninths? Location of the constant, its window and the question: *Why These Numbers*, chapter 11, "The Electron, the Muon and the Tau", sections "The Turnover" and "Summary". The five lighter quarks each have their place on the step formula, every quark's mass is measured, and the top's coupling of one is a structural value (chapter 18, section "The Twenty-Six Numbers"). The *step formula* places every charged particle of matter by one rule (chapter 9, "The Ladder of Masses", section "Families, Rungs and One Formula"). A particle's count of halvings below the top is its sector's offset, plus its generation number times the sector's step cost, plus the square of its generation number times the sector's curvature, all multiplied by the step factor.

The standings are different relations between a number and the world, and not degrees of confidence. Location: *Why These Numbers*, chapter 1, section "Four Ways a Number Can Stand".

"The structure draws the proportions; measurement writes the legend". In one account of what measurement supplies the legend has six lines, and in a second account, both true, a stated identification lets the electron

alone carry the chain further. Location: *Why These Numbers*, chapter 18, sections "The Legend of the Map", "Two Accounts of What Measurement Supplies" and "The Twenty-Six Numbers". In the working account, measurement supplies four numbers (the electron's mass, the strength of light, the strength of color and the vacuum value of the Higgs field) and the two ladder offsets, 391/60 for the charged leptons and 53/10 for the down quarks. In the closure account, the step is written as a product, and from the electron alone the vacuum value comes out at 246.21966 GeV against the measured 246.21967 (22.0 bits) and the top's mass at 172.5622 GeV against 172.60 (9.3 bits). The Higgs mass, 125.1715 GeV against the measured 125.13, lands within less than half a margin (10.2 bits), and that landing is measured, with its reason still a question.

A value that lands, before its reason is found, is a question, and it is evidence of a reason not yet known. Location: *Physics Is Not Math*, chapter 13, section IV, "A Value That Lands Is a Question"; that a grade such as "coincidence" closes the inquiry, where a question opens it, is argued in section V, "A Grade Closes; a Question Opens".

A measured number with its question written beside it is a complete state of knowledge. Location: *Physics Is Not Math*, chapter 15, "The Descent", section VII, "Not Fixed by This Route": "A measured value, with its question written beside it, is a complete state of knowledge".

There are three ways of validation, and only three. Measurement is the first, in the first person. Agreement among people is the second, in the second person. Proof is the third, in the third person. Only measurement and proof validate truth, and agreement among people validates nothing by itself. Location: *Physics Is Not Math*, chapter 19, "A Right Method of Evaluation", section IV, "Three Ways of Validation".

Proof validates that a conclusion follows from its premises, and measurement validates whether a claim holds of the world. Location: *Physics Is Not Math*, chapter 6, "Mathematics, the Science of the Timeless", section VII, "Summary": "Mathematical truth is the truth of a necessary connection: if

these premises, then this, in every case the premises cover". The same book separates the two questions in chapter 12, section VI, "Merit and Truth". There an argument has merit when its claims follow from its premises, and it is true when it has merit and its premises are also true of the world.

A value shown not derivable is closed under reason as fully as a derived value: it has an argument that states exactly why no law fixes it, as the carpenter's proof that the diagonals of a square frame are equal fixes theirs. Location: *Why These Numbers*, chapter 1, section "Two Ends for Every Number".

The strength of light is left to measurement because no argument from the structure of comparison, of any length, fixes its value, since that structure is the same at every value of the strength of light. Location: *Why These Numbers*, chapter 1, section "Which Numbers Measurement Supplies"; the argument is in chapter 3, "The Electron and the Strength of Light", section "Why the Strength of Light Stays Measured", with one stated hypothesis, the *circle's rule*: a value is fixed by concepts alone only when one form supplies all the terms that the value relates. The measured value is 1/137.035999177, give or take twenty-one in the last two digits.

Eddington derived the strength of light as exactly 1/136 and then 1/137, and measurement settled the matter against him. The coupling is not a count, since Dirac's algebra holds at any coupling. Location: *Side by Side*, Volume One, Section XV, "Can the Constants Be Derived?". In Section XV of *Side by Side, Volume One*, I set Eddington's three derived numbers beside the measured values of the three numbers. For the strength of light the measured value is 1/137.035999177. For the ratio of the proton's mass to the electron's, Eddington's 1847.6 stands against the measured 1836.152673426. For the rate of recession, his 528 kilometers per second per megaparsec stands against the measured 67.4 and 73.04. Primary paper: Eddington, 1929.

A proof in mathematics is a chain, and for a proof the rule of the weakest link is exactly right. An argument about the world is a cable, whose strength comes from the number and the independence of its strands. Location: *Physics Is Not Math*, chapter 12, "Chains and Cables", sections I, "A Chain and a Cable", II, "The Rule of a Chain", and III, "A Court Weighs Many Strands". Section V, "Two Routes to One Value", quotes both of Peirce's sentences, which he wrote of philosophy's reasoning. Philosophy, he wrote, "ought to imitate the successful sciences in its methods". "Its reasoning should not form a chain which is no stronger than its weakest link, but a cable whose fibers may be ever so slender, provided they are sufficiently numerous and intimately connected". *Physics Is Not Math* carries the picture to inquiry about the world, in the same section: "The cable is the form of the court's reasoning, of Perrin's count, and of inquiry into the world". Primary source: Peirce, 1868.

When independent routes, resting on different premises, arrive at one value, that meeting is convergence, and it is the strongest evidence that inquiry into the world can have. Location: *Physics Is Not Math*, chapter 12, section V, "Two Routes to One Value"; for the numbers of the Standard Model, *Why These Numbers*, chapter 18, section "Two Accounts of What Measurement Supplies": "where routes from different premises meet on one value, that meeting is the strongest evidence the book has for that value". The same section of *Physics Is Not Math* states the rule for counting strands: "Two laws that rest on the same premise are one constraint, however many forms they take".

The charges in thirds are reached by argument from the structure of comparison. A second route reaches the same charges, from the demand that quantum effects never break the symmetry of the forces in the physicists' sense, and it works only when quarks and leptons are taken together. Location: *Why These Numbers*, chapter 2, section "Charges in Thirds". The same section checks the charges on the proton, two up quarks and one down: "two thirds and two thirds, less one third, is one, exactly the electron's charge with its sign reversed, so hydrogen is neutral". Measurement

agrees: experiments on the neutrality of atoms and molecules have shown that the charges of the proton and the electron cancel to better than one part in a hundred billion billion. Location of that measurement: *The Particular Evidence*, Case 3, "The Hard Center", section III, "The Resolution: The First Thing". Primary paper for one such measurement, which finds the two charges equal and opposite to within about one part in a thousand billion billion: Bressi and colleagues, 2011.

The structure gives three generations of matter, and no fourth. The measured spread of the Z particle counts 2.9963 kinds of light neutrino, give or take 0.0074, half a margin from three. Location: *Why These Numbers*, chapter 2, section "Three Generations, and No Fourth".

Chapter Six: One Bubble Among Many?

The background radiation was found by Penzias and Wilson in 1965 as a glow from every direction, at about 2.7 degrees above absolute zero. In 1992 the satellite called the Cosmic Background Explorer (COBE) found its ripples, of one part in a hundred thousand. In the standard history, regions of the sky more than about a degree apart never exchanged a signal before the glow was released. Location: *At the Edge of Reality*, chapter 2, "What Came Before the Big Bang?", sections "The Afterglow" and "Two Puzzles". Primary papers: Penzias and Wilson, 1965; Smoot and colleagues, 1992.

Our whole picture of the past is built from what arrives now: "From those impressions we piece together one history". Location: *What the Beginning Left Behind*, chapter 1, "Where the Last Book Left Us", section "A History Made from What Arrives Now".

My book *Comparison; The Necessary Basis* holds that to say that there exists only one world, or more than one, or that "many domains exist", applies the concept of existence outside its range of meaning, since existence is always relative to a particular domain. In that book's words, "What can be said is that many worlds are real". Location: *Comparison; The Necessary*

Basis, chapter 12, "Domains and What Is Real", section V, "Being, Existence, Reality, and Objectivity", under "The Impossibility of 'One Universe'". The "worlds" of that sentence are domains, each the whole range of places, or of things, that can be joined to one another, and their being, in the same passage, is "immanent and relational". *What Comes After the Dark* calls the epochs worlds in that sense, in chapter 10, section "No Other Sky Along Any Path". There it says: "The epochs before ours and after ours are worlds, each real in its own acts of comparison, and no act is real in two of them". In this book's own words the one world is everything any path can reach, and so it holds no other epoch. In the words of the same book, "The next epoch is joined to ours by no path and no act, and whatever a path can reach belongs to our own one world" (chapter 12, "What Comes After the Dark?", section "What Crosses"). The scope of outcomes is that of *Side by Side*, Volume One, and has its own entry below: for every comparer, one outcome is real, the one found. The two words are defined in *Comparison; The Necessary Basis*, chapter 10, section II. Its definitions read: "To say that something exists is to say that it stands as structure: timeless, the same in every instance ... To say that something is real is to say that it is given in an actual act of comparison". *Side by Side*, Volume One, quotes the same definitions in the chapter on Sean Carroll, "The Wave Function and the One Who Finds", section III, "The Branches".

In this physics, space is the pattern of which events a signal can join. A journey to another universe therefore asks for one of two things, an arrival somewhere in our own world or an arrival at a "place" that no path could ever reach, and neither of the two things is another universe. Location: *What Comes After the Dark*, chapter 10, "Could Anyone Escape?", section "No Other Sky Along Any Path". Regions beyond a horizon interact with what is near them, so they exist. They are further parts of one world, and not another universe (*Side by Side*, Volume Two, the chapter on Max Tegmark, "The Structure and the Act", section VI, "The Four Levels, Level by Level").

No domain contains every domain. A domain is the whole range of places, or of things, that can be joined to one another, and each epoch is one. A house that held every domain as one of its rooms would have to perfect sameness (one way of belonging shared by all the rooms) and unbrokenness (every room joined to every other) in the one comparison that holds its rooms together. Sameness and unbrokenness here are symmetry and continuity in the theorem's sense, and the Incommensuration Theorem forbids perfecting both in one comparison. Location: *What Comes After the Dark*, chapter 10, section "No Other Sky Along Any Path"; and *The Gravitational Companion*, "Two Formal Triples of a Domain", section III, "Across the Turn", where the same ground is given: "no domain contains every domain". The definitions of symmetry and continuity in the theorem's sense are in *Incommensuration; The Theorem and the Three Axioms*, chapter 2, section I, "Four Characters". The theorem's statement is quoted from *Incommensuration; The Theorem and the Three Axioms*, chapter 2, section VI, "The 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.

Every epoch has ten dimensions, one of time, three of space and six of possibility. Inside every black hole everything falls toward an end ahead in time. The six keep their place only while a large space stands around them as their setting, smooth in space and time. That large space must also hold a reference for what it means to stand still and not spin, as the distant stars fix it for a spinning gyroscope. At the end of the interiors these conditions fail together: the large space outside the black holes has emptied, the smooth description of space and time reaches the Planck curvature, and no reference for standing still survives. Then three directions open up while the six close in. I identify the Big Bang that our history finds with that passage, the turn, as it appears from our side. Location: *What the Beginning Left Behind*, Preface, "Before We Begin", section "Where the Story Stands"; the conditions are named in chapter 5, "One

Vacuum", section "Nowhere to Tunnel", which calls them "the compactification conditions"; and chapter 1, "Where the Last Book Left Us", section "What Holds the Six", where they are stated with the gyroscope and the distant stars.

The account answers every puzzle inflation was introduced to solve, from the turn and from the structure of the forces, so it needs no inflation. The sky is alike because the interiors of all the black holes of the epoch before end in one end. They end in one end because only the large space of the old epoch drew the distinctions between them, and the end of the interiors falls at no moment of that space's time, so no comparison tells their ends apart. Space is flat, with no overall bend, because a bend needs a length to set it, and no length of the old epoch passes the turn. The turn holds one length of its own, about the Planck length, and a bend that tight would close the new epoch within a few Planck times or leave it dominated by its bend, which no epoch that goes on to make stars does. And the forces were never one larger force, so the heavy particles that the breaking of such a force would leave, each carrying a single magnetic pole (*magnetic monopoles*), never form. Location: *What the Beginning Left Behind*, chapter 13, "No Inflation Needed", in its opening paragraphs and its sections "The Sameness and the Flatness, Answered From the Turn" and "No Monopoles, No Strings, No Walls". Primary paper: Guth, 1981.

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. Location: *What the Beginning Left Behind*, chapter 11, "The Oldest Light", section "What Passes the Turn". The account fixes the kind of the ripples, and takes their values from measurement (chapter 11, section "What the Measurements Find"). The spectral index (how the strength of the ripples changes with their length) is 0.9649, give or take 0.0042, and the amplitude is 2.10×10^{-9}, about two and one tenth billionths.

On that identification a long inflation, one long enough to stretch the lengths we see today from inside the earliest reach of any signal to beyond it, is excluded. The earliest reach of any signal, the *early horizon*, is the greatest distance a signal could have crossed since the turn. Such an inflation would make the ripples on those lengths as the trembling of its own empty space, and on the identification the ripples on those lengths are the carried form. Location: *What the Beginning Left Behind*, chapter 13, section "A Long Inflation Is Excluded"; the early horizon is defined in the chapter's opening paragraphs. The same holds of eternal inflation, the endless making of further regions by inflation. In the words of *Side by Side*, Volume Two, the chapter on Max Tegmark, section VI, "The Four Levels, Level by Level": "It needs no inflationary phase and excludes a long one, so there is no eternal inflation to make the regions".

A second strand reaches the same place from the dark matter, which in this account is a lasting vibration of the six dimensions of possibility, made at the turn. In inflation, the first waves in the shape of space are made by the inflating empty space, and their strength grows with the energy that empty space holds. The measured limit on the first waves therefore caps that energy, and with it the heat that the end of an inflation could hand on to the young universe. An inflation stretches space so much that whatever was made before it is spread too thin to matter, so in a history with inflation the dark matter 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 (*What the Beginning Left Behind*, Chapter 13). So after an inflation that made the ripples, the young universe would be too cool to make the dark matter in the amount measured. Location: *What the Beginning Left Behind*, chapter 13, section "A Second Reason, From the Dark Matter", quoting *The Weight of Possibility*. The measured limit: the ratio of first waves to first ripples is below 0.036 at ninety-five percent confidence, and below 0.032

in a joint analysis with the Planck polarization data (*What the Beginning Left Behind*, chapter 11, section "What the Measurements Find"). Primary paper: the BICEP and Keck collaboration (Ade and colleagues), 2021.

No act of comparison spans the turn. The epochs follow one another like the cars of one train, each coupled to the one before it, and not the branches of a tree. All the interiors of an epoch give one new epoch, and not one new universe for each black hole. The cycle, the sequence of epochs each coming from the end of the one before, has no first iteration, since each epoch begins its own count of disorder. Location: *What the Beginning Left Behind*, chapter 21, "What the Beginning Left Behind", section "A Cycle with No First Turn". The same section says: "The script repeats: the same numbers of dimensions, the same shape of the six, the same held size and the same vacuum". Each epoch beginning its own count answers Tolman's question about cycles, whether disorder would pile up from one cycle to the next (Tolman, 1934). Primary paper for one universe from each black hole: Smolin, 1992.

In this account gravity is built on the ten dimensions from the geometry alone. So this account has no flux and no flux integers, and nothing in this account corresponds to the landscape of vacua. Location: *What the Beginning Left Behind*, chapter 5, "One Vacuum", sections "A Ball Among Valleys" and "No Threads to Count". Estimates of the number of valleys in the string landscape run to ten to the five hundred (Bousso and Polchinski, 2000; Kachru, Kallosh, Linde and Trivedi, 2003; Douglas, 2003; Douglas and Kachru, 2007).

There is one vacuum: the held point of the six is the only minimum, with no second valley for a bubble to tunnel to. Location: *What the Beginning Left Behind*, chapter 5, section "Nowhere to Tunnel". The exact statement has four parts. At the first order computed, among homogeneous shapes with a ratio of the radii between $\sqrt{3}$ and $\sqrt{12}$ (about 1.7 and 3.5), the held point is the only minimum in shape. The held point lies at $\sqrt{6}$ Planck lengths (about 2.45). The held six have an energy of about -0.049 of the

Planck density, rising to zero with no ridge as the six grow. The one ridge lies toward smaller size, at a radius of about 1.79 Planck lengths. The rate of tunneling between vacua is that of Coleman and De Luccia (1980).

The shape of the six is reached by two routes, one through algebra and one through the mathematics of shape, and no route picks the space from a list of candidates. Location: *What the Beginning Left Behind*, chapter 5, section "One Algebra, One Space". The first route is the finite algebra $\mathbb{C} \oplus \mathbb{H} \oplus M_3(\mathbb{C})$ of *Non-Commutative Geometry and the Immanent Metaphysics*, and the second is the classification of compact homogeneous products in *The Gravitational Passage*. Both arrive at $\mathbb{C}P^2 \times S^2$ (the entries of Chapter Three give the space and its symbols).

Everett's program has one dynamics, which applies without change to closed systems and to the universe as a whole. As an account of outcomes it is kept, and as a description of a whole world it is excluded. Location: *Side by Side*, Volume One, the chapter on David Deutsch, "Tasks, Runs and Worlds", section V, "The Multiverse". Primary works: Everett, 1957; Deutsch, 1999; Wallace, 2012.

A whole world completely fixed by a law perfects symmetry and continuity together, in the theorem's sense, whichever account describes it, and the theorem forbids that pairing. Location: *Physics Is Not Math*, chapter 8, "Physics Has the Arrow", section VII, "Three Grounds".

For every comparer, one outcome is real, the one found, and the branches exist as structure. Location: *Side by Side*, Volume One, the chapter on Sean Carroll, section III, "The Branches".

Why the Quantum Is the Way It Is says of its own argument that it "does not refute many worlds". The phrase "does not refute many worlds" is a statement about the argument of *Why the Quantum Is the Way It Is*, and not a contrary claim. Location: *Why the Quantum Is the Way It Is; Quantum Mechanics from the Act of Comparison, in Plain Words*, chapter 18, "The Interpretations, Each Missing a Role", section "What the Interpretations Were Do-

ing". The same section reads the uncertainty of an observer who has not yet looked which branch it is in, the self-locating uncertainty of Sebens and Carroll (2018), as "ignorance of the omniscient".

An improbability is a comparison of the actual case with alternatives that some context distinguishes, and at the turn there is no such context: the large space of the old epoch has emptied, and the turn falls at no moment of that space's time. Location: *What the Beginning Left Behind*, chapter 10, "The Counts of an Epoch", section "One Draw Among Many?". The same section, following *The Compactification* (chapter 3, section VIII), applies this to Penrose's figure for how improbable our beginning was, one part in 10 raised to the power 10^{123} (Penrose, 1979). At the turn there is no context relative to which the beginning of the new epoch is one draw from that many distinguishable alternatives.

Fine-tuning by selection has nothing to select from: the structure of comparison yields one world, with its constants fixed, and an ensemble of others would have to be laid out from a vantage no comparison can occupy. Location: *Side by Side*, Volume Two, the chapter on George Ellis, "The Open Future", section VI, "The Multiverse".

The energy of empty space, taken as a uniform total, would be the same at every place, the same for every comparer in steady motion, and without a break anywhere. No comparison takes it in as a whole, and "What no comparison finds shapes nothing". So the mismatch of 123 orders of magnitude between that total and the measured value "never needed to be canceled". Kaku's figure of a hundred and twenty powers of ten and the hundred and twenty-three here come from two different reckonings of the same total. I identify the cosmological constant with the share of the energy of empty space that is open to a measurement made from inside it. From that share the fraction of the universe's energy that is matter comes out at 0.311, against the measured value of 0.315, give or take 0.007. Location: *The View from Inside*, Preface, "On the Purpose of This Book". The share is three, the number of roles in any act of comparison, among the *degrees of freedom* (the independent ways of varying) that the comparer's ho-

rizon counts, about 10^{123}. The share follows in three steps (*The View from Inside*, chapter 11, section "Tiles on the Horizon"). Every one of the independent ways holds an equal part of the energy, since nothing tells one from another. A measurement takes in what it finds through three channels, one for each role of comparison. I take each channel to take in one whole way, since what a comparison finds comes whole, in steps. Each channel takes a different one, since the three roles are distinct (Axiom III). And the comparer is one stance, so the ways it takes in are counted once, however many instruments it carries. The vacuum's total energy, about the Planck density, is trimmed by the curvature of the six at their held size. The curvature takes three parts in 8π off that total and leaves the factor $1 - 3/(8\pi)$, about 0.881 (*The View from Inside*, chapter 9, "The Shape of the Internal World", section "A Small Trim"). Combined with the equation that governs the expansion of the universe, it gives one equation from which both the strength of gravity and the present rate of expansion cancel. Write I for the size of the comparer's horizon counted in Hubble radii, a Hubble radius being the speed of light divided by the present rate of expansion, and Ω_Λ for the share of the universe's energy held by empty space. Then the one equation reads $I^2 \times \Omega_\Lambda = 8 - 3/\pi$, an equation in pure numbers alone, numbers with no unit (chapter 13, "One Equation, One Number", section "Setting the Two Equal"). Without the trim it would read 8, and the share of matter would come out at 0.280. The same equation gives a cosmological constant that is exactly constant, and it reproduces the measured energy density of empty space to within about two percent. Primary paper for the problem of the cosmological constant: Weinberg, 1989.

The strength of light is measured: no argument from the structure of comparison, of any length, fixes its value, since that structure is the same at every value of it. Location: *Why These Numbers*, chapter 1, "Numbers Physics Cannot Explain", section "Which Numbers Measurement Supplies", with the one stated hypothesis of chapter 3, the circle's rule (the entries of Chapter Five state it).

Chapter Seven: The Quantum Machine

Two questions about a quantum computer are kept apart, reach (what it can simulate at all) and cost (how fast). The account answers reach, and "The account makes no claim on the cost of computation". Location: *The Quantum Bridge; Entanglement, Error Correction, and the Limits of Simulation*, chapter 7, "The Reach of Simulation", sections I, "The Question", and IV, "The Reach of a Simulation".

A mosaic made of smaller and smaller tiles comes as close to a curve as one wishes, and no stage of it is the curve. Location: *What Cannot Be*, chapter 22, "Why No Computation Is Everything", section "Why a Computation Cannot Be What Consciousness Is".

Any machine, quantum or classical, approaches what it simulates as closely as one wishes and never contains it, and the boundary is the same for both machines. Location: *The Quantum Bridge*, chapter 7, section IV, "The Reach of a Simulation", Proposition 7.1, stated there for a simulation of the arena (space and time): a simulation on any computing device, classical or quantum, "reaches the findings of the arena densely and never exhaustively: refinement can bring its results as close to those findings as is wished, and no stage of refinement contains them. The boundary is the same for classical and for quantum devices". The argument uses only the finite program and the finite record of the device. The same section gives a second ground for the failure of containment, from the Incommensuration Theorem. The plain form, for both kinds of computer, is in *What Cannot Be*, chapter 21, "Are We Living in a Simulation?", section "The Consequence, and the Amplifier". A quantum computer's program is a finite string of symbols, and everything it reports comes from finitely many readings, which can be listed.

Georg Cantor proved that no list, however long it is allowed to run, can name every point of a continuum. In 1874 he proved it for the real numbers, all the points of the number line, and in 1891 he gave his diagonal ar-

gument, which shows why and gives the general result about lists. Location: *What Cannot Be*, chapter 21, "Are We Living in a Simulation?", section "What No List Can Hold"; *The Quantum Bridge*, chapter 7, section IV, rests its own step on the diagonal argument. Primary papers: Cantor, 1874 and 1891.

A simulation "can be refined without limit, and every refinement brings it closer; at no stage of refinement does it become what it describes". Location: *Physics Is Not Math*, chapter 11, "Why the Order Surprises", section V, "What a Simulation Shows".

A count of steps is a measure of time: the time a computation must take. Location: *Physics Is Not Math*, chapter 7, "Computation Has Sequence", section V, "Measures of Computation Are Measures of Time".

In general, there is no way to know what a program will do except by running it. Location: *Physics Is Not Math*, chapter 7, section IV, "Known Only by Running It"; Turing's result on the halting problem is in section III, "Will It Stop?". Primary paper: Turing, 1936.

Chemistry is made of nothing but electrons, nuclei and light, and in principle no description, however refined, contains everything that it describes. Location: *Physics Is Not Math*, chapter 11, section V, "What a Simulation Shows".

In 2019 a processor of fifty-three qubits ran circuits chosen at random, each new, and sampled each between half a million and two and a half million times. Its authors report that the machine's "system fidelity is well predicted by a simple model" built from the errors of its single gates and readings. The fidelity is how closely the machine's output matched the output of an error-free machine. Location: *Side by Side*, Volume Two, the chapter on Lee Smolin, "Time Is Real", section IX, "Where the Predictions Part, and Why", under "Quantum statistics for states without precedent". Primary paper: Arute and colleagues, 2019.

A classical computer that reproduces the statistics of quantum theory by the direct method pays a cost that is multiplied by a fixed factor with each particle added to the entangled group. My books make no claim that a quantum computer outruns every classical method. Such a claim would need a theorem that some problem a quantum computer solves quickly has no quick classical solution, and no one has proved such a theorem. Location: *Side by Side*, Volume One, the chapter on Gerard 't Hooft, "The Cell and the Comparison", section IX, "Where the Predictions Part, and Why", under "The reach of a quantum computer as it is scaled"; the cost per particle is in *What Cannot Be*, chapter 21, section "The Quantum Wave as Evidence". The statement of the classical cost, with its exception for the Clifford circuits, is quoted in the same section of *Side by Side* from *The Last Turtle*, chapter 26, section IV.

A quantum computer simulates any local quantum system efficiently. Location: *The Quantum Bridge*, chapter 7, section VI, "What a Quantum Computer Can Do for Gravitational Physics". Primary paper: Lloyd, 1996. Proposition 7.3 of the same section states that for gravitational physics a computing device can simulate two things, each with dense reach: the quantum content on a given classical geometry, and the classical geometry of each alternative of that content. On the account there is no third thing, a quantum state of the geometry, to be simulated.

One structure for the particles and one space for the six, reached by two routes from different premises, "leave nothing to select": there is no landscape of universes to search. Location: *What the Beginning Left Behind*, chapter 5, "One Vacuum", Summary.

A quantum computer is described by its formalism, in which the blended possibilities are held at once, and its readout is one outcome, a string of bits. Location: *The Quantum Bridge*, chapter 7, section II, "What a Quantum Computer Is". In symbols: the state of a register of n qubits is a ray in a complex Hilbert space of dimension 2^n, and its evolution between preparation and readout is unitary (it keeps the total weight of the possib-

ilities equal to one). A finite gate set reaches a single-qubit operation to accuracy ε (epsilon) with a circuit of length $\ell(\varepsilon) = O(\log^c(1/\varepsilon))$, read "of the order of the logarithm of one over epsilon, raised to the power c" (equation 7.1, the Solovay–Kitaev bound). Chapter 4 of the same book gives $c = 3.97$ for the construction of Dawson and Nielsen (Dawson and Nielsen, 2006).

A quantum computer does its work in possibility, where the alternatives interfere, and the work becomes a result in one finding, in one world. Location: *Side by Side*, Volume One, the chapter on David Deutsch, "Tasks, Runs and Worlds", section V, "The Multiverse".

Entanglement is necessary for a computation to escape efficient simulation by an ordinary computer, and it is not sufficient. By the theorem of Gottesman and Knill, circuits built from the gates of the first kind, which physicists call *Clifford gates*, are followed efficiently by an ordinary computer, even when those gates entangle the qubits. A computation on *pure states* whose qubits, at every step, fall into groups of at most a fixed number, with no entanglement between the groups, can be simulated efficiently by a classical computer, as Jozsa and Linden proved in 2003. Pure states are states known as completely as quantum theory allows. Location: *The Quantum Bridge*, chapter 4, "Quantum Error Correction Across the Bridge", section VII, "The Resources of Quantum Computation"; and *Beyond the Quantum Passage; Work Held Outside the Derivation of Quantum Mechanics*, chapter 4, "Entanglement, Magic and the Count of Non-Clifford Gates", section I, "Entanglement Is Free". Primary papers: the theorem of Gottesman and Knill (Gottesman, 1998; Aaronson and Gottesman, 2004); Jozsa and Linden, 2003.

The globe and the octahedron: the six states that the gates of the first kind can reach on one qubit sit at the corners of an octahedron inside the globe of all states. The gates of the first kind only carry the octahedron into itself. Location: *The Quantum Bridge*, chapter 4, section VII. In the specialist's terms, a state of one qubit is a point of the Bloch ball with Bloch vector $\mathbf{r} = (x, y, z)$. The six stabilizer states are $(\pm 1, 0, 0)$, $(0, \pm 1, 0)$ and

$(0, 0, \pm 1)$, and their mixtures fill the octahedron $|x| + |y| + |z| \leq 1$. The 24 Clifford operations of one qubit are the 24 rotations that carry the octahedron into itself. The gate T is a rotation by π/4 about the z axis, which carries $(1, 0, 0)$ to $(1/\sqrt{2}, 1/\sqrt{2}, 0)$, on the sphere outside the octahedron. A state of one qubit has *magic* exactly when it lies outside the octahedron. The fifteen-to-one distillation of magic states gives an output error $p_{\text{out}} = 35\ p_{\text{in}}{}^3$ (equation 4.12; Bravyi and Kitaev, 2005).

I identify magic as what lets a finite list of gates reach the whole continuum of the formalism (every point of the globe, and every way of rotating it) as close as one wishes. Location: *The Quantum Bridge*, chapter 4, section VII: "I identify the non-stabilizer resource as what lets a finite gate set reach the continuum of the formalism". Proposition 4.3 of the same section concerns a finite gate set on n qubits: the set of unitaries reached by circuits of finite length is countable. When the gate set is universal, that set is dense in the unitary group $U(2^n)$, taken up to a global phase, and it is not the whole group.

Entanglement carries the magic across the qubits, and the gates of the second kind supply it. The magic is bounded by the number of those gates, not by the number of qubits they act on. Location: *Beyond the Quantum Passage*, chapter 4, sections V, "What Counts: Gates, Not Qubits", and VII, "Summary": "The count that magic constrains is the count of non-Clifford gates, not of the qubits they act on". Proposition 4.1 of that chapter (section II, "Entanglement Does Not Create Magic") bounds the count: any preparation of a state of log-robustness M (a measure of how much magic the state holds) uses at least $2M$ gates of the kind T.

In an error-correcting code, "The carriers decohere, and the logical state does not". If each single operation fails less often than the threshold, and the failures stay local and nearly independent of one another, a calculation of any length can be carried out with as small a chance of failure as one wishes. Location: *The Quantum Bridge*, chapter 4, section III, "Decoherence and Correction", where the premise reads: "the failures are local and weakly correlated". The threshold theorem's cost grows as a power of the

logarithm of the length of the computation (Aharonov and Ben-Or, 2008; Kitaev, 1997; Knill, Laflamme and Zurek, 1998). For the rotated surface code of distance d, the number of physical qubits is $n = 2d^2 - 1$. Below threshold the logical error per round falls roughly as $(p/p_{\mathrm{th}})^{(d+1)/2}$, where p is the physical error per operation and p_{th} the threshold (*The Quantum Bridge*, chapter 5, "Gravity in the Error Budget of Real Hardware", section II, "The Baseline of Real Hardware", equations 5.1 and 5.2).

The account sets no ceiling of its own on the distance of a quantum error-correcting code. Location: *The Quantum Bridge*, chapter 4, section IV, "What Gravity Adds", Proposition 4.2. In its words, "The limits on the distance are those of quantum theory applied to the degrees of freedom available: the number of carriers, through the quantum Singleton bound, and the strength and correlation of the noise, through the Knill–Laflamme conditions and the threshold theorem".

Chapter Eight: When the Stars Go Out

Astronomers who have followed the standard calculation forward report that the sky beyond our own group of galaxies empties in a hundred billion to a trillion years. Location: *What Comes After the Dark*, chapter 1, "What Happens to the Sky We Can See?", section "Clumping and Departing". In 2007 Lawrence Krauss and Robert Scherrer calculated that every galaxy outside the one galaxy our group will have become passes beyond the horizon about a hundred billion years from now. A hundred billion years from now is the near end of the span of a hundred billion to a trillion years (same chapter, section "Astronomers Who Will See No Expansion"). Primary papers: for the speeding up of the expansion, Riess and colleagues, 1998, and Perlmutter and colleagues, 1999; for the emptying of the sky, Krauss and Scherrer, 2007.

An epoch is one long era, in which stars, galaxies and black holes form, and which begins and ends at a turn. Our own epoch is the era whose history runs back to the Big Bang, and our one world, everything any path from here can reach, lies within it. Location: *What Comes After the Dark*,

chapter 1, section "A Passing Stage", for the epochs; and chapter 12, "What Comes After the Dark?", section "What Crosses", for the one world, where the next epoch is joined to ours by no path and no act.

The space of our epoch is flat, with no overall bend at the scale of the whole sky, and the energy of empty space is a positive amount, one number for all of our epoch's time. The rate of expansion is set by a sum of three parts. The part from the bend of space is zero, the part from the matter is never negative, and the part from the energy of empty space is positive. So the sum is always larger than its last part alone, and the rate of expansion never falls to zero, whatever the amount of matter, since more matter only adds to a sum that is already positive. So gravity holds the expansion back, and it never stops it. Location: *What Comes After the Dark*, chapter 2, "Will It All Fall Back?", sections "The First Way: Space Is Flat" and "What This Means for You"; the chapter's key idea says it in one sentence: "In this physics the space of our epoch is flat, so matter cannot close it". The grounds are tabled in the same book, Appendix A, "For the Specialist", under "Chapter 2. Will It All Fall Back?". Each epoch's model is spatially flat, its curvature a constant of integration set at the turn, where no length of the old epoch passes (*The Gravitational Passage*, chapter 18, section IX). The cosmological constant is positive, since every factor of the formula for its energy density is positive (*The Gravitational Passage*, chapter 12, section IV). Within one geometry the constant does not vary, by the contracted Bianchi identity (*The Gravitational Passage*, chapter 13, section VI). That identity of Einstein's geometry ties the change of curvature to the conservation of the energy and momentum of matter.

The long, cold emptying of the sky does happen: the cold, dark sky of the popular accounts is the true view of the far future from inside our epoch. Location: *What Comes After the Dark*, chapter 8, "Is the Long Emptying the End?", section "What This Means for You".

Even the smallest comparison needs a second thing to compare against, a lasting structure in which the record is kept, and a signal between them. So thinking forever would be an endless run of findings by one thinker,

"each made against something actually there, and each kept in a lasting structure of the thinker's own". Location: *What Comes After the Dark*, chapter 7, "Can a Mind Keep Thinking for Ever?", section "What a Thought Needs".

The forms that matter takes in our epoch depend on the six dimensions of possibility keeping their held shape, and the six are held while a large space is there around them, with things in it to compare against. That condition fails at the end of a black hole's interior and for a body carried away alone. Inside a black hole the way inward is the way forward in time, and on the clock of a body that falls in, the end comes after a finite time, as a limit. Location: *What Comes After the Dark*, chapter 7, section "What the Emptying Leaves a Thinker".

No thinker of our epoch thinks forever. The emptying leaves every thinker with nothing outside to compare against, and the six dimensions of possibility no longer keep the held shape on which the forms of its matter depend. That conclusion uses neither the size of the thinker's store of energy, nor its temperature, nor the speed at which it thinks. Location: *What Comes After the Dark*, chapter 7, "Can a Mind Keep Thinking for Ever?", sections "What a Thought Needs", "What the Emptying Leaves a Thinker" and "Dyson's Three Questions". For a black hole of the Sun's mass, the end of the inside comes at most about fifteen millionths of a second after the crossing, on the clock of the body that falls in. Locations of that figure: the same chapter, section "What the Emptying Leaves a Thinker"; and *The Gravitational Passage*, chapter 18, "The Interior Passage", section I, "The Singularity Is Not Now". Primary papers: Dyson, 1979; Krauss and Starkman, 2000.

Near the end of the inside of a black hole, Einstein's equations, written for all ten dimensions, have an exact solution on which the three directions of space shrink while the six grow. Read backward, three dimensions open out while six close up. Location: *What Comes After the Dark*, chapter 8, section "The First Ground: No Content Without a Context"; *At the Edge of Reality*, chapter 14, "The Dimensions Trade Places", sections "Three

Shrink, Six Grow" and "The Same Arc, Read Backward"; the picture of the space around you shrinking while the six grow is in its section "What This Means for You". The solution has the *Kasner form* (Kasner, 1921). Each direction has a size proportional to the time remaining to the end, on the faller's own clock, raised to a fixed exponent. Einstein's equations require the exponents to add to one and their squares to add to one. At the upper end of the ring of allowed exponents, each of the three directions of space has the exponent 5/9, and each of the six has $-1/9$. The two sums check: $3 \times 5/9 - 6 \times 1/9 = 1$, and $3 \times 25/81 + 6 \times 1/81 = 1$. Read toward the end, the three shrink while the six grow. Location: *At the Edge of Reality*, chapter 14, sections "A Power of the Time Remaining" and "The Arc at the Upper End", and Appendix A, "The Kasner Curve".

Kaku's plan rests on three things: that the universe ends in a final cold dark, that there is another universe a passage can reach, and that something of us can cross as itself. Location: *What Comes After the Dark*, chapter 10, "Could Anyone Escape?", section "Kaku's Plan of Escape".

The long emptying ends in a turn to a new epoch, not in a final dark. The turn is the one end shared by the insides of all the black holes of an epoch, approached from both sides and reached from neither. Location: *What Comes After the Dark*, chapter 8, section "The Dark Sky Is Not Where the Story Stops", and its closing section, "What This Means for You".

Three grounds show that the dark ends in a turn, and each stands on its own, so the answer stands on each of them alone. Location: *What Comes After the Dark*, chapter 8, sections "The Dark Sky Is Not Where the Story Stops" and "Three Strands".

The first ground: content cannot be without a context, by the third axiom. When the large space of the epoch has gone, a context forms again from the geometry of all ten dimensions. Location: *What Comes After the Dark*, chapter 8, section "The First Ground: No Content Without a Context", where the thermometer comparing morning and evening also stands. In that section's words, "What remains is the content and the ten-dimension-

al geometry itself". The end of an interior is an edge of the descriptions: "The edge belongs to the descriptions. It is not an ending of what they describe" (chapter 8, section "What Is Left When the Sky Is Empty").

The second ground: a final state of featureless emptiness, the same everywhere and with no break anywhere, would be perfectly symmetric and perfectly continuous at once, in the theorem's sense, "the one character no comparison ever finds". Location: *What Comes After the Dark*, chapter 8, section "The Second Ground: A Featureless Emptiness Is Never Found"; the quoted phrase is in *The View from Inside*, chapter 16, "The Observer Inside", section "Context Must Be Restored". The theorem's statement is quoted from *Incommensuration; The Theorem and the Three Axioms*, chapter 2, section VI, "The 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.

The third ground: an entropy is always a count made against a context, and the heat death, a final maximum that holds forever, has no context in which to be counted. Location: *What Comes After the Dark*, chapter 8, section "The Third Ground: Every Count Has a Context". The same section identifies what the entropy of a black hole counts (the Bekenstein–Hawking entropy) as the states of the hole's interior that no comparison from outside can tell apart, a count made against the space outside the hole. The no-hair theorem shows why the count is so large, since a settled hole shows the space outside only its mass, its electric charge and its spin. The end of an interior lies at no moment of the time of the space outside, and in the words of *The Gravitational Passage*, "the count has no reference left".

The turn comes whatever the faster expansion does, and I identify the beginning of the new epoch's large space and time with that epoch's Big Bang. The epochs then form a sequence with no first turn, following one another like the cars of one train, and not a single arc from a Big Bang to a heat death. The books call this sequence the cycle. Location: *What Comes After the Dark*, chapter 8, section "One End, and the Turn"; "No turn in the

cycle is the first" is in chapter 11, "Has This Happened Before?", section "The Sky Has Done This Before". The ends of all the interiors are one end, because no comparison can tell them apart, and a difference that no comparison can register is no difference (same section). The cycle is argued in *The Gravitational Passage*, chapter 18, section XII, "The Cycle".

In this account space is the pattern of which events a signal can join, so any region a path from here can reach is part of our own world. A journey to another universe asks for one of two things, an arrival somewhere in our own world or an arrival at a "place" that no path could ever reach, and neither of the two things is another universe. Location: *What Comes After the Dark*, chapter 10, section "No Other Sky Along Any Path".

Kaku's steps are, one after another, new ways of traveling in the road country, and *What Comes After the Dark* walks them, gathered into six ways. The way down through a black hole meets a horizon that is crossed one way, with nothing returning across it, and it leads to the turn. The way of new roads and faster cars gathers the baby universe, the machines of the Planck scale, negative energy and the warp drive. It meets one vacuum, a state of empty space with no second state beyond it, so a made bubble has nowhere outside the one world to open into. The way back to the past arrives at a later finding of the traveler's own. The waiting meets the end of the epoch. The request for a theory of everything asks for a better theory, and a better theory describes more exactly every path there is, and it describes no path that is not there. And the letter, the seed of the last hope, crosses only as a share of the one averaged form. Location: *What Comes After the Dark*, chapter 10, section "The Plan, Step by Step".

The six dimensions of possibility are the range of what a comparison could find, from which each outcome is one selection, and nothing travels through them. Location: *What Comes After the Dark*, chapter 4, "Could Empty Space Change Its Nature?", section "The Six Small Dimensions"; *At the Edge of Reality*, chapter 7, "Six Dimensions of Possibility", sections "Where the Six Are", "Why We Never See Them" and "What This Means for You".

No path runs from any place in our epoch to any place in the next, and no domain contains every domain. Each epoch is whole, complete from inside, and no journey links any two epochs. What joins two epochs is the law that holds again in each and the one averaged form of the content that crosses, with no act and no path between them. Location: *What Comes After the Dark*, chapter 10, section "No Other Sky Along Any Path". The same section gives the step before it: "No signal from the end of an interior reaches any moment of the outside world, so that end lies at no moment of our time, earlier, now or later".

At the turn no length crosses, no shape of the old large space and no field of matter, so no body crosses as a body. What crosses is the form of the content, and every thing, as the thing it was, stays on this side of the turn. Location: *What Comes After the Dark*, chapter 10, section "What Reaches the Turn"; and chapter 9, section "What Stays Behind", where "every thing stays behind as the thing it was".

Information has two senses. The first sense of information is the form of the content (what the matter is, and which alternatives the matter has taken). The form of the content goes wherever the matter goes, as the words of a letter go with the letter. The second sense of information is a count of states made against a context, as a post office counts letters that look alike to the sorting machine of the post office. Location: *What Comes After the Dark*, chapter 9, "What Crosses Over, and What Stays Behind?", section "Two Things Called Information".

The form of the seed's content is carried to the turn. As a message, a record or an identity, the seed does not cross, since no act of comparison spans the turn. Location: *What Comes After the Dark*, chapter 10, section "No Message, No Record, No Identity".

A person is not a very large file. Location: *What Cannot Be*, chapter 22, "Why No Computation Is Everything", section "A Person Is Not a File"; the same point is made in *What Comes After the Dark*, chapter 10, section "No Message, No Record, No Identity".

At the turn no comparison can tell the form of one black hole from the form of another, so the forms cross as one averaged form, as every voice in a stadium goes into one roar. Location: *What Comes After the Dark*, chapter 9, section "What Crosses".

I identify the faint pattern of the microwave background, found by the COBE satellite in 1992, with the form of the content of the epoch before ours, carried through the turn and averaged into one. Location: *What Comes After the Dark*, chapter 9, section "The Faint Pattern". The same section notes that every ingredient of the new epoch, its matter, its dark matter and its light, departs from evenness together. Primary paper: Smoot and colleagues, 1992.

The cosmic egg of this account is the one averaged form of everything an epoch's black holes took in, the seed of the next epoch's structure. Location: *What Comes After the Dark*, chapter 10, section "The Cosmic Egg".

What crosses the turn is the form of the content, as one averaged form; the same law holds again on the far side, and it is not carried across. Location: *What Comes After the Dark*, chapter 9, section "What Returns": "The law returns in every epoch, and it is not carried across the turn".

In this account the far future needs no rescue from the dark: what comes after our sky is the next epoch, which comes from the end of this one by the same law, seeded by the form of the content of our own. Location: *What Comes After the Dark*, chapter 10, section "What This Means for You".

Chapter Nine: Where Every Road Arrives

The words spoken on Apollo 8 as the Earth came up over the Moon, on 24 December 1968, are given to William Anders by NASA's transcript of the onboard tape, as the NASA Science page "The Story Behind Apollo 8's Famous Earthrise Photo" prints it. The corrected transcript of the Apollo Flight Journal, by W. David Woods, Frank O'Brien and William Smeaton, also gives them to Anders, at 75 hours, 47 minutes and 30 seconds into the mission, in the form "Oh, my God! Look at that picture over there! Here's

the Earth coming up. Wow, is that pretty!" The fourth pass, the roll of the craft that brought the Earth into view, and the black-and-white photograph taken before the color film are described by NASA's Earth Observatory, "Earthrise Revisited" (2013). Two visualizations of NASA's Goddard Scientific Visualization Studio, "Earthrise" (2012, visualization 3936) and "Earthrise: The 45th Anniversary" (2013, visualization 4129), recreate the crew's view from the Lunar Reconnaissance Orbiter's maps of the Moon. The best known of the color photographs is NASA photograph AS08-14-2383.

A request that names nothing, like a point north of the North Pole, is excluded in principle, and therefore in all future practice. Location: *What Cannot Be*, chapter 12, "The Shape of What Can Reach What", section "Beyond the Farthest Point"; and Preface, section "What 'Cannot Be' Means Here".

"Time travel", in the sense in which the phrase is used, names no concept: a loop brings the traveler to a later finding, not back to the earlier occasion. Location: *What Cannot Be*, chapter 16, "Why Time Travel Names Nothing", sections "Very Hard, or Nothing There?", "The Geometric Reading" and "The Conclusion".

A wormhole or a warp drive, if one is ever made, is a shortcut within the one geometry, a road within our world and not a road out of it. It still needs negative energy, and on whether such energy exists in the needed amount, my books make no claim either way. Location: *What Comes After the Dark*, chapter 10, "Could Anyone Escape?", section "The Plan, Step by Step"; and Appendix A, "For the Specialist", under "Chapter 10. Could Anyone Escape?", where whether a wormhole can form and be held open by negative energy is stated as not argued in the collection.

This account counts ten dimensions, one of time, three of space and six of possibility, and the count comes from what every act of comparison must contain. The four of time and space are traversed, and the six of possibility are met only as what could be found. Location: *Measurement*, chapter 4,

"Ten Dimensions in Plain Words", in its abstract; the full count is in chapter 11, "The Ten-Dimensional Context" (the entries of Chapter Three give it step by step).

The same six serve in two ways. As a space of states with no size, they are where the kinds of particle are read. Held at every point of the four dimensions of space and time, they have an extent to which the strength of gravity is tied. Location: *What the Beginning Left Behind*, chapter 1, "Where the Last Book Left Us", sections "One Space, Taken Two Ways" and "Summary"; and *At the Edge of Reality*, chapter 7, "Six Dimensions of Possibility", section "Why We Never See Them".

Gravity and the quantum are two descriptions of one world, joined side by side and never merged. Location: *Two Theories, One World*, Preface, "The Argument in Brief", section "The Answer in a Page": "The two theories are two descriptions of one world, each capturing what the other leaves out. They are joined side by side, from the one act of comparison"; and chapter 24, "Joined, Not Merged".

The three forces of the particles are inseparable and distinct: their strengths draw close, and they never become one force. Location: *The Strengths of the Kinds*, chapter 3, "Where the Couplings Cross", section III, "Where the Crossings Are", under "The measured couplings draw close and stay apart".

Each of the nineteen constants of the Standard Model as first written has one of four standings toward the world, and the seven numbers of the neutrinos stand at a fork, with two arguments for each carried side by side until a measurement decides. Location: *Why These Numbers*, Preface, "To the Reader", section "What This Book Is For"; chapter 1, section "Four Ways a Number Can Stand"; and chapter 18, section "The Twenty-Six Numbers".

Measurement and proof validate truth; agreement among people validates nothing by itself. Location: *Physics Is Not Math*, chapter 19, "A Right Method of Evaluation", section IV, "Three Ways of Validation".

There is one vacuum, and the epochs follow one another like the cars of one train, and not the branches of a tree. As an account of outcomes, the words "many worlds are real" hold: for each comparer, one outcome is real, the one that comparer finds. Location: *What the Beginning Left Behind*, Preface, "Before We Begin", section "What This Book Finds", and chapter 21, section "A Cycle with No First Turn"; *Side by Side*, Volume One, the chapter on Sean Carroll, section III, "The Branches".

Any machine, quantum or classical, approaches what it simulates as closely as one wishes and never contains it; a quantum computer's advantage is in time, on particular tasks. Location: *The Quantum Bridge*, Preface, "What This Book Claims and How It Is Set Out", section I, "The Claims", and chapter 7, "The Reach of Simulation", section IV, Proposition 7.1; the advantage is placed in time because a count of steps is a measure of time (*Physics Is Not Math*, chapter 7, "Computation Has Sequence", section V, "Measures of Computation Are Measures of Time").

The long emptying ends in a turn to a new epoch, not in a final dark, and nothing escapes as itself. What crosses the turn is the form of the content, as one averaged form; the same law holds again on the far side, and it is not carried across. Location: *What Comes After the Dark*, chapter 8, "Is the Long Emptying the End?", section "What This Means for You"; chapter 9, "What Crosses Over, and What Stays Behind?", sections "What Crosses" and "What Returns"; and chapter 10, section "Stepping Off the Step". The gloss of the form of the content is that of chapter 9, in the passage that opens the chapter's answer, where what crosses is "what the matter of our epoch is". The same passage says: "What stays behind is every count, every length, every record, and every thing as the thing it was".

In the road country, a "town" that no road could ever reach is no place at all for the traveler, and wherever a journey arrives, it arrives somewhere in our own world. Location: *What Comes After the Dark*, chapter 10, section "No Other Sky Along Any Path"; and chapter 12, section "What Crosses", where the next epoch is joined to ours by no path and no act.

A decision selects within what is already laid out. A choice realizes what was open but not yet laid out. In the one world, which is causal and not determined, the difference between the two is real. Location: *Causality Without Determinism; Free Will, Measurement and Mind*, chapter 6, "Choice, Creation, and the Soul", in its opening and section I, "Two Ways to Spend an Evening", where the free evening and the friend's call stand. That causes are real while the world is not determined is the matter of *Home in the World*, chapter 7, "The Open Future", section "Causes Are Real".

The order runs from choice to change to causation and back to choice, in three steps. Choices originate changes. Changes can be understood causally. Causal patterns create the conditions for new choices. Location: *Causality Without Determinism*, chapter 6, section II, "Change, Causality and Choice", quoting *Incommensuration; The Theorem and the Three Axioms*, chapter 9, section II, on Axiom II, the second of the three axioms of the Immanent Metaphysics. The theorem from which Axiom II is derived 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. The chapter's glosses of symmetry, asymmetry, continuity and discontinuity, each in the theorem's sense, are those of *Incommensuration*, chapter 2, section I, "Four Characters", as the entries of Chapter One give them.

Where choice selects among what is open, creation generates the range of what is open. Where choice is personal, the act of one self, creation is cooperative. Location: *Causality Without Determinism*, chapter 6, section III, "Decision, Choice and Creation", quoting *Incommensuration; The Theorem and the Three Axioms*, chapter 8, section X: creation is "the convergence of many agents, processes, and evaluations into one shared outcome".

A living being is a place where choosing is gathered and known from inside. Meaning, known from inside, lives only where life is. Life is rare in the universe, as a share of all its matter, and it is here. Location: *Home in the World*, chapter 8, "The Bottle, the Note and the Living", section "A Village That Is Alive".

"That is why I hold that all life is sacred, and why I can call the Earth a temple": a place where choosing is known from inside, and so a place where meaning lives at all. Sacred means ultimately meaningful, and it names nothing supernatural. Location: *Home in the World*, chapter 8, section "A Village That Is Alive".

The epochs follow one another in a single line, and the law holds again in each of them. Location: *What Comes After the Dark*, chapter 9, section "What Returns".

Appendix A: What the Coming Measurements Will Find

The state before a measurement gives the weight of each outcome: in the book's words, "the state before the measurement, known as fully as the theory allows, gives the weight of each outcome, and the outcome found is not contained in it". Location: *The Quantum Passage*, chapter 7, "The Born Rule from the Structure of Comparison", section II, "Why Probability Is Necessary". The statement on the first outcomes of many states, each prepared once and measured once, rests on that sentence.

One ratio among the strengths of the forces has two values carried side by side, 5 and 21/4, and the strength of color of 0.11888 goes with 21/4. Location: *The Strengths of the Kinds*, chapter 3, "Where the Couplings Cross", section VI, "The Gaps at the Span's End", where the measured ratio of the gaps at the end of the span, 5.093, give or take 0.128, is set beside both values.

The matching that a measured W mass will serve is the step that fixes the strengths of the three forces at the top quark's mass from measured quantities, so that their change with energy can be carried upward from

there. Two published matchings are carried side by side, and one of them takes the W mass as an input. Location: *The Strengths of the Kinds*, chapter 2, "The Couplings and Their Running", section V, "Beyond One Loop, and the Matching at the Top"; and chapter 3, section VI.

Each proposed rule of a computer beneath the world fixes a precision beyond which its statistics would differ from the world's, and precision measurement and quantum information science are approaching the range at which such statistics can be tested very finely. Locations: *The Basis of Physics*, essay 18, "The Continuum Argument Against Simulation", section VII, "The Continuous Wavefunction as Evidence"; and *What Cannot Be*, chapter 21, "Are We Living in a Simulation?", section "The Quantum Wave as Evidence".

Kaku's Words and This Book's Words

This glossary has two parts. The first part sets each of Michio Kaku's words, from his books on physics, beside the word that this book uses in place of Kaku's word. The second part lists the other words that this book uses in a meaning of its own. I explain each word in full where you first meet the word: in the Preface, in a chapter, or in the appendix "What the Coming Measurements Will Find". Each entry of this glossary is a reminder, and the last line of each entry, in parentheses, says where I explain the word.

Kaku's Word Beside This Book's Word

Big Bang. This book's words: the turn, as our history finds it. The Big Bang is the hot, dense beginning to which the history of our universe, traced backward, runs. I identify the Big Bang that our history finds with the turn seen from our side. The turn is the passage in which the epoch before ours, the long era of stars, galaxies and black holes before our own, gave way to our epoch. (Preface; Chapter Four; the identification, Chapter Six.)

big freeze. This book's words: the long emptying, and the turn to a new epoch. Kaku's big freeze is the long cooling in which the universe goes dark and cold, and life can no longer go on. This book calls the long cooling the long emptying, because during the long cooling every galaxy beyond our own small family of nearby galaxies passes out of reach, and the stars burn out. The long emptying ends in a turn to a new epoch, not in a final dark. (Preface; this book's words, Chapter Eight.)

choice, in Kaku's "The choice is ours". This book's words: decision and choice. A decision selects within what is already laid out, and a choice realizes what was open but not yet laid out. Someone with a free evening weighs three options on a list, a film, a dinner and an early night, and

gives up two to have one: the weighing is a decision. When a friend calls with a walk at sunset, an idea on no list, the friend's walk is a choice. Decision and choice are both ours. Kaku ends his book *Parallel Worlds* with three sentences. The first of the three, "The choice is ours", is true in this book's sense of the word "choice": realizing what was open but not yet laid out. (Chapter Nine.)

Class I impossibility. This book's words: not yet built. Kaku sorts impossible things into three classes in his book *Physics of the Impossible* (2008). Kaku's Class I is the class of technologies that "are impossible today but that do not violate the known laws of physics". This book calls a technology of Kaku's Class I a thing not yet built. A thing not yet built waits on knowledge and power, on money, skill and time. (Chapter One.)

Class II impossibility. This book's words: for each thing in it, either not yet built or a request that names nothing. Kaku's Class II is the class of things of which he writes, "If they are possible at all", such as time machines and travel through wormholes. For each thing in Kaku's Class II, we have still to ask which of the two kinds of "impossible" the thing is: a thing not yet built, or a request that names nothing. A request names nothing when it asks for something that the shape of its domain has no place for, like a point north of the North Pole. Chapter Two shows that two things in Kaku's Class II, a message faster than light and a journey into one's own past, are requests that name nothing. (Chapters One and Two.)

Class III impossibility. This book's words: an empirical verdict, a verdict that rests on a law of physics. Kaku's Class III is the class of things that break the laws of physics as we know them. Kaku says that the known laws can change, so each verdict of Class III is an empirical verdict: a verdict that rests on a law learned from measurement. An empirical verdict stands as long as its law stands, and the verdict can be revised together with its law. Kaku's verdict on the perpetual motion machine is an empirical verdict. A perpetual motion machine is a machine that would run and do work forever with nothing fed to it from outside. The machine is excluded by the conservation of energy, a law learned from measurement,

and the machine is not among the requests that name nothing. Where an exclusion is this account's own, the exclusion rests on no law of physics, and the thing excluded is a request that names nothing. (Chapter One.)

compactification. This book's words: the six held by the four dimensions of space and time. Compactification is the physicists' name for holding extra dimensions finite. In my books the word means only one thing: the six dimensions of possibility are held by the four dimensions of space and time, present at every point of the four and kept finite there. (Chapter Three.)

constants "put in by hand". This book's words: the twenty-six numbers, each with its standing or its fork. Kaku writes that the Standard Model, the theory of the particles of matter and of the forces among them, has "about twenty constants that had to be put in by hand": numbers taken from measurement and written into the theory, with no understanding of where the numbers came from. Counted exactly, the constants of the Standard Model are nineteen as the model was first written, and twenty-six when the numbers of the neutrinos, the lightest particles of matter, are counted. Each of the nineteen numbers has one of four standings, four ways a number can stand toward the world: set by the structure of comparison, set by the structure once a stated step is taken, measured, or measured with its reason still a question. The neutrinos add seven numbers (twenty-six less nineteen). The seven numbers of the neutrinos stand at a fork: for each of the seven, two arguments are carried side by side until a measurement decides between the two arguments. (Chapter Five.)

convincing evidence, in Kaku's hope that masses derived "from first principles" might be "convincing evidence that this is the final theory". This book's words: derived numbers set beside measurement, strand by strand. Deriving the constants proves that they follow from a theory's premises, measurement shows whether they hold of the world, and a theory holds as a cable holds, strand by strand. A derived number is one strand of evidence when the number agrees with its measured value, and a cable holds by the number and the independence of its strands. (Chapter Five.)

escape to another universe. This book's words: nothing escapes as itself; the form of the content crosses the turn. Kaku asks whether intelligent life could escape a dying universe into a new universe, through a wormhole, or by sending through a wormhole the information to re-create itself. No body, message, identity or person crosses the turn into the next epoch. What crosses the turn is the form of the content, as one averaged form; the same law holds again on the far side, and it is not carried across. The form of the content is what the matter is, and which alternatives the matter has taken. At the turn there is no comparison by which the form of one black hole could be told from the form of another, so the forms of all the black holes cross as one averaged form. (Chapter Eight.)

fine-tuning. This book's words: the lottery that needs another ticket-holder. Physicists call the fit of the constants of nature to life fine-tuning: the constants look as if they had been set with care. Our universe was drawn in no lottery, because, in the words of my book *Side by Side*, "the structure of comparison yields one world, with its constants fixed". For our universe to be the lucky ticket, the other universes would have to be laid out side by side and told apart. Someone could lay the other universes out only from a place where no comparison can be made. A lottery needs someone who holds all the tickets and can tell the tickets apart, and there is no place for anyone to stand and hold all the tickets. (Chapter Six.)

God equation; *theory of everything*. This book's words: one account, two descriptions. Kaku's God equation is the one equation of a final theory, "a single formula from which, in principle, one could derive all other equations". The theory of everything is another name for Kaku's final theory. Gravity and the quantum are two descriptions of one world, joined side by side and never merged. So this account is a theory of everything in one sense, an account that leaves nothing out, and this account has no single equation from which everything else follows. (Preface; this book's words, Chapter Four.)

hyperspace; *higher dimensions*. This book's words: the six dimensions of possibility. Kaku's hyperspace is a space of more dimensions than the four dimensions we know, and string theory, he reports, counts ten: the four we know, and six more dimensions of space. In this book the six further dimensions are the dimensions of what can happen at each place, of another kind from the three dimensions of space. The six dimensions of possibility are present everywhere, and nothing travels along them. (Chapter Three.)

inflation. This book's words: no inflation needed. Inflation, which Alan Guth proposed in 1981, is a brief burst of ever faster expansion that stretched a tiny region, whose parts had once been in touch, to far beyond everything we can now see. The sky is alike in every direction because the large space of our epoch, the space outside the black holes in which the stars and galaxies lie, re-formed from one end: the shared end of the interiors of the black holes of the epoch before ours. So no inflation is needed to explain why the sky is alike in every direction. In this account a long inflation is also excluded, on two grounds. One of the two grounds is that the faint ripples in the microwave background are the form of the content carried through the turn, and not the trembling of an inflating empty space. (Chapter Six.)

information, in Kaku's hope of sending it to a new universe. This book's words: the form of the content; a count made against a context. Kaku hopes that a civilization could send enough information to re-create itself, through a wormhole, into a new universe. Information has two senses in this book. In the first sense, information is the form of the content: what the matter is, and which alternatives the matter has taken. Information in the first sense crosses the turn as one averaged form. In the second sense, information is a count made against a context, which is entropy, and information in the second sense does not cross the turn. (Chapter Eight.)

light barrier. This book's words: the edge of the domain of comparison. Kaku calls the speed of light, as a limit that no rocket reaches, the light barrier. The speed of light marks the outer edge of the whole range within

which comparisons can be made. No rule is needed to keep anything from passing the edge that the speed of light marks, because the edge of a domain has nothing beyond it to reach. (Chapter Two.)

many worlds. This book's words: many outcomes, each real for its comparer; and, in the sense of my book *What Comes After the Dark*, the epochs, each real in its own acts of comparison. In 1957 the physicist Hugh Everett proposed that every possibility in the wave function happens, each in its own branch of the world. In Chapter Six I take up three kinds of many universes in Kaku's books: the bubbles of eternal inflation, the many universes of the string landscape, and Everett's many worlds. (In *Physics of the Impossible* Kaku counts his three types as higher dimensions, the multiverse, and quantum parallel universes.) For each comparer one outcome is real, the one found, and the branches exist as structure, the laid-out range of what could be found. My book *What Comes After the Dark* says that the epochs before ours and after ours are worlds, "each real in its own acts of comparison, and no act is real in two of them". No path joins the epochs before ours or after ours to our epoch, so none of those epochs is part of the one world. As a description of a whole world fixed completely by one law, many worlds is excluded, because a whole world fixed completely by one law would perfect symmetry and continuity together, and the Incommensuration Theorem forbids that pairing. (Chapter Six.)

multiverse; *bubble universes*. This book's words: one world, everything a path from here can reach; epochs in sequence, each real in its own acts of comparison. Kaku's multiverse is the whole collection of universes, in which our universe may be one bubble among countless others, with new bubbles forming all the time, like bubbles in boiling water. There is one world, everything any path can reach, and the epochs follow one another like the cars of one train, and not the branches of a tree. Each epoch is joined to the epoch before it by two things: the sameness of the law, which holds again in each epoch, and the averaged form of the content, which crosses the turn. No path and no act runs from one epoch to the next. (Preface; this book's words, Chapter Six.)

only a quantum system can fully explain another quantum system, Kaku's principle for the chemistry of molecules. This book's words: two questions, reach and cost, each with its own answer. Reach is how close a computer's results can come to what the world is found to do, and cost is how many steps the computer needs for a given closeness, and so how much time. On cost this account agrees with Kaku. In 1996 the physicist Seth Lloyd showed that a quantum computer follows any quantum system built of parts that act on their near neighbors, and follows the system efficiently, without the cost that multiplies with every particle. On reach, a quantum computer follows a molecule as closely as one wishes, and no stage of the computer is the molecule. Kaku also writes the principle at a second strength: ordinary computers, "no matter how powerful, can never successfully simulate a quantum process". At Kaku's second strength, the result of this account differs from Kaku's: given unlimited time, an ordinary computer reaches whatever a quantum computer reaches. (Chapter Seven.)

parameters. This book's words: the constants, each with its standing or its fork. Kaku's parameters are the numbers of nature, such as the masses of the quarks and the strengths of their forces, which physicists take from measurement and put into the Standard Model by hand. (Chapter Four; this book's words, Chapter Five.)

quantum supremacy. This book's words: an advantage in time, on particular tasks. Kaku defines quantum supremacy as the point at which a quantum computer "could decisively outperform an ordinary digital supercomputer on specific tasks". In this account a quantum computer has the same reach as any other machine, and the quantum computer's advantage is in time, on particular tasks. (Preface; this book's words, Chapter Seven.)

string landscape. This book's words: one vacuum. The string landscape is the range of vacua that string theory allows, one vacuum for each way a field can be wound through the six dimensions that string theory adds to the four we know. Physicists estimate the number of vacua at ten to the five hundred. In this account the six dimensions of possibility have one

shape and no field wound through them, so there is one vacuum, one settled state of lowest energy, and no range of rival vacua to choose among. (Chapter Six.)

superforce; *master symmetry*. This book's words: three forces, inseparable and distinct. Kaku's superforce is the single force into which, in his picture, the four forces (gravity, electromagnetism, the strong force and the weak force) were merged at the instant of the Big Bang. Kaku's master symmetry was a change that "could rotate all the particles of the universe into one another". The three forces of the particles are electromagnetism, the strong force and the weak force. The three positions of every comparison are the act of comparing, the thing compared, and the thing it is compared against. In this account the three forces of the particles come from the three positions of every comparison, and the three forces were three from the start. Because the three forces are inseparable, their strengths draw close, and because the three forces are distinct, they never become one force. (Chapter Four.)

symmetry, in Kaku's sense. This book's words: symmetry in the physicists' sense, told apart from symmetry in the theorem's sense. The two senses differ in what the word is said of. In the physicists' sense, which Kaku uses, the word is said of a thing or of the equations of a law: a symmetry is a change after which the thing is as it was, as a sphere looks the same however it is turned. In the sense of the Incommensuration Theorem, the word is said of what is found in a comparison. "*Symmetry* is a sameness of content where there is a difference of context", in the words of my book *Incommensuration; The Theorem and the Three Axioms*. In the theorem's sense, a symmetry is the same content found in different settings, such as the same law here and there, today and tomorrow. (Chapters One and Four.)

time travel to the past. This book's words: a request that names nothing. "Time travel" names no concept, in the sense the phrase means: going back to an earlier occasion as the occasion was. A loop in time brings the traveler to a later finding, a new occasion in the order of the traveler's findings, and not back to the earlier occasion as it was. (Chapter Two.)

warp drive. This book's words: a faster car, in the road country. The physicist Miguel Alcubierre proposed a warp drive in 1994: a warp drive would shrink the space ahead of a ship and stretch the space behind the ship. A warp drive would carry the ship along by a shortcut within the one shape of space and time, so whatever the ship reaches is part of our own world. In the road country a warp drive is a faster car, and a faster car, however fast, arrives at a town of the same country. A warp drive needs negative energy, a state with less energy than empty space has. My books make no claim either way on whether negative energy exists in the amount a warp drive needs. (Chapter Two.)

wormhole. This book's words: a new road within the one geometry. Kaku's wormhole is a tunnel linking distant parts of space and time. A wormhole would be a shortcut within the one shape of space and time. In the road country a wormhole is a new road, so wherever a wormhole arrives is a town of the same country, part of our own world. (Preface; this book's words, Chapter Two.)

Other Words of This Book

absolute zero. The coldest anything can be. (Chapter Six.)

agreement among people. A claim counted as settled because many people have said so. Agreement among people validates nothing by itself. At most, agreement among people is circumstantial evidence, standing in for a measurement where no measurement can be made. (Chapter Five.)

algebra. The rulebook of a physical structure: the set of rules for combining and transforming the quantities that the structure can show. (Chapter Four.)

antiparticle. The mirror partner that every particle of matter has, with every charge reversed. (Chapter Five.)

arena. The setting of space and time in which everything is found. (Chapter Three.)

asymmetry. In the sense of the Incommensuration Theorem, a difference of content where there is a difference of context: a content that changes as the setting changes. (Chapter One.)

axiom. A starting statement from which the rest of an account is reasoned. The Immanent Metaphysics has three axioms. The first says that the act of comparing is the most fundamental of the three positions of comparison, and that the thing compared and the thing it is compared against are conjugate; the second gives the order within every comparison, from the range of what is possible, to the act, to the record; the third says that the three positions are distinct, inseparable and non-interchangeable. (Chapter Four.)

baby universe. Kaku's name for a tiny region squeezed and heated until it swells into a universe of its own, joined to ours by a thin tunnel. (Chapter Eight.)

Big Crunch. Kaku's name for a final collapse in which the universe falls back on itself. (Chapter Eight.)

black hole. A body whose gravity is so strong that not even light escapes from it. (Chapter Two.)

Born rule. The rule of quantum theory by which each possible outcome of a measurement is given its weight. (Appendix A.)

cable. An argument about the world, which holds as a steel cable holds: by the number and the independence of its strands. The strands of an argument are independent when they rest on different sources, so that a mistake in one strand does not carry into the others. A proof in mathematics is a chain instead, and for a proof the rule of the weakest link is exactly right. A chain fails where its weakest link fails, and a proof fails where any one of its steps fails. (Chapter Five.)

carrier. The particle that passes a force from one thing to another, as the photon, the particle of light, carries electromagnetism. (Chapter Four.)

category error. A concept applied where the concept does not belong, so that a request using the concept is malformed rather than hard. (Chapter Two.)

causal. Of the world: such that every change in it can be understood as an effect that follows from causes, without the world being *determined*, fixed in every detail by what came before. (Chapter Nine.)

character. One of the four characters that can be found in a comparison: symmetry, asymmetry, continuity or discontinuity, each in the sense of the Incommensuration Theorem. My book *Two Theories, One World* uses "character" in a second meaning: one of the two joinings of characters that the Incommensuration Theorem leaves, symmetry with discontinuity, and asymmetry with continuity. (Chapters Two and Four; the second meaning, Chapter Four.)

classical. The physics before the quantum, in which every piece of the world has a definite state at every moment. (Chapter Seven.)

closed and *open*, of a universe. In Kaku's use, a closed universe is one whose expansion stops and gives way to a collapse, and an open universe is one that expands forever. (Chapter Eight.)

closed timelike curve. A path that a clock can follow and that returns to its own starting place and moment, called more plainly a time loop. (Chapter Two.)

color. The physicists' name for three ways a quark can be, the charge of the strong force. Color in the physicists' sense has nothing to do with the colors we see. (Chapter Four.)

commute. Two measurements commute when either can be made first without changing what the other finds. (Appendix A.)

comparer. Anyone or anything that makes a comparison, a person or an instrument. (Chapter Six.)

comparison. The act by which anything is known: setting one thing beside another and telling them apart; every measurement is an act of comparison. (Preface.)

components. The numbers needed at each point of space to say how the shape of space and time is bent there. Einstein's gravity in four dimensions needs ten components. (Chapter Three.)

conservation of energy. The finding that the total amount of energy is never made and never lost, only passed from one form to another. (Chapter One.)

constant of nature. One of the fixed numbers that the laws of physics contain, such as the speed of light. (Preface.)

constraint. A limit laid on something, which could in principle be otherwise: a rule that might be relaxed, a wall that might be climbed, a limit that better instruments might exceed. (Chapter One.)

content. What is found in a comparison. (Chapter One.)

context. The setting in which the content is found, such as a place or a moment: the respect in which the two things compared are two. (Chapter One.)

continuity. In the sense of the Incommensuration Theorem, the word is said of what is found in a comparison. "*Continuity* is a sameness of content where there is a sameness of context", in the words of my book *Incommensuration; The Theorem and the Three Axioms*. Within one unbroken setting, the content does not jump. (Chapter One.)

continuum. A smooth range in which between any two values there is always another, with no gaps. (Chapter Seven.)

convergence. Independent routes of reasoning, resting on different premises, arriving at one value. Convergence is the strongest evidence that inquiry into the world can have. (Chapter Five.)

cosmological constant. The energy of empty space that drives the speeding-up of the expansion of the universe. (Chapter Six.)

cosmologists. The physicists who study the universe as a whole. (Chapter Six.)

count of disorder. The measure of how far the matter of an epoch has mixed and run down. Each epoch begins its own count of disorder. (Chapter Six.)

count of light species. The astronomers' count of the energy of all the radiation other than light itself in the young universe, counted in units of the energy that one kind of neutrino carries. In the count of light species, the word "light" means of small mass. (Appendix A.)

curvature. An overall bend of space on the largest scales, which would need a length to set the bend, as the bend of a circle is set by its radius. (Chapter Six.)

cylinder world. Einstein's phrase for the five dimensions of space and time of the mathematician Theodor Kaluza, taken with Kaluza's assumption that nothing changes along the fifth direction, as nothing changes along the length of a straight pipe. (Chapter Three.)

dark matter. The unseen matter whose weight holds the galaxies together. In this account the dark matter is a lasting vibration of the six dimensions of possibility, made at the turn. (Chapter Six.)

decoherence. What happens when the surroundings of a qubit come to carry a trace of the qubit's state, so that the blend the qubit holds spreads into the surroundings and the calculation is spoiled. (Chapter Seven.)

densely and never exhaustively. A simulation reaches what it simulates densely, which means as close as one wishes, and never exhaustively, which means never all of what it simulates. (Chapter Seven.)

dimension. A direction in which things can be laid out and measured. Length, width and height are three dimensions. In this book's own sense, a dimension is one independent way in which two findings can differ, the sense under which the six of possibility count as dimensions though nothing is laid out along them. (Preface; this book's own sense, Chapter Three.)

Dirac particle. A particle distinct from its own antiparticle. (Appendix A.)

discontinuity. In the sense of the Incommensuration Theorem, a difference of content where there is a sameness of context: a content that jumps within one setting. (Chapter One.)

distance of a code. How many of the physical qubits of an error-correcting code a fault must reach before the fault can change the stored value. (Chapter Seven.)

domain. The whole range of places, or of things, that can be joined to one another, as the surface of the Earth is for a walker and the towns and roads are for a traveler. (Chapter One.)

domain of comparison. The whole range within which comparisons can be made, whose outer edge the speed of light marks. (Chapter Two.)

edge of a domain. Where the domain ends, with nothing beyond it to reach, as the North Pole is the edge of north for a walker on the Earth. (Chapter One.)

effective neutrino mass. The combination of the three neutrino masses that neutrinoless double beta decay would measure, if the decay happens. Each kind of neutrino is a blend of three neutrinos, each with its own mass. Neutrinoless double beta decay is a decay in which a nucleus gives off two electrons and no neutrino. (Appendix A.)

electromagnetism. The force of electricity and magnetism, of which light is a traveling wave. (Chapter Three.)

empirical. Of an exclusion or a verdict: made by a law learned from measurement, so that the exclusion or verdict rests on what measurement has found and stands as long as the law stands. The first kind of "impossible" is the kind that can change, and the first kind has two forms: a thing not yet built, and an empirical verdict. An empirical verdict is the second form of the first kind. An empirical verdict can change because a law, as we know the law, may itself be revised when a new measurement disagrees with the law. The perpetual motion machine is excluded empirically, by the conservation of energy. (Chapter One.)

energy. The capacity to make things move, warm up or change. (Chapter One.)

entanglement. The link by which two particles that have met stay joined after they part, so that their findings, measured far apart, agree in a pattern no separate instructions could give them. Entanglement carries no message. (Chapter Two.)

entropy. A count of the arrangements of a thing's parts that leave the thing looking the same from where the thing is seen, and so always a count made against a context. (Chapter Eight.)

epoch. A long era in which stars, galaxies and black holes form. Each epoch has its own beginning: traced backward from inside the epoch, the epoch's history runs to that beginning, which is the epoch's own Big Bang. Each epoch ends in a turn into the next epoch. The one world lies within our own epoch, since the next epoch is joined to ours by no path and no act. (Chapter Six.)

equation. A statement, written in mathematics, that two quantities are equal. The laws of physics are written as equations. (Preface.)

error correction. Storing one qubit of a calculation across many physical qubits and checking the physical qubits over and over, so that a fault in a few of the physical qubits can be found and undone without ever reading the stored value itself. (Chapter Seven.)

eternal inflation. An inflation that goes on without end in some places while it stops in others. (Chapter Six.)

event. A single happening at one place and one moment. (Chapter Two.)

event time. The order of a traveler's findings. (Chapter Two.)

exact solution. A history of space and time that Einstein's equations allow exactly, with nothing approximated. (Chapter Eight.)

exists. A thing exists when it stands as structure: laid out, timeless, the same in every instance, as a map or a law exists. "A law exists; a measurement is real", in the words of my book *Why Time Travel Is Not a Concept*. (Chapter Two.)

field. Something spread through space with a value at every point, as the temperature of a room has a value at every point in it. (Chapter Three.)

finding. What one act of comparison yields: one outcome, laid down as a record. (Chapter Two.)

flat. Of space: with no overall bend at the scale of the whole sky. (Chapter Eight.)

force. A push or a pull by which one thing acts on another. (Preface.)

fork. A number stands at a fork when two arguments for the number are carried side by side until a measurement shows which argument is right, as a doctor keeps two diagnoses open until a test shows which diagnosis is right. (Chapter Five.)

form of the content. What the matter is, and which alternatives the matter has taken. The form of the content is information in the first of this book's two senses of the word. At the turn the forms of all the black holes of an epoch cross as one averaged form. (Chapter Six; as information, Chapter Eight.)

formalism. The body of mathematics that describes a quantum computer, in which all the blended possibilities are held at once. (Chapter Seven.)

from first principles. By reasoning from the foundations of a theory, with nothing taken from measurement. (Chapter Five.)

fundamentally. In the statement of the Incommensuration Theorem, at the foundation of a comparison, exactly and not approximately. (Chapter Eight.)

galaxies. The great systems of billions of stars, many of them turning like wheels. (Chapter Six.)

gates. The small operations a quantum computer applies to one or two qubits at a time. (Chapter Seven.)

general relativity. Einstein's account of gravity as the shape of space and time, in which matter bends the shape and the bent shape guides how things move. (Chapter Two.)

generations. The three copies of the whole set of particles of matter, alike in charge and different in mass. (Chapter Five.)

geometric time. The time laid out in the shape of space and time, read by a clock along each path. (Chapter Two.)

geometry. Geometry is the mathematics of shapes; one of its oldest games is drawing with only a pair of compasses and an unmarked ruler. A geometry, in physics, is one whole shape of space and time. (Chapters One and Two.)

heat death. The end that popular accounts foresee, in which everything has one temperature and nothing ever happens again. (Chapter Eight.)

held. Of the six dimensions of possibility: present at every point of the four dimensions of space and time and kept finite there, with those four as their setting. (Chapter Three.)

hibernation. The physicist Freeman Dyson's name for a life spent mostly asleep, waking only for short stretches of thought. (Chapter Eight.)

hidden sector. A family of particles that would feel none of the three forces of the known particles (electromagnetism, the strong force and the weak force). (Appendix A.)

Higgs field. The field that gives the particles of matter their masses. (Chapter Five.)

horizon. The farthest distance from which any signal can ever reach us. (Chapter Eight.)

identification. A stated step in which something in the structure of comparison is taken to be a quantity of the world, as a surveyor takes the stake in the ground to be the stake the deed names. (Chapter Five.)

Immanent Metaphysics. The study of what must be so for anything at all to be known, worked from inside the act of knowing, here and now, while that act takes place, and never from a place outside the world. (Preface.)

Incommensuration Theorem. The Incommensuration Theorem is a structural fact about the nature of knowing. In its own words, the theorem says: "Symmetry and continuity cannot both be applied, simultaneously and fundamentally, to any event or comparison; and neither can asymmetry and discontinuity". My book *Incommensuration; The Theorem and the Three Axioms* proves the theorem from comparison alone. Incommensurate means having no common measure. (Chapter One.)

inverse square law. The rule that the pull of a mass weakens with the square of the distance from it. (Chapter Three.)

joining. Of the characters of a comparison held exactly: symmetry or asymmetry taken together with continuity or discontinuity. Four joinings are possible. The Incommensuration Theorem excludes two of the four joinings, symmetry with continuity and asymmetry with discontinuity, and two joinings remain: symmetry with discontinuity, and asymmetry with continuity. (Chapter Four.)

Kaluza-Klein theory. Kaluza's idea that one geometry with one extra direction produces both gravity and light, named after Theodor Kaluza and Oskar Klein, who took up the idea in 1926. (Chapter Three.)

Koide's relation. A rule, named after the physicist Yoshio Koide, that ties the masses of the electron and of its two heavier relatives, the muon and the tau, together in one number. Koide's relation has two parts, for the square roots of the three masses: the part the three square roots share, and the part by which the three square roots differ. Exactly, the sum of the three masses is two thirds of the square of the sum of their square roots. (Chapter Five; stated exactly, Appendix A.)

large space. The space outside the black holes of an epoch, in which the stars and the galaxies lie. (Chapter Six.)

law of physics. A rule that nature has been found to follow wherever the rule has been checked, written down by physicists so that others can check the rule again. (Chapter One.)

lepton. The electron or one of its relatives. (Chapter Four.)

light cone. The forward light cone of a happening is every place and moment that its light, or anything slower, can reach, which is everything the happening can affect. The backward light cone of a happening is everything that can affect the happening. (Chapter Two.)

located comparer. Anything that compares from a place in the world: you, a thermometer, an instrument on a laboratory bench. (Chapter Three.)

logical qubit. The one qubit of a calculation that error correction stores across many physical qubits. (Chapter Seven.)

long inflation. An inflation long enough to take the lengths we see across today's sky, which once lay within the greatest distance a signal could have crossed since the turn, and stretch them beyond that distance. (Chapter Six.)

magic. The physicists' name for what a qubit has when its state lies off the octahedron, the shape whose six corners mark six states of one qubit on the globe of all its states. The easy gates are the gates that an ordinary computer can follow efficiently. The easy gates only rotate the globe so that the six corners trade places, so the easy gates alone never bring a state off the octahedron. I identify magic as what lets a finite list of gates come as close as one wishes to every state of the formalism. (Chapter Seven.)

matching. The calculation that fixes the strengths of the three forces of the particles (electromagnetism, the strong force and the weak force) at the energy of the top quark's mass from measured quantities, so that their change with energy can be carried upward from there. (Appendix A.)

measurement. A comparison made here and now, by the one who compares, as in physics. Measurement and proof validate truth. (Chapter Five.)

measures. Six independent respects in which what is found can vary, one measure coming from each of the six ideas that every comparison contains, in three pairs: same and different, what is found and its setting, and the one who compares and the thing compared. The shape of the six dimensions of possibility is derived from the six measures. (Chapter Three.)

microwave background. Light left over from the time when the whole universe was hot and glowing, stretched by the expansion of space ever since. (Chapter Six.)

mixings. The numbers that say how often the weak force turns one kind of particle into another. (Appendix A.)

moduli. The two fields of the geometry that set the size and the shape of the six dimensions of possibility, taken as held by the four dimensions of space and time. The moduli are apart from the fields that join the six dimensions to the four. One of the two moduli mostly sets the size of the six

dimensions, and the other mostly sets the shape of the six. A vibration of either modulus would carry a pull of its own between masses, of very short reach. (Chapter Three.)

M-theory. The one larger theory of which, as the physicist Edward Witten showed in 1995, the five versions of string theory are five ways of seeing. (Chapter Four.)

names nothing. A request names nothing when it asks for something the shape of its domain has no place for, like a point north of the North Pole. A request that names nothing is excluded in principle, and therefore in all future practice. (Chapter One.)

negative energy. A state with less energy than empty space has, which a wormhole or a warp drive would need. (Chapter Two.)

neutrinos. The lightest particles of matter, with no charge at all. (Chapter Five.)

no-go result. A result showing that a research program cannot be carried through. (Chapter Three.)

noise. In a quantum computer, the faults that the surroundings cause. (Chapter Seven.)

non-commutative geometry. The branch of geometry that the mathematician Alain Connes founded, so called because in it the order in which two quantities are combined can change the result. (Chapter Four.)

normal order. Of the neutrino masses: the order in which the two neutrinos that make up most of the electron's neutrino are the lighter two. Each kind of neutrino, the electron's among them, is a blend of three neutrinos, each with its own mass. (Appendix A.)

not yet. The first form of the first kind of "impossible", the kind that can change: a thing not yet built waits on knowledge and power. (Chapter One.)

one to one. Of a simulation: matching every part of what it simulates exactly, with nothing approximated. (Chapter Seven.)

perfected. Held exactly, at the foundation of a description. (Chapter Four.)

phase. A setting on a circle, like the position of the pointer on a dial. In the act of comparing, the content of a comparison is read by its phase. (Chapter Four.)

possibility. The range of what could be found in a comparison. With time and space, possibility is one of the three settings in which the findings of every comparison are placed. (Chapter Three.)

precluded. Shut out before the question of building arises. (Chapter One.)

proof. An argument laid out so that it holds the same for whoever checks it, as in mathematics; proof and measurement validate truth. (Chapter Five.)

pure number. A number with no unit. (Appendix A.)

pure states. States known as completely as quantum theory allows. (Chapter Seven.)

quantum. The physics of the very small, where energy and matter come in tiny indivisible amounts. (Preface.)

quantum computer. A computer built from parts that follow the rules of quantum physics. (Preface.)

quantum information science. The study of how quantum systems store and process information. (Appendix A.)

quark. One of the particles inside the proton. (Chapter Four.)

qubit. The quantum computer's unit of memory: where an ordinary bit holds a zero or a one, a qubit can hold a blend of the two, and the qubit gives one or the other only when the qubit is read. (Chapter Seven.)

reach and cost. Reach is how close a computer's results can come to what the world is found to do, and cost is how many steps the computer needs for a given closeness, and so how much time. (Chapter Seven.)

real. A thing is real when it is given in an actual act of comparison: when it is found, here, by someone or something. (Chapter Two.)

road country. The picture that runs through this book: a country where the only way to travel is by road. The road country stands for the one world, which is everything any path can reach. (Preface.)

simulation. A calculation that follows a piece of the world step by step, so that its results can be set beside what the world itself is found to do. (Chapter Seven.)

six dimensions of possibility. The six further dimensions of the world, which are dimensions of what can happen at each place: present everywhere, met only as the range from which each actual finding is one selection, and never traveled along. (Chapter Three.)

special relativity. Einstein's theory of 1905 that tells how lengths and durations compare for observers moving steadily past one another. (Chapter Two.)

Standard Model. The theory of the particles of matter and of the forces among them, apart from gravity. (Chapter One.)

standing. The way a number stands toward the world: set by the structure of comparison, set by the structure once a stated step is taken, measured, or measured with its reason still a question. A number stands at a fork when two arguments for it are carried side by side until a measurement decides between them, as the seven numbers that the neutrinos add to the constants of the Standard Model do. (Chapter Five.)

stated step. A step taken in the open and marked where it is taken, as the surveyor's deed names its stake; a number with the second standing follows by argument once one such step, an identification, is made. (Chapter Five.)

strength. Of a force: a single number that says how strongly the force acts; each strength changes slowly as the energy of a collision rises. (Chapter Four.)

string theory. The theory in which the smallest pieces of matter are tiny vibrating strings, and each way a string can vibrate is a different kind of particle. (Preface.)

strong force. The force that binds the center of the atom. (Chapter Three.)

structure of comparison. The set of parts that every comparison must contain, on which the four standings of the numbers of nature rest: set by the structure, set by the structure once a stated step is taken, measured, or measured with its reason still a question. (Chapter Three.)

supersymmetry. The pattern in which every known particle would have a heavier partner. (Chapter Four.)

superdeterminism. The idea that the outcome of every measurement, and the experimenter's choice of what to measure, were fixed together from the start. (Appendix A.)

symmetry. The word has two senses in this book, and each sentence that uses it says which. The two senses differ in what the word is said of. In the sense of the Incommensuration Theorem, the word is said of what is found in a comparison. "*Symmetry* is a sameness of content where there is a difference of context", in the words of my book *Incommensuration; The Theorem and the Three Axioms*. In the theorem's sense, a symmetry is the same content found in different settings, such as the same law here and there, today and tomorrow. In the physicists' sense, which Kaku uses, the word is said of a thing or of the equations of a law: a symmetry is a change after which the thing is as it was, as a sphere looks the same however it is turned. (Chapters One and Four.)

theorem. A statement proved by mathematics. (Chapter One.)

three positions of comparison. The act of comparing, the thing compared, and the thing it is compared against. The three forces of the particles are electromagnetism, the strong force and the weak force. The three forces of the particles come from the three positions, one force from each position. (Chapter Four.)

threshold. The rate of failure per operation below which a calculation of any length can be carried out with as small a chance of error as one wishes, by making the code larger. The threshold theorem proves that a threshold exists. The threshold theorem also requires that each failure touch only a few neighboring qubits, and that the failures be nearly independent of one another. (Chapter Seven.)

turn. The passage at the end of the interiors of the black holes of an epoch, where three directions of space open out while the six dimensions of possibility close in, and the next epoch begins. (Chapter Six.)

type I civilization. Kaku's name for a civilization that can use all the energy of the sunlight that falls on its planet. (Preface.)

unified theory. One theory that covers forces once thought to be separate. (Chapter Three.)

vacuum. In a laboratory, a vacuum is a chamber pumped empty of air. In physics, a vacuum is the settled state of lowest energy that a system rests in, from which small pushes roll back. (Chapters Three and Six.)

value that lands. A value that agrees with what is measured. When a value lands before anyone knows why the value agrees, the reason for the agreement is a question to follow. (Chapter Five.)

wave function. A spread of possibilities that says how likely each result of a measurement is. (Chapter Six.)

weak angle. The number by which physicists and my books write the strength of the weak force. The three forces of the particles are electromagnetism, the strong force and the weak force. In the structure of comparison the three forces of the particles have equal weight, and at that equal weight the structure sets the weak angle's number at exactly three eighths. At the energies that experiments reach, the weak angle is measured, with its reason still a question. (Chapter Five.)

weak force. The force behind some kinds of radioactivity, which turns one kind of particle into another. (Chapter Three.)

weighting and *phasing*. Each alternative that can be found is held with a weighting, its share of the chance of being the one found, and with a phasing, a setting on a circle, like the angle of a dial. Heads and tails are the two alternatives of a tossed coin, and each of the two is held with its own weighting and its own phasing. (Chapter Three.)

world. In this book's own words, the one world: everything any path can reach. The next epoch is joined to ours by no path and no act, so no other epoch is part of the one world. Where my book *What Comes After the Dark*

says that the epochs are worlds, each real in its own acts of comparison, the word is used in that book's sense. This book calls the space outside the black holes of an epoch, with the things in it, the large space of that epoch. Where Kaku speaks of other universes or other worlds, the words are Kaku's, and I give them in this book as Kaku's words. (Preface.)

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For further reading

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