

What the Balance Shows

The Immanent Metaphysics
for Readers of Sabine Hossenfelder

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UVSM PUBLICATIONS
Wytheville, Virginia

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

uvsmpublications.com
contact@uvsmpublications.com

ISBN 979-8-90710-439-6

DOI: https://doi.org/10.67291/NOOM6185

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Preface

Her Message, and How to Read This Book

You have read the books of the physicist Sabine Hossenfelder. Something in her books rang true for you. What can another book add to the questions that Hossenfelder has already asked so well?

Two Books, One Thread

Sabine Hossenfelder is a theoretical physicist who writes for readers outside her field. Her book *Lost in Math* appeared in 2018. A *pure number* is a number with no units, such as the ratio of one mass to another. When a physicist expects the pure numbers of a theory to be neither very large, nor very small, nor very close to one another, the physicist's expectation is what Hossenfelder means by *naturalness*. In *Lost in Math*, Hossenfelder asks whether physicists who judge untested theories by beauty, naturalness and simplicity are still doing science.

Hossenfelder and many other physicists struggle with one tension, and she names the tension in the Preface of *Lost in Math*: "we believe the laws of nature are beautiful, but is not believing something a scientist must not do?"

Hossenfelder draws three lessons in the last chapter of *Lost in Math*. The first lesson is to "first make sure it really is a problem", before reaching for mathematics to solve the problem. The second lesson is "State your assumptions", and the third lesson is "Observational guidance is necessary". Hossenfelder gathers the three lessons into two short sentences:

> Physics isn't math. It's choosing the right math.
>
> (*Lost in Math*, chapter 10, section "Lost in Math")

Hossenfelder's book *Existential Physics* (2022) takes up the questions that people bring to a physicist about their own lives. Does the past still exist? How did the universe begin? Are you just a bag of atoms? Has physics ruled out free will? Was the universe made for us? About each question, Hossenfelder asks three things: which beliefs about our existence the established laws of physics rule out, which beliefs the laws of physics support, and which beliefs the laws of physics leave outside what science can decide. Hossenfelder states her aim in the Preface of *Existential Physics*: to "tell you how much scientists currently know, and also where science crosses over into mere speculation".

When the laws of physics neither rule out certain beliefs nor support those beliefs, Hossenfelder calls those beliefs "ascientific", because "science says nothing about them". She takes the word 'ascientific' from the physicist Tim Palmer, in the Preface of *Existential Physics*. Hossenfelder also asks that everything she says carry one preamble: "as far as we currently know".

One view runs through both of Hossenfelder's books, like a thread that joins the two books, and she names the view in the Epilogue of *Existential Physics*: "researchers in the foundations of physics don't reflect enough on what they are doing". In my words, Hossenfelder's message across both of her books has three parts. First, physics answers to what is observed: every theory is judged by observation. Second, the beauty of a theory is no reason to believe the theory. Third, a physicist owes the reader a plain report of what is known, of how it is known, and of where the knowing stops.

On beauty, Hossenfelder is right. I set a second account of physics beside Hossenfelder's account. In the second account, I reach the same conclusion about beauty as Hossenfelder, by a route of my own: the beauty of a theory is no reason to believe the theory.

A Balance on a Bench

Picture a two-pan balance, the kind that stands on a market stall or on a school laboratory bench. A beam rests on a pivot, and a pan hangs from each end of the beam. You set a thing in one pan and known weights in the other pan. The beam tips toward the heavier pan, or the beam stays level.

The balance sets one thing beside another and shows how the two things stand: which thing is heavier, or that both things weigh the same. When someone or something sets one thing beside another and finds how the two stand, the act is called *comparison*. Every measurement is an act of comparison: a ruler is set beside an edge, one clock's ticks are set beside another clock's ticks, and a detector's count is set against a 'threshold', a level fixed in advance.

When whoever or whatever does the comparing is itself a part of the world that it compares, with no place outside the world to stand, I say that the comparison is made from *inside the world*. I identify every 'finding' of physics, every result that physics has found, with an act of comparison made from inside the world.

The picture of the balance appears again in every chapter of this book, and in every chapter the balance with its weighing stands for the act of comparison, and for nothing else. In the picture, the things set in the pans are what is compared, and the tip of the beam is the 'result'. The things weighed occupy two places, the left pan and the right pan, and the floor and the room hold the two places. The weighing happens at one moment. The 'setting' of the weighing is the two places, the floor and the room that hold the two places, and the moment of the weighing. The beam joins the two pans and carries the comparison, and the beam is part of the setting too.

In the picture, the weighing can be divided in two different ways. By the first way, the weighing divides into two parts: what the result is about (here, how heavy the things in the pans are) and the setting. Chapter Three calls the first part, what the result is about, the 'content'. Chapter Three calls the second part, the setting, the 'context'.

The same weighing can also be divided in a second way. By the second way, the weighing divides into the 'side from which' the weighing is made and the 'side about which' the weighing is made. The side from which the weighing is made is the instrument itself, together with whoever reads the instrument, and the side about which the weighing is made is the things in the pans. The two ways of dividing the weighing are distinct: by the first way, the pans and the beam belong to the setting, while by the second way, the pans and the beam belong to the instrument.

Each time the balance appears in a chapter, the balance pictures one more step of the chapter's answer to the chapter's question.

The Account Beside Hers

In this book, *metaphysics* is the study of what must be so for anything at all to be known. The word *immanent* means within. The second account starts from a metaphysics that works from within, called the 'Immanent Metaphysics', which works from inside the act of knowing, here and now, and never from a place outside the world.

I start the Immanent Metaphysics from the act of comparison. I ask what every comparison must contain, whatever is compared and whoever or whatever does the comparing. The place where an argument starts is the argument's 'ground', and the ground of the Immanent Metaphysics uses nothing from physics: no measurement, no law, and no result of any experiment. I work out a physics from the ground of the Immanent Metaphysics. The Immanent Metaphysics is my own work: I first set it out in my book *An Immanent Metaphysics* (2001), and I work out its physics in a

series of later books, every one of them mine, which Appendix B, For the Specialist, names chapter by chapter, with the place in each book that every step draws on.

Hossenfelder's account and mine start from different places: Hossenfelder starts from the record of physics and the practice of physicists, while I start from what every comparison must contain. When the two accounts arrive at one result, the two accounts arrive at the result by separate 'routes', each route being the steps from one account's ground to the result. When two routes start from separate ground and meet at one place, the two routes together give more reason to trust the place where the routes meet than either route gives alone. For the two accounts, the place where the routes meet is a result that both accounts share. When the two accounts arrive at different results, the chapter first states what my account establishes and why, then where I part from Hossenfelder. I present Hossenfelder's books at their full strength, in her own words. I add two things to the questions that Hossenfelder asks. First, this book adds a second route to the results that Hossenfelder reaches, a route that starts from the act of comparison. Second, where the two routes part, this book adds a different result, with the reason for the different result. From the structure of comparison, I derive the energy of empty space, which agrees with the measured value to within about two percent, as I show in Chapter Four. I sealed my forty-two predictions of measurements still to come in a dated record on 1 November 2026, before any of those measurements, as I tell in Chapter Fourteen.

Fourteen Questions

Each chapter answers one question, a question that a reader of Hossenfelder's books carries away. The title of each chapter asks the chapter's question:

1. Can Beauty Tell Us Which Laws Are True?
2. If Physics Is Written in Mathematics, Why Is Physics Not Mathematics?

3. Why Did the New Particles Not Appear?
4. Do the Unexplained Numbers Need Explaining?
5. Was the Universe Tuned for Us, or Is Ours One of Many?
6. What Happens When a Quantum System Is Measured?
7. Could Everything, the Experimenter's Choice Included, Have Been Fixed in Advance?
8. Has Physics Ruled Out Free Will?
9. Are You Only a Bag of Atoms?
10. Does the Past Still Exist, and Why Does Time Run One Way?
11. How Did the Universe Begin, and How Will It End?
12. What Is the Dark Matter, If Every Search Comes Back Empty?
13. Is Gravity's Meeting with the Quantum the One Real Problem?
14. Whom Can We Trust When Scientists Agree?

Some words in the fourteen questions may be new to you. Each new word is explained in the chapter whose question contains the word, at the place where you first need the word. Each question arises from the answer to the question before it: each chapter ends on the question that the next chapter answers. The closing chapter, "What the Balance Shows", gathers the fourteen answers into one picture.

How to Read This Book

This book is written for Hossenfelder's readers, and I assume no knowledge of physics. Every technical word is explained at the place where you first meet the word. The word may be Hossenfelder's, such as 'naturalness', or this book's own, such as 'comparison'. The back of this book holds a glossary called "Her Word and This Book's Word", which sets Hossenfelder's words beside this book's words, as a reminder. The chapters contain no equations.

Each chapter keeps the same order. Each chapter opens on the chapter's question, asked in a reader's words, and next comes a scene from the history of science: a date, a place, and a person at work. Each chapter then has a section headed "What Sabine Hossenfelder Showed", which gives Hossenfelder's answer in her own words. In that section I quote her books by chapter and section, and where Hossenfelder sets out her position only in her papers, I quote her papers. Some questions need a picture, such as the balance. The picture may come before the section headed "What Sabine Hossenfelder Showed". After the section headed "What Sabine Hossenfelder Showed", I set out the ground of my account, and the notes name the books that carry the ground of my account. When I reach Hossenfelder's result from the ground of my account, the chapter takes you over that ground, and when I reach a different result, the chapter gives the reason for the different result. The chapters tell measurements already made as stories: what was done, what was found, and what we now know.

Hossenfelder's readers know the boxes at the ends of her chapters, called "IN BRIEF" in *Lost in Math* and "THE BRIEF ANSWER" in *Existential Physics*. Each chapter of this book ends in a similar way: a short paragraph that begins with the words "The short answer" states where the chapter has arrived, and then I end the chapter on the question that the next chapter takes up.

Physics is still being measured: physicists have yet to make some of the measurements that bear on the chapters of this book. Appendix A, "What the Coming Measurements Will Find", gathers the measurements still to be made, and for each coming measurement, Appendix A states what the measurement will measure and what I say the measurement will find. Appendix B, "For the Specialist", gathers the mathematics. For every claim that the chapters make, Appendix B names the book of mine that carries the argument for the claim, together with the chapter and the section of the book where the argument is made. Appendix B also gives the exact values and the algebra that the chapters state in words. The chapters never need Appendix B, so you can read every chapter, from the first to

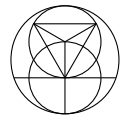
the last, without turning to Appendix B once. The references at the back of this book list the primary papers and books, and list each book that has an ISBN with its ISBN.

Here, in brief, is what this book holds that Hossenfelder's books do not: a second route, from the act of comparison, to her results on beauty, on unexplained numbers and on the agreement of experts (Chapters One, Four and Fourteen); the order of depth, and why physics is not mathematics (Chapter Two); a closed list of the kinds of particle, with no superpartner, no single larger force and a stable proton (Chapter Three); a standing for every number, a strong angle of zero, and a cosmological constant derived from the structure of comparison (Chapter Four); one world, with the other universes existing as structure and never real (Chapter Five); the measurement update as a change of the shared record (Chapter Six); the exclusion of determinism and of superdeterminism (Chapter Seven); choice as the outcome that no law fixes, seen from inside (Chapter Eight); consciousness found in interaction at every scale, and why computation cannot be consciousness (Chapter Nine); time as existing structure and as the real order of findings, with an arrow in every interaction (Chapter Ten); the turn, the cycle of epochs and the flatness of space (Chapter Eleven); the dark matter as a ringing of the six small dimensions (Chapter Twelve); an arena of space and time that cannot be quantized, and information that is not destroyed (Chapter Thirteen); and the three ways of validation, with the sealed record of my predictions (Chapter Fourteen). If you have read another of my books written for the readers of another author, you know the ground I lay in the Preface and Chapter Two already: comparison, its four characters and the Incommensuration Theorem, told here with a two-pan balance, a box of stamped weights and a settling beam. What is new for you is every answer to Hossenfelder's questions, from Chapter One on. Read the chapters in order, because each chapter builds on the ones before it. Where a chapter uses a word or a result that an earlier chapter teaches, a short box at the head of the chapter lists the word or result, with the chapter that teaches it. Where a chapter retells what Hossenfelder showed, the retelling stands

in a shaded box headed "From Hossenfelder's pages": a reader who knows her books can pass over the boxes, and a reader new to them can read the boxes first.

Hossenfelder writes in the last pages of *Existential Physics* that her book is a way to help you "hold part of the universe in your head, using words and images rather than equations". I keep to the same way and also use words and images rather than equations, with one image above all the others: the balance. Hossenfelder's first book, *Lost in Math*, begins with beauty, and I begin with beauty too.

Can beauty tell us which laws are true?



Chapter One

Can Beauty Tell Us Which Laws Are True?

Sabine Hossenfelder says that beauty has led physics astray. Is Hossenfelder right? And if beauty is no guide to which laws of nature are true, what is the guide?

A Lesson in Graz

What guides us to the true laws is a question older than the physics Hossenfelder writes about. A young mathematics teacher faced the question in his own work, long before anyone asked the question in Hossenfelder's words. The teacher was Johannes Kepler, who taught in the Austrian town of Graz.

On 19 July 1595 Kepler was teaching a class. Saturn and Jupiter meet in the sky at one place after another, and Kepler was showing his students how the meeting places of Saturn and Jupiter creep around the 'zodiac', the band of stars through which the planets travel. Kepler drew a great many triangles inside a circle to show the creeping of the meeting places. The triangles marked out a second, smaller circle inside the first circle, and Kepler saw that the ratio of the sizes of the two circles was very nearly the ratio of the sizes of the paths of Saturn and Jupiter.

Triangles drawn inside a circle had given Kepler very nearly the ratio of the paths of two planets, and so Kepler next carried the idea from flat figures, such as triangles, to solid figures. A *regular solid* is a solid whose faces are all the same regular shape, meeting in the same way at every

corner. There are exactly five regular solids: the cube, and the solids with four, eight, twelve and twenty faces. The five regular solids are often called the 'Platonic solids'. In Kepler's day six planets were known: Mercury, Venus, Earth, Mars, Jupiter and Saturn. Six paths leave five gaps between neighboring paths, and there are five regular solids.

So Kepler nested the five regular solids in the five gaps between the six paths. Picture a hollow sphere that holds the path of Saturn. A cube sits inside the sphere of Saturn, touching the sphere, and a sphere for Jupiter sits inside the cube. The solid with four faces sits inside the sphere for Jupiter, and a sphere for Mars sits inside the solid with four faces. The nesting goes on inward, one solid in each gap, down to the sphere of Mercury. Kepler worked out the sizes of the spheres, and the sizes of the spheres came out generally within a tenth of the sizes that the astronomers of his day gave for the paths of the planets. Where a size missed, Kepler put the miss down to errors in the measurements. Kepler published the nested design in Tübingen in 1596, in a book called *Mysterium Cosmographicum*, the Mystery of the Cosmos.

The nested design was a beautiful idea, and Kepler held to the nested design *because* the design was beautiful. Hossenfelder quotes Kepler in *Lost in Math* (chapter 2, "Where We Come From"): "It is absolutely necessary that the work of such a perfect creator should be of the greatest beauty". Kepler saw the greatest kind of beauty he knew in a solar system built from the five perfect solids. Kepler's solar system had exactly as many planets as the five solids allow.

Eight Minutes of Arc

The Danish astronomer Tycho Brahe had made the finest measurements of the planets of Kepler's time. Tycho had recorded where each planet stood among the stars, night after night, over many years. Tycho made the sightings with large instruments, aimed by eye. In February 1600 Kepler arrived at Tycho's observatory, in the castle of Benátky near

Prague, to work with Tycho. Tycho died in October 1601, and Kepler then inherited the task of making sense of Tycho's records. Above all, Kepler worked on Tycho's record of Mars.

Kepler began in the old way: he built the best model of circles he could. Kepler checked the model against Tycho's positions of Mars. A *minute of arc* is a sixtieth of a degree. The model missed some of Tycho's positions by eight minutes of arc. The full Moon is about half a degree across, which is thirty minutes of arc. So eight minutes of arc is about a quarter of the width of the full Moon.

The old method had a ready answer to a miss of eight minutes of arc: 'add one more circle'. An *epicycle* is a small circle whose center is carried around a larger circle. If an astronomer adds enough epicycles, the astronomer can match the path of a planet as closely as anyone wishes. Kepler did not add one more circle, because Kepler trusted Tycho's measurements, and Tycho's measurements were accurate to better than eight minutes of arc. So Kepler took the miss as a finding about the world: the path of Mars is *not* made of circles. Kepler later wrote a book about the work on Mars, and in the book Kepler wrote that the eight minutes of arc alone had shown the way to the reform of the whole of astronomy.

Kepler looked for the shape of the path of Mars and for the cause of the path at the same time. Kepler proposed that a force from the Sun moves the planets, and that the force is weaker the farther a planet is from the Sun, so that a planet moves faster when the planet is nearer the Sun. And Kepler found the shape of the path. The path of Mars is an oval of the kind you can draw with a loop of string around two pins, and the Sun sits at one of the two pins. Mathematicians call an oval drawn with a loop of string around two pins an *ellipse*. Kepler published the book in 1609. The title of the book says what Kepler was after: *Astronomia Nova*, the New Astronomy, Based upon Causes, or Celestial Physics.

Some astronomers wanted the circles back. The astronomer David Fabricius wrote to Kepler with a suggestion, and Hossenfelder quotes the suggestion:

> "If you could only preserve the perfect circular orbit and justify your elliptic orbit by another little epicycle", Fabricius wrote to Kepler, "it would be much better".
>
> (*Lost in Math*, chapter 2, "Where We Come From")

Kepler kept the ellipse. In 1687 Isaac Newton showed, in his *Principia*, that one law of gravity gives the planets paths of exactly Kepler's shape, the ellipse. Newton's law of gravity describes one pull, which makes a stone fall and also gives the planets their paths. Kepler kept his love of the nested solids, whatever the measurements showed: in 1621 Kepler brought out a second edition of the book of 1596, the *Mysterium Cosmographicum*, with notes on what the years since 1596 had taught him. Then William Herschel found a seventh planet, on the night of 13 March 1781, while looking through a homemade telescope in his back garden in Bath. The seventh planet is the planet we call 'Uranus'. Seven paths leave six gaps between neighboring paths, and there are still only five regular solids.

A Balance on a Market Stall

Come back to the two-pan balance from the Preface, and set the balance on a market stall. The seller sets a bag of apples in one pan and a known weight in the other pan. The beam tips toward the heavier pan when one load is heavier, and the beam stays level when the two loads weigh the same.

The balance sets one thing beside another and finds how the two things stand, the same or different, in some respect. I call the act of setting one thing beside another, and finding how the two stand, *comparison*. On the market stall, the balance sets the apples beside the weight and finds the apples heavier, lighter, or the same, in weight.

Every measurement is an act of comparison. You find a length by setting an edge beside a measuring rod, a duration by setting an event beside the ticking of a clock, and a weight by setting a load beside a standard mass. Each of Tycho's sightings set the place of Mars beside the stars and beside the marks on Tycho's instrument. A measured result says how the measured thing compares with the standard of the measurement. In this book, the balance with its 'weighing' stands for the act of comparison, and for nothing else.

Now imagine two balances side by side on the stall. One balance is plain tin, a little dented, with a beam that squeaks. The other balance is polished brass, with engraved pans and a beam so finely made that the beam is a pleasure to look at. Which of the two balances tells you what the apples weigh?

Either balance tells you what the apples weigh, once the apples are in a pan and the beam has come to rest: on either balance, the weighing tells you. The beauty of the brass balance is a fact about the brass balance: the beauty was there before any apples came near the brass balance, and the beauty stays the same whatever the apples weigh. The brass balance is a fine thing to own, and a well-made balance may weigh more accurately than a dented balance. Even so, you still find the weight of the apples by weighing the apples.

The result of a weighing comes from the weighing alone. Suppose a thing is in place before the weighing, and the thing stays the same whatever the weighing shows. Then the thing tells nothing about the result of the weighing. Kepler's nested solids were beautiful from the day Kepler conceived the solids, and so were the perfect circles that the solids carried. The beauty of the solids and the circles stayed the same whatever

the measurements showed. Tycho's records were made of 'weighings', in the sense of the picture. Each of Tycho's sightings was an act of comparison that set the place of Mars beside the stars. Kepler set his best model of circles beside Tycho's record of Mars, and in the picture the 'beam' tipped by eight minutes of arc: the model missed Tycho's positions by eight minutes of arc. Kepler believed the beam: Kepler trusted the measurements over the model.

From Hossenfelder's pages

What Sabine Hossenfelder Showed

Sabine Hossenfelder trained and worked as a theoretical physicist. Hossenfelder researched how gravity can be joined to 'quantum physics', the physics of atoms and light, in which energy comes in smallest steps. Hossenfelder also researched what might lie beyond the physics already confirmed. Hossenfelder used her knowledge from inside physics to examine the habits of her own field in *Lost in Math* (2018). Hossenfelder's starting question is simple: "Why should the laws of nature care what I find beautiful?" (*Lost in Math*, chapter 1, "The Conundrum of the Good Scientist").

Hossenfelder charges that physicists judge new, untested theories by rules that no textbook teaches. Hossenfelder names the 'hidden rules': naturalness, simplicity or elegance, and beauty. Hossenfelder sets out what she finds wrong with the hidden rules:

> These hidden rules are ubiquitous in the foundations of physics. They are invaluable. And in utter conflict with the scientific mandate of objectivity.
>
> (*Lost in Math*, chapter 1, "The Conundrum of the Good Scientist")

Hossenfelder explains why the hidden rules matter more now than the hidden rules once did: testing a new law of nature takes longer and longer. Confirming a predicted particle or effect has taken twenty-

five years, fifty years, even a hundred years. Hossenfelder writes that the time needed for a test can now be longer than a scientist's whole career, and so, she writes, theorists choose what to work on by other means, and beauty is one of the other means. Of beauty, she writes: "It's a guide, a reward, a motivation. It is also a systematic bias" (chapter 1, "Physics Envy"). Hossenfelder also writes that the further a subject is from any test, the more physicists rely on the beauty of the theories of the subject (chapter 2, "What We Are Made Of").

Hossenfelder shows from history that physicists who took beauty as their guide were sometimes led to wrong ideas. Kepler's nested solids are Hossenfelder's first case. Between 1870 and 1890 about twenty-five scientists held that atoms are knots in a fluid that fills space. The Nobel laureate Albert Michelson wrote in 1903 that the idea of atoms as knots "ought to be true even if it is not". Physicists call the idea that the universe began in a hot, dense state the 'big bang'. The astronomer Fred Hoyle disliked the big bang. Hoyle confessed that the dislike was a matter of taste: "I have an aesthetic bias against the big bang". (Hossenfelder quotes both Michelson and Hoyle in chapter 2, "Where Beauty Lies".) And ideas that physicists thought 'ugly' turned out right. James Clerk Maxwell was unhappy with his own theory of electricity and magnetism. Maxwell's theory has electric and magnetic 'fields', the influences that fill the space around charges and magnets, and Maxwell was unhappy because the fields of his theory rested on no machinery of gears or fluids beneath the fields. Half a century later, physicists built a theory of how light and electrons act on one another. The physicists built the new theory on Maxwell's theory. The theory of light and electrons was right too, though the physicist Paul Dirac called the theory 'ugly'. Hossenfelder's summary is short: "aesthetic criteria work until they don't" (chapter 2, "Where Beauty Lies").

Hossenfelder also answers physicists who defend beauty as a judgment learned from experience. The physicist Steven Weinberg shared the Nobel Prize in Physics in 1979. Weinberg compares a physicist to a horse breeder, who calls a horse 'beautiful' because long experience has taught the breeder that the kind of horse the breeder calls beautiful is the kind of horse that wins races. Hossenfelder replies: "But just as experience with horses doesn't help when building a race car, experience with last century's theories might not be of much help conceiving better ones" (chapter 2, "What We Are Made Of"). Hossenfelder also talks with the physicist Frank Wilczek about past revolutions in physics. In the conversation, she presses the point that experience with past theories is no guide to new ones: "people only found that new beauty after data forced them to look at it" (chapter 7, "A Theory of Something").

Of the hidden rules, naturalness gets the most room in Hossenfelder's book, with an appendix of its own. Physicists have written naturalness as mathematics. A *dimensionless number* is a 'pure number': a number with no units, such as the ratio of one mass to another. Suppose no dimensionless number of a theory is very large, very small, or very close to another dimensionless number of the theory. Then physicists call the theory *natural*. When a number is very large, very small, or very close to another number, the number breaks the rule of naturalness. Physicists call a number that breaks the rule of naturalness *fine-tuned*. Hossenfelder writes: "In summary, numbers that are very large, very small, or very close together are not natural" (chapter 2, "Why Trust a Theorist?"). Naturalness began as a matter of taste: in Hossenfelder's words, naturalness "started as an aesthetic criterion, but now it has become mathematically formalized". Hossenfelder adds that physicists wrote naturalness as a mathematical rule. Then, she writes, physicists largely forgot that naturalness began in taste (chapter 4, "Where the Numbers Have No Name").

Hossenfelder examines simplicity and elegance as well (chapter 5, "Simplicity" and "Elegance"). Hossenfelder writes that simplicity is "merely of relative value": a theory can be simpler than some other theory, but there are many theories simpler than the theories that describe our world. So no one can pick out the true theory by simplicity alone. As physicists use the word, 'elegance' is simplicity joined with surprise: the moment when everything falls into place. Hossenfelder calls elegance "an unabashedly subjective criterion", and then she sums up the hidden rules in one sentence: "Beauty, then, is a combination of all of the above: simplicity, naturalness, and a dose of the unexpected" (chapter 5, "Elegance"). Hossenfelder adds that our sense of beauty "is partly universal and partly due to exposure during education" (chapter 5, "Emancipating Dissonance"), and that perceptions of beauty "can and do change" (chapter 5, the box "IN BRIEF").

Hossenfelder's book ends with three lessons for her field (chapter 10, "Lost in Math"):

> (*Lost in Math*, chapter 10, "Lost in Math")

Hossenfelder's charge is right. Hossenfelder's history of the field shows that beauty, naturalness and elegance, as physicists have used the three, are no evidence about nature: beautiful ideas failed, and ideas thought ugly turned out right. The word 'immanent' means within. The Immanent Metaphysics works from inside the act of knowing, here and now, and never from a place outside the world.

The first lesson I draw, therefore, is this: If you want to solve a problem with math, first make sure it really is a problem. Because of this my second lesson is: State your assumptions. And so, my third and final lesson is this: Observational guidance is necessary. I reach Hossenfelder's result from a second direction: from the Immanent Metaphysics, together with the books of physics built on the Immanent Metaphysics.

The Same Result, on Separate Ground

I begin the second direction with a beautiful machine. An *orrery* is a working model of the solar system. A brass Sun sits in the middle, and the planets ride on arms around the Sun. Underneath the planets, a train of gears carries each planet around at the planet's proper pace. One model of the solar system was built in about 1712 for the Earl of Orrery, and the instrument took the Earl's name: 'orrery'. Watch an orrery turning, and you see the heavens on a table, all at once, in exact proportion.

Now turn the handle of the orrery the other way. The planets go around backward, just as smoothly, each at its proper pace: the orrery runs just as well in either direction. Picture a visitor who has watched the orrery for an hour. The visitor might say: so the solar system could run backward just as well as forward.

The solar system runs one way only. The Moon raises tides in the Earth's oceans, and the tides drag against the turning Earth. The drag slows the turning of the Earth and pushes the Moon slowly outward. The Apollo astronauts left reflectors on the Moon. Laser light bounced off the reflectors shows the Moon moving away from us by about 3.8 centimeters a year. The gears of the orrery carry only the turning of the planets, and leave out the tides, the drag and the Moon drawing away. How easily the orrery runs backward is a property of the orrery, and the visitor took a feature of the orrery for a feature of the solar system, the thing the orrery shows.

My answer in this chapter depends on keeping two things apart: a property of a model, and a property of what the model shows. A description of the world written in mathematics is a model too, just as the orrery is a model: a thing made to show the world, with properties of its own. When a description stays the same under every change of place or setting, the description has the property called *symmetry*. Economy is a second property a description can have, and having no large unexplained ratios is a third. Symmetry, economy and having no large unexplained ratios are

properties of the description. You find out whether the world shares a property of the description by setting the description beside the world, in measurement. Mathematics is written from one view only, the 'third-person view', which is the same for every reader: a mathematical result is laid out whole in the third-person view, and no one in the result is doing the comparing. If someone makes 'the visitor's mistake' with mathematics, the person takes the third-person view of mathematics for the whole of what is, and so takes a property of the description for a property of the world. My book *Side by Side*, in two volumes, sets my account beside twenty-four models of the universe. In its first volume I treat naturalness as a case of the visitor's mistake made with mathematics, in these words: "Naturalness is that error in a precise form: the demand that the numbers of nature be of a size the mathematics finds unremarkable". I add a line in which the word 'instrument' means mathematics: "The world is under no obligation to the instrument".

Why is the visitor's mistake so easy to make, even for the best of us? I state the reason. People find a description by acts of comparison, and we receive the description only after the acts of comparison are done. By then the description is finished, written down, and the same for everyone who looks, and *because* the description is finished, the description seems to have been there all along, waiting. The most shareable, the most exact and the most finished description is easily taken for the deepest. Kepler's nested solids were 'shareable', 'exact' and 'finished', while Tycho's tables were a long record of nights at the instrument, line by line. So the nested solids looked deeper than Tycho's tables.

I also tell Kepler's story, and show what Kepler's work did that the circles could not do. A model of circles riding on circles can follow any path whatever, if enough circles are added. So circles that fitted the path of Mars closely said nothing about why Mars takes the path Mars takes. Kepler let one question about the world guide his work on Mars: 'what moves the planets?' Kepler judged which mathematics was worth doing by the question 'what moves the planets?', and one more circle was not worth doing, because a circle can only change the fit and leaves the ques-

tion unanswered. Kepler found the shape of the path of Mars and proposed a cause, a force from the Sun, and Newton then found the one law of gravity that gives the ellipse. Kepler and Newton answered the question 'what moves the planets?' by physics reasoning, and the physics reasoning used mathematics at every step. The circles stayed useful as a fine way to calculate where a planet will be seen on a given night.

I take a third route to the result that naturalness is no evidence about the world. I compare the theory of particles that physicists use today to a large old computer program, inherited from earlier programmers. A large old program comes with running code, input numbers, outputs, and a manual written around the program. In the theory of particles, the 'input numbers' are numbers such as the masses and strengths of the particles. The 'running code' is the machinery of calculation that turns the input numbers into predictions, the program's 'outputs'. The predictions can be set beside measurement. The 'manual' says what the program is supposed to do. In an old program, the manual is often out of date, or simply wrong. In the picture of the old program, naturalness belongs to the manual. I give a rule for old programs: trust nothing in the manual until the running code confirms what the manual says. The manual of the theory of particles, naturalness included, is consulted for orientation but trusted for nothing. None of my books uses naturalness or fine-tuning as an argument.

I also give beauty a place of its own. 'Truth' is found in the way things actually are: in logic, in mathematics, in what holds the same for everyone who looks. 'Beauty' is found in the here and now: in the meeting of one particular person with what is before the person. I count truth and beauty as two of a triple whose third member is 'goodness', found in values and virtue, and I hold that truth, beauty and goodness are distinct, always found together, and never standing in for one another. When a person meets what is before the person, the meeting has two sides: what a person meets as beautiful depends on what is before the person, and also on who the person is. What the person has seen and learned shapes who the person is. So what a physicist meets as beautiful changes when the physicist's

training changes. The way things actually are stays the same, whoever looks. Hossenfelder found that a sense of beauty is formed partly by education and changes over time. Hossenfelder's finding fits exactly where I place beauty, *because* who a person is changes what the person meets as beautiful.

Each of Hossenfelder's three lessons also has a partner in my account. Hossenfelder's first lesson is "first make sure it really is a problem", and the first lesson matches a simple table of results that I ask for before anyone begins any piece of mathematics. In the table, you list each result the mathematics could give, and beside each result you write down what the result would change in the answer to the question about the world. Kepler's case shows how the table works. The question about the world is: 'what moves the planets?' The mathematics on offer is one more circle in the model of Mars, and one more circle has two possible results: the fit becomes closer, or the fit stays as it was. The answer to 'what moves the planets?' is the same with either result. So, for the question 'what moves the planets?', you do not add the circle. You do a piece of mathematics for a question *only* when some result of the mathematics would change the answer to the question.

Hossenfelder's second lesson is "State your assumptions", and stating assumptions is also a rule of my account. I set out what every comparison must contain. I call what every comparison must contain 'the structure of comparison'. A step can go from the structure of comparison to a quantity measured in the world. I call a stated step from the structure of comparison to a measured quantity an *identification*. I state each of my identifications in the first person ("I identify ..."), and I check each identification against measurement. Hossenfelder's third lesson is that observation must guide, and the third lesson is the lesson of Kepler's eight minutes of arc: Kepler let Tycho's measurements of Mars overrule the circles Kepler had built.

Elegance Anyone Can Check

I keep the word 'elegance', and I give the word a sense that anyone can check. I call elegance "a sign of understanding and not of style", and name three parts of elegance. The first part of elegance is many results from few starting points, and I call the first part *parsimony*. The plain case of parsimony is Newton's one law of gravity, which gives the path of every planet. The second part of elegance is whether the form of a body of work could not have been otherwise. When the form of a body of work could not have been otherwise, the work shows why its conclusions hold, and not only that the conclusions hold, and I call the second part *structural inevitability*. The third part of elegance is whether every part of a body of work has a job to do in the work, and I call the third part *economy of means*. Of structural inevitability, I add that "independent thinkers arriving at the same structure is evidence of it".

When independent thinkers arrive at the same structure, why does the agreement of the thinkers count as evidence? Suppose two arguments both produce the same value, and each argument is right nine times in ten. Suppose also that the two arguments rest on different starting points. So a mistake in one argument does not make the other argument wrong. Then the value is wrong only if *both* arguments are wrong at once, and both arguments are wrong at once with a chance of one tenth of one tenth: one in a hundred. So the value is surer with two independent routes than with either route alone. When independent routes, resting on different starting points, arrive at one value or one conclusion, I call the agreement *convergence*. I hold convergence to be the strongest evidence that inquiry into the world can have.

Physics has a famous case of convergence. At the start of the twentieth century, scientists still argued about atoms. Some held that matter is made of atoms, and others held that atoms are only a useful way of speaking. In 1913 the French physicist Jean Perrin gathered thirteen different ways of counting the molecules in a given amount of matter. Perrin set out the

thirteen ways in his book *Les Atomes*. The thirteen ways rested on things as different as the jiggling of tiny grains in water and the way tiny grains settle under their own weight, and the thirteen ways agreed on the count. The agreement of the thirteen ways did much to end the long dispute about atoms. We now know that matter is made of atoms, and we know how many atoms there are in a given amount of matter.

The agreement of Perrin's thirteen ways is a fact anyone can inspect: anyone can lay the thirteen routes side by side and see that the thirteen routes rest on different things and arrive at one number. I join elegance and convergence. In that volume, elegance, taken as a sign of understanding, "is the convergence of independent routes on one result, a convergence anyone can check (as distinct from a preference of the theorist)".

Hossenfelder takes the word 'elegance' in the sense that her field gives the word: simplicity joined with surprise. In the sense of simplicity joined with surprise, Hossenfelder finds elegance subjective. I agree with Hossenfelder about 'elegance' in her field's sense: elegance in her field's sense is no evidence about the world. I also have a second sense of the word 'elegance'. Anyone can find elegance in the second sense by a stated procedure, and anyone can check the finding. Elegance in the second sense is few starting points, many results, and independent routes arriving at one place. I also separate elegance from simplicity: "elegance is not simplicity; a theory need not be simple to be called elegant. To call a theory elegant is to say that it is profoundly clear".

Hossenfelder closes *Lost in Math* by saying that the next breakthrough in physics will come in this century, and then she writes, in a line of its own: "It will be beautiful". I add one thing to Hossenfelder's last line: the 'weighing', a measurement made in the world, will say whether the breakthrough is true.

What the Weighing Decides

Go back to the market stall, and to the two balances: the dented tin balance and the polished brass balance. The brass balance is lovely, and the brass balance may be the better balance. The loveliness of the brass balance was there before any apples came near the balance. The loveliness is there still, whatever the apples weigh. So you learn the weight of the apples from the weighing, *because* the weighing does change with the apples. The weighing has three parts: the apples sit in one pan, the known weight sits in the other pan, and the beam tips or stays level. *Only* the weighing tells you what the apples weigh, and a beautifully made balance tells you nothing about anything you have yet to weigh.

Kepler's nested solids were as lovely as anything in the history of science, and so were the perfect circles of the solids. The nested solids matched the sizes of the paths of the planets to within a tenth. Measurement determined what became of the nested solids and the circles. Kepler set his best model of circles beside Tycho's records of Mars, and the beam tipped by eight minutes of arc: the model missed Tycho's positions by eight minutes of arc. Kepler gave up the circles for the ellipse. Then Herschel found a seventh planet, and seven paths needed six solids, but there are only five regular solids. Kepler found the ellipse by trusting the 'beam', that is, by trusting Tycho's measurements. The ellipse now has a beauty of its own, of the kind Hossenfelder describes: people found the beauty of a new idea only after data forced people to look at the idea.

The short answer: Comparison with the world, made by measurement, shows which laws are true. A comparison is stronger when independent routes arrive at one result. Where no measurement has yet been made, independent routes that arrive at one result are firmer ground than taste, and anyone can lay the independent routes side by side and check the routes. Beauty, naturalness and simplicity are properties of a mathematical description, in the sense that the field has given the words 'beauty',

'naturalness' and 'simplicity'. So beauty, naturalness and simplicity are no evidence about the world. Hossenfelder shows the conclusion from history, and I show the conclusion from the act of comparison.

What, then, is the difference between physics and mathematics?



Chapter Two

If Physics Is Written in Mathematics, Why Is Physics Not Mathematics?

What this chapter uses

Comparison is setting one thing beside another and finding how the two stand; the two-pan balance stands for the act of comparison, and for nothing else (Preface).

The *setting* of a weighing is the two places, the floor and the room that hold the two places, and the moment of the weighing (Preface).

Suppose a thing is in place before the weighing, and the thing stays the same whatever the weighing shows; then the thing tells nothing about the result of the weighing (Chapter One).

An *identification* is a stated step from the structure of comparison to a measured quantity (Chapter One).

Sabine Hossenfelder says that physics isn't math, and that the claim that the world *is* math is not science. What is the difference between physics and mathematics, and does the difference matter?

A Lecture in New York

The physicist Eugene Wigner gave the Richard Courant Lecture in Mathematical Sciences at New York University on 11 May 1959. Wigner's lecture was printed the next year, under a title that has been quoted ever

since: "The Unreasonable Effectiveness of Mathematics in the Natural Sciences". The printed lecture opens with a story of two friends talking about their jobs, two friends who had been classmates in high school. One friend has become a statistician, and he shows the other friend a paper he wrote on how populations change. A bell-shaped curve describes how measurements scatter around their average, and statisticians call the bell-shaped curve the *Gaussian distribution*. The statistician's paper begins with the Gaussian distribution, as statistical papers on populations do. The formula of the Gaussian distribution contains the symbol π, and the statistician explains the symbol: π is the ratio of the circumference of a circle to the diameter of the circle. The friend thinks that the statistician is teasing him. In Wigner's telling, the friend answers that "surely the population has nothing to do with the circumference of the circle".

Wigner granted that the friend's reaction was plain common sense, and then he took the puzzle behind the reaction seriously. His point was that mathematicians work out mathematics for their own reasons, and yet, again and again, the mathematics they worked out turns up in physics, exactly where physicists need it. The mathematics fits. Wigner called the fit of mathematics to physics "a wonderful gift which we neither understand nor deserve", near the end of the lecture.

The question of this chapter comes from Wigner's gift. The question has two parts. Why does mathematics fit the world so well? And since mathematics fits the world so well, is the world itself made of mathematics?

From Hossenfelder's pages

What Sabine Hossenfelder Showed

Hossenfelder takes up Wigner's gift in the first chapter of her book *Existential Physics*. She names the fit with Wigner's own word.

> It is a curious fact that mathematics is "unreasonably effective" in the natural sciences, as Eugene Wigner put it so unforgettably.
>
> (*Existential Physics*, chapter 1, "Transcendent Math")

Hossenfelder grants the fit in full. Her own example is *Existential Physics* itself. Whether you read the book on a screen or on laser-printed paper, the book reached you through physicists who worked deep in the mathematics of *quantum mechanics*, the physics of atoms and light. Then Hossenfelder writes:

> And yet physics isn't math. Physics is a science and as such has the purpose of describing observations of natural phenomena.
>
> (*Existential Physics*, chapter 1, "Transcendent Math")

Hossenfelder reasons in plain steps, in the same section of *Existential Physics*, "Transcendent Math". She writes: "All we can tell from observations is that math is useful to describe the world". The claim that the world *is* mathematics is a further claim, which says that mathematical objects have a being of their own, apart from anyone who thinks of them, and that the world is one of those objects. Philosophers call the further claim *Platonism*. A *mathematical structure* is a set of objects together with the relations among the objects, laid out whole. A triangle is a mathematical structure, and so are the whole numbers. 'Laid out whole' means that every part of the structure is there at once, with nothing still to come. Max Tegmark is a 'cosmologist', a physicist who studies the universe as a whole, and he holds the strongest form of Platonism. Hossenfelder reports Tegmark's view in

these words: "all of mathematics is real and it's all equally real". In Tegmark's view, every mathematical structure is real, and not only the mathematics that describes what we see. Hossenfelder answers that the further claim, Platonism, explains nothing we observe. In her words: "And because this additional assumption is unnecessary to explain what we observe, it's not scientific". Hossenfelder says of Tegmark's form of Platonism: "But however you feel about it, it's not wrong; it's just not scientific".

In *Lost in Math*, Hossenfelder makes the point that physics is not mathematics from inside the working life of a physicist.

> But physics isn't math. Besides being internally consistent (not giving rise to conclusions that contradict each other) a successful theory must also be consistent with observation (not be in contradiction with the data).
>
> (*Lost in Math*, chapter 1, "Made of Math")

A theory of physics, then, answers to two judges, the theory's own logic and the world, but mathematics can satisfy only the first judge. Hossenfelder gives the reason in one sentence:

> But we can never prove any math to be a true description of nature, for the only provable truths are about mathematical structures themselves, not about the relation of these structures to reality.
>
> (*Lost in Math*, chapter 4, "Making Problems")

Hossenfelder draws several lessons from the fact that no mathematics can be proved true of nature, and the lessons run through *Lost in Math*. A proof is only as good as the assumptions the proof starts from, so the assumptions of a proof must be stated. Physicists borrow many of their assumptions from philosophy, and no one says so. One

of the borrowed assumptions is a habit: when a quantity comes out infinite in a theory, physicists rule that the quantity can never be infinite in nature. Hossenfelder says of the habit, in *Lost in Math* (chapter 9, "The Bedrock of the Sciences"): "It's a philosophical requirement turned into a mathematical assumption". Simplicity is another borrowed assumption. Hossenfelder finds no reason to expect a deeper theory to be a simpler theory. Hossenfelder writes that a good theory "allows us to calculate the results of many observations from few assumptions" (*Existential Physics*, chapter 2, "What Does It Mean to Explain Something?"). No theory contains the answer to every question, because physicists choose each theory by how well the theory describes what we see. Physicists use the name *theory of everything* for one theory that would explain all the particles, the forces among the particles and the constants of nature. Hossenfelder writes of a theory of everything: "So even if we had a theory of everything, science alone would never explain why that particular theory is the one" (*Existential Physics*, chapter 7, "Will We Ever Know It All?"). Hossenfelder closes her lessons in the last chapter of *Lost in Math*, where she gathers the lessons into two short sentences:

> Physics isn't math. It's choosing the right math.
>
> (*Lost in Math*, chapter 10, "Lost in Math")

Hossenfelder is right on four points: mathematics does not tell us whether the starting points of the mathematics are true of the world; hidden assumptions do harm, and stating the assumptions is the cure; simplicity is no evidence; and no theory explains everything.

What the Weights Remember

Come back to the two-pan balance of the Preface and Chapter One: a beam on a pivot, with a pan hanging from each end. In this book the balance and its weighing stand for one thing *only*: an act of comparison, the act of setting one thing beside another and finding how the two things stand.

Suppose you want to know how much a bag of flour weighs. You set the bag in the left pan. You take a brass weight stamped "500 g" from a wooden box and set the brass weight in the right pan. The beam tips to the left, so you add a weight stamped "200 g". Now the beam tips the other way. You take the 200-gram weight out, put in a 100-gram weight, and keep trying weights until the beam rests level.

Four different things have happened in the weighing of the flour.

First, there is the bare act of comparing: you set two things side by side and saw that one thing was heavier, before you looked at a single number. You can compare weights with no balance at all: if you hold a stone in each hand, you can tell which stone is heavier. When you find that one thing is heavier than another, the finding is complete by itself: the finding needs no law of physics, no rule and no 'theorem' (a statement proved from starting assumptions).

Second, there is the weighing as it happens in the world. The beam swings and settles on this bench, this morning, and the swing runs forward in time and never backward. The swinging and settling of the beam is a physical event.

Third, there is the procedure you followed: put on the largest weight, and if the beam tips the wrong way, take the weight off and try the next smaller weight. The procedure is a fixed rule applied step by step. Each step of the procedure starts from where the step before ended.

Fourth, there is the mathematics. The numbers stamped on the weights add up to the weight of the flour. Multiply each weight by the weight's distance from the pivot, and the beam rests level when the res-

ults come out the same on both sides. The arithmetic of the beam is exact, and the arithmetic holds for every beam that fits the starting assumptions of the arithmetic: a straight, rigid beam turning on a fixed pivot.

Now ask which of the four things needs which. Someone checks the arithmetic of the beam by working through the arithmetic step by step. Working through step by step is the third thing, a procedure. A hand, a brain or a circuit carries out every step of the working, in the world, and carrying out a step in the world is the second thing, a physical event. Every physical weighing is, at bottom, a comparison, and a comparison is the first thing, the bare act. The three links run one way: in each link, the thing with the higher number needs the thing with the lower number, while the thing with the lower number goes on without the thing with the higher number. The procedure of trying weights runs without waiting on any theorem about beams. The beam swings and settles whether or not anyone follows a procedure. And your bare comparison of the two stones needed nothing that physics states about the event of holding the stones.

Look at the brass weight again. The "500 g" stamped on the brass weight is the record of an earlier weighing, in which someone set the brass weight beside a standard and found that the brass weight matched the standard. So the number on the brass weight came after a comparison. The arithmetic of the beam is a description worked out from numbers like the stamped 500. The stamped numbers record weighings, and the arithmetic describes the weighings. The weighing is the act, and the weighing comes first.

The four things in the weighing are pictures of four fields of knowledge. Metaphysics is the study of the act of comparison itself, because every act of knowing is an act of comparison or is built from acts of comparison. *Physics* is the study of acts of comparison as they happen in the world. *Computation* is the carrying out of a sequence of steps by a fixed rule. *Mathematics* is the study of structure: shape, number and the patterns of valid reasoning, held in view as a whole. One field *presupposes* a second field when the first field needs the second to be carried out, stated or checked, while the second field can be carried out without the first. Ar-

range the four fields by what each field presupposes, with the deepest field first, and the four fields run: metaphysics, physics, computation, mathematics. I call the arrangement *the order of depth*.

'Depth' means presupposition in the order of depth, and nothing else: depth says nothing about which field is more exact, more useful or more admired. Mathematics keeps every bit of its certainty: a theorem, once proved, holds in every case that the theorem's starting points cover. Mathematics is the finest instrument there is for what is laid out as structure, and the instrument of mathematics stands last in the order of depth, resting on the acts that make it and check it.

One rule follows from the order of depth. A field that rests on another field cannot set conditions on the field it rests on. Where the two fields disagree, the field that rests on the other is at fault. The arithmetic of the beam cannot tell the flour what to weigh. An arithmetic that disagreed with the weighing would be a poor arithmetic, *not* a poor weighing. I build the order of depth from the ground, chapter by chapter. I then draw a consequence from the order of depth. The consequence gives my book *Physics Is Not Math* its name: physics is not mathematics.

If These Premises, Then This

What exactly does mathematics give us, then, and what does mathematics leave for the world to decide?

Every argument starts from *premises*, the statements taken as given in the argument. A *theorem* is a statement shown to follow, step by step, from its premises. A theorem guarantees the connection between the premises and the conclusion: wherever the premises hold, the conclusion holds. The form of a theorem is "if these premises, then this". Within the 'if-then' form, a theorem is as certain as anything can be. A second question is whether the premises hold of the world, and measurement answers the second question.

Geometry shows that the two questions are separate: whether a conclusion follows from its premises, and whether the premises hold of the world. Euclid built his geometry on a few starting statements, which he called 'postulates'. One of Euclid's postulates is the parallel postulate. In its usual form, the parallel postulate says that through a point beside a straight line, exactly one straight line can be drawn that never meets the first line. Mathematicians tried for two thousand years to prove the parallel postulate from the other postulates, and the mathematicians failed. Then, in 1829 and 1830, Nikolai Lobachevsky published a geometry in which many lines through the point never meet the first line, and János Bolyai published a geometry with many such lines in 1832. In 1854 Bernhard Riemann set out a geometry in which no line through the point avoids the first line. Each of the new geometries is as free of contradiction as Euclid's geometry.

A further question belongs to physics: which of the geometries is the geometry of the space we live in? Albert Einstein's theory of gravity says that what space and time contain curves space and time. So near heavy bodies, the geometry of space is not exactly Euclid's geometry. A *black hole* is a region where gravity is so strong that nothing escapes the region. Physicists tested Einstein's theory against measurements, from the slow turning of Mercury's orbit to the ripples in space sent out when two black holes merge. Physicists found space and time smooth and shaped by what space and time hold, in each of the measurements. We now know that Euclid's geometry describes the space near us very closely, but holds near us only nearly. Measurement settled which geometry holds. Mathematics alone could not settle which geometry holds.

I use two words, 'merit' and 'true', to keep the two questions apart. When the claims of an argument follow from the argument's premises, the argument has *merit*. When an argument has merit and its premises are also true of the world, the argument is *true*, in the sense used here for arguments. Mathematics certifies merit, while we seek truth by measurement, and by independent routes that arrive at one result. Merit and truth match Hossenfelder's two judges, internal consistency and consistency

with observation, and the order of depth shows why there are two judges. Mathematics stands last in the order of depth and checks the connection between the premises and the claims, while the question whether the premises are true is settled in the world, by the acts that come before mathematics in the order of depth.

I also use the order of depth to give the reason for Hossenfelder's other three points: simplicity, philosophy and completeness.

On simplicity, I offer a picture: a sphere of black coal beside a large cut diamond. The coal sphere perhaps represents the simplest possible physical object, and the coal sphere lets no light through. The diamond is complex, and yet light passes through the diamond. In the picture, the light stands for understanding. A description has 'clarity of essence' when understanding passes through the description, as light passes through the diamond, and 'simplicity of appearance' when the description has few parts. The coal and the diamond show that clarity of essence and simplicity of appearance can come apart. So, in thinking about metaphysics, I ask for clarity of essence in place of simplicity of appearance. I apply the measure of clarity of essence to a theory of physics too. To call a theory of physics 'elegant' is less to say that the theory is demonstrably simple than to say that the theory is profoundly clear.

On philosophy, Hossenfelder says that physics needs philosophy to examine the assumptions of physics, and I agree. The 'setting' of a comparison is the places, the moment and the conditions in which the comparison is made. I identify a 'law of physics' with a statement of what stays the same when the setting of a comparison changes. I identify the 'continuity' that physics assumes, which is smoothness, with a statement of what stays the same when the setting stays the same. In the next section of this chapter, "A Balance That Could Never Tip", I show why continuity takes the form of a statement of what stays the same when the setting stays the same. So both a law of physics and continuity are statements about comparison, and metaphysics, the study of the act of comparison, therefore studies the assumptions that physics already makes. Metaphysics comes before physics in the order of depth, as the ground that physics rests on. I

set out what every comparison must contain, which I call 'the structure of comparison'. Metaphysics is about the foundations of physics: the structural conditions that must obtain for physics to be possible at all. In the sentence just quoted, 'structural conditions' means the conditions that the structure of comparison itself sets.

On completeness, I state: "No theory will ever be able to completely explain, predict, or model all observable behavior and phenomena in a domain", and I apply the sentence to my own theory of comparison as well.

So Hossenfelder's result also follows in my account, by a road of my own: physics is not mathematics. Mathematics stands after the acts that make it and check it, so mathematics cannot decide what anyone will find by acts of comparison.

A Balance That Could Never Tip

Can a single act of comparison be perfect in every way at once?

Picture the setting of a weighing on the balance: the setting is the places, the conditions and the moment of the weighing. The places are the two places that the things weighed occupy: the left pan and the right pan. The conditions are the floor and the room that hold the pans. The moment is the moment of the weighing itself, and the beam that joins the two pans is part of the setting too. The tip of the beam is the result of the weighing. In Chapter Three, I give the setting a second name: the 'context' of the comparison.

Think about what you want from your balance. You want the balance to be steady: the same bag of flour should show the same weight on Monday and on Friday, in this kitchen and in the shop down the road. You also want the balance to be smooth: if you carry the balance a hair along the bench, or wait a moment longer, what the beam shows should change by no more than a hair, with no sudden lurch.

The two wishes, 'steadiness' and 'smoothness', have names. The name for steadiness is *symmetry*: being the same under every change of place or setting, so that what is found stays the same when the setting changes. The name for smoothness is *continuity*: having no gaps, so that a small change of setting gives a small change in what is found. Symmetry and continuity each have an opposite. The opposite of symmetry is *asymmetry*: being different from place to place, so that what is found changes with every change of setting. The opposite of continuity is *discontinuity*: coming in steps with gaps between, so that in one unchanged setting what is found jumps from one value to another, with no value between. 'Symmetry', 'continuity', 'asymmetry' and 'discontinuity' are everyday words, used exactly. In this book, each of the four words names something that is found in a comparison. I call symmetry, continuity, asymmetry and discontinuity the four *characters* that can be found in a comparison.

Your balance shows all four characters, in two acts of comparison made with the balance.

The first act is weighing with the stamped pieces in the wooden box. Set one ten-gram piece against another ten-gram piece, and the beam rests level. The beam rests level in this town or on another continent, this year or in a century. The result stays the same under every change of setting. So the result shows symmetry. The box sets amounts against the flour in steps: adding a piece makes the amount found jump from ten grams to twenty, with no amount between, in one and the same setting, the same pan on the same bench. The jump from ten grams to twenty shows discontinuity. So weighing with the box of weights is symmetric and discontinuous.

The second act is watching the beam settle after you set the flour down, and in the second act you compare where the beam is at one moment with where the beam was a moment before. In the first act the beam is part of the setting, but in the second act the beam itself, at two moments, is what is compared. The passing moments belong to the setting of the second act. The beam swings, and the swing is smooth. The beam passes through every position between one end of the swing and the oth-

er, with no jump. A moment later, the beam has moved only a little. A swing with no jump shows continuity. Each swing is a little smaller than the swing before, so no swing repeats the swing before. Swings that never repeat show asymmetry, and so watching the settling beam is continuous and asymmetric.

Now ask for a third kind of balance: a balance that is perfectly steady and perfectly smooth at once, with steadiness and smoothness *both* held exactly, at every scale, all the way down.

Take smoothness all the way down first: if a change of setting is too small for a comparison to register, then, for the comparison, the change of setting is no change of setting at all. So perfect continuity says that where the setting is the same, what is found is the same, while perfect symmetry says that where the setting is different, what is found is the same. Put perfect continuity and perfect symmetry together, and what is found is the same whatever the setting: at every moment, on every floor, and in either pan. The left pan and the right pan are two places in the setting, so whatever is in the left pan is found the same as whatever is in the right pan. The beam rests level whatever you set in the pans, whenever and wherever you set the things in the pans.

A balance weighs by finding a difference where there is a difference: the beam of the balance tips. If the beam of a balance rests level whatever is set in the pans, then the balance has stopped weighing, because the balance could never have found a difference. A finding of 'same' tells you something *only* because a finding of 'different' could have come in place of 'same'. Sameness and difference come together in every comparison.

Exchange 'same' and 'different' in the reasoning, and the same reasoning shows that the other pair fails: asymmetry with discontinuity. Perfect asymmetry with perfect discontinuity says 'different' whatever the setting, in either pan and at every moment. Picture the beam of a balance with perfect asymmetry and perfect discontinuity: the beam never once

shows the two pans equal, even when the same piece is set in each pan. The balance with perfect asymmetry and perfect discontinuity has stopped weighing too.

So two kinds of comparison survive, and *only* two. A comparison held perfectly at its foundation is either continuous and asymmetric, like the settling beam, or symmetric and discontinuous, like the weighing with the box, so there is no third perfected kind.

The reasoning you have just walked through is the main step in the proof of the *Incommensuration Theorem*. The Incommensuration Theorem states, in full:

> Symmetry and continuity cannot both be applied, simultaneously and fundamentally, to any event or comparison; and neither can asymmetry and discontinuity.
>
> (*Physics Is Not Math*, chapter 2, "The Theorem")

The name of the theorem comes from an old word, 'incommensurable'. Two lengths are *incommensurable* when they have no common measure: no unit, however small, fits a whole number of times into each length. The side and the diagonal of a square are one example: no unit fits a whole number of times into both. The Incommensuration Theorem states a gap between two characters, like the gap between incommensurable lengths. Symmetry and continuity have no 'common perfection': there is no comparison in which both symmetry and continuity hold exactly. The statement uses the word 'applied'. Applying a character to a comparison means holding the character in the comparison. 'Simultaneously' means in one and the same comparison. 'Fundamentally' means held exactly, at the foundation of the description of the event or comparison, with no exception at any scale.

The Incommensuration Theorem is a structural fact about the nature of knowing. The word 'structural' means that the theorem belongs to the make-up of every act of knowing. Every act of knowing is an act of com-

parison or is built from acts of comparison, and the theorem holds of every comparison. The proof of the theorem uses nothing but three things: sameness and difference; what is found and the setting in which it is found; and the fact that sameness and difference always come together. So the theorem holds wherever anything is compared, and no fact about the physical world can unsettle the theorem. The full proof includes every way of pairing the four characters: pairing each character with itself makes four pairings, and pairs of two different characters make six more pairings, ten in all. A character paired with itself says nothing new, while a character paired with its opposite contradicts itself. Symmetry with continuity, and asymmetry with discontinuity, fail in the way the balance has just shown. Two pairings survive: continuity with asymmetry, and symmetry with discontinuity. The result of the proof comes from examining ten cases, so the result is settled the way a count is settled: by the count itself, with no need to trust whoever made the count. Every measurement is a comparison, so the theorem applies to every measurement that physics has made or will make. Whoever challenges the theorem sets the theorem beside something and finds that the theorem and the other thing differ, so the act of challenging is itself a comparison, and the same ten pairings apply to every challenge. The Incommensuration Theorem holds with no condition of any kind.

I can say exactly what the theorem is about: the theorem concerns two characters perfected together in one comparison. Things in the world show symmetry and continuity together approximately, all the time, and a ripple spreading on a still pond is one case: the ripple is smooth, and almost the same in every direction. The theorem concerns what is found in a comparison, while the mathematics of a theory is written down as structure and is no finding. So the mathematics of a theory can contain symmetry and continuity together exactly, while the findings of the theory, made by comparison, never show symmetry and continuity together exactly. Every word of the statement is built from the ground, and the theorem proved in full, in the book that Appendix B names.

The World Is Not a Mathematical Structure

Is the world, then, made of mathematics?

I establish that the world we find by comparison is not a mathematical structure. A mathematical structure is 'laid out whole', with every part of the structure there at once. The triangle, the whole numbers and the circle are mathematical structures. Take the circle of geometry. The circle is perfectly smooth and exactly the same under every turn, so symmetry and continuity are both perfected in the circle, together. The Incommensuration Theorem says that no one, by any comparison, can find symmetry and continuity perfected together.

Mathematics can write the circle down because the frame of mathematics has no place for the one who compares: within mathematics, no one stands anywhere, comparing at some moment. A theorem names no one who proves the theorem, no place where the theorem is proved and no moment at which the theorem is checked. The objects of mathematics do not change: the number 31 is not on its way to becoming 32. I put in two sentences the reason that mathematics can write symmetry and continuity down together. In the two sentences quoted below, 'temporal comparison' means comparison made in time.

> In a domain from which temporal comparison is removed, symmetry and continuity can be written down together. Such a domain is not a real world, precisely because the real world has a temporal element and that domain does not.
>
> (*Incommensuration*, chapter 6, "Scope")

Every mathematical structure contains symmetry and continuity together, both perfected, when the structure is taken as a whole, whether the parts of the structure are smooth or jagged. Picture a staircase drawn on a page. In its parts, the drawing jumps: each step rises sharply from the step below, with nothing between. Taken as a whole, the drawing has no gap: every step is there at once, and nothing is missing or still to come.

The drawing is also the same in every instance: every copy of the drawing, and every person who looks at the drawing, has the same staircase. So a structure taken whole contains perfect sameness and gapless completeness together, whatever the parts of the structure look like. 'Perfect sameness' is symmetry perfected, and 'gapless completeness', with no gap anywhere, is continuity perfected. By the Incommensuration Theorem, no one can hold perfect symmetry and perfect continuity together in any act of comparison. Every finding of physics is a comparison, made at some moment, after one moment and before another. The world we find by comparison is the only world physics has, so the world we find by comparison is not a mathematical structure. If someone writes a mathematical description of the world we find by comparison, the description is never complete, however exact the description is.

I give two everyday words, 'exist' and 'real', exact senses, to keep a structure and a finding apart. To *exist* is to stand as structure: timeless, the same in every instance, able to be held in view as a whole. To be *real* is to be given in an actual act of comparison: here, now, with the future still open. A law exists. A measurement is real. In Hossenfelder's report, Tegmark calls all of mathematics real, but Tegmark uses the word 'real' in the everyday sense, not in the exact sense of my account. Every physical theory has a part that 'exists' and a part that is 'real': the theory's mathematics, which exists, and the theory's findings, which are real. Someone who claims that the world is mathematics takes a theory's mathematics, which exists, for the whole.

Tegmark's argument has two steps: first, that there is a world which does not depend on human beings; and second, that the world which does not depend on human beings is a mathematical structure. In its second volume, I set Tegmark's argument beside my account at full strength, and I agree with Tegmark's first step but part from him at the second.

Hossenfelder shows that a theory can be consistent and still describe nothing we see (*Existential Physics*, chapter 7, "Will We Ever Know It All?"). Hossenfelder's example is a theory in which "the universe is a per-

fect, empty, two-dimensional sphere". The Incommensuration Theorem is a further reason why no one could ever find a perfect-sphere universe by comparison, because a perfect sphere is smooth and the same under every turn, both exactly.

Hossenfelder leaves the claim that the world is mathematics outside what science can decide. In her view, the claim is not scientific, and the claim is not wrong. I decide the claim by an argument about what anyone can find by comparison. By the argument, I exclude the claim. Hossenfelder names Platonism in chapter 1 of *Existential Physics*, in the section "Transcendent Math". In the same section, Hossenfelder names the belief that mathematics is timeless as one of the "usually unstated articles of faith that our scientific inquiry is based on". I agree that mathematics is timeless, and I call mathematics 'the science of the timeless'. People wrote out every timeless structure we have, by acts made in sequence in the world: for example, someone drew the curve of a falling stone on a page, from measurements made by comparing. The Incommensuration Theorem is a theorem about acts of comparison. The theorem is held in the very act of checking the theorem. Every attempt to doubt the theorem is a comparison, so each attempt to doubt the theorem uses the very theorem being doubted. The Incommensuration Theorem is therefore no article of faith.

Wigner's Gift, Explained

Why, then, does mathematics fit the world as well as it does?

Mathematics fits the world for the same reason that it never becomes the world. Physicists set the mathematics of a physical theory beside what is found, as you set one thing beside another in a weighing, and setting the mathematics beside the findings is itself an act of comparison. The mathematics is one of the two things compared, and the findings are the other. The mathematics and the findings are made of the same parts: sameness and difference, and the same four characters. Mathematicians

made mathematics to capture ideas of structure, and the same ideas of structure are at work in physics, because the mathematics and the findings are made of the same parts.

Go back to Wigner's statistician. π stands for 'the symmetry of turning', and the number π appears wherever the symmetry of turning appears. Picture darts thrown at a mark on a wall, missing a little left or right and a little up or down. Suppose the misses in each direction scatter along a bell curve, that the bell curve is the same for both directions, and that the misses in one direction are independent of the misses in the other. Then the cloud of holes is perfectly round: turn the cloud about the mark by any angle, and the cloud looks the same. The bell curve is the *one* spread of misses for which two copies, set at right angles, make a round cloud. The formula of the bell curve has π in it. The π comes from the roundness of the cloud, which is the symmetry of turning. So π turns up in the bell curve for the same reason that π turns up in the wheel. The friend's doubt was natural, but the population figures in the statistician's paper share a symmetry with the circle after all.

The fit of mathematics to the world can be very close. In 2023 a team from Northwestern and Harvard universities held a single electron in a trap made of electric and magnetic fields, and cooled the trap almost to absolute zero, the lowest temperature there can be. The team measured the strength of the electron's magnetism more finely than anyone had measured the strength before. Physicists compute the strength of the electron's magnetism from *quantum electrodynamics*, the quantum theory of electrons and light. The computed value agrees with the measured value to about one part in a trillion.

Findings come in the two kinds that survive the Incommensuration Theorem. Some findings are 'countable', coming in steps, each step exactly like the last, as the weighing with the box does, while other findings are smooth and differ from moment to moment, as the settling beam does. The countable kind is symmetric and discontinuous, and the smooth kind is continuous and asymmetric. Mathematics has structures of each character: the mathematics of symmetry is about quantities that stay the same

under change, and the mathematics of continuity is about smooth spaces, and about quantities that vary without jumps. Each kind of finding has a mathematics of the other kind: smooth mathematics for countable findings, and symmetric mathematics for smooth findings. The mathematics of the other kind comes as close to each finding as anyone likes, but the mathematics never covers all the findings: a remainder always stays outside the mathematics. If a mathematics matched its findings exactly, the mathematics would perfect symmetry and continuity together, and the Incommensuration Theorem forbids perfecting symmetry and continuity together. So the mathematical description comes as close to the world as we care to take the description, but the description never becomes the world. The power of the description and its incompleteness come from one source, and neither can be had without the other.

Wigner called the fit a gift we neither understand nor deserve, but the fit has a reason: the mathematics and the findings are the two things compared in one act of comparison, and both are made of the same parts. The same reason sets the limit of the fit.

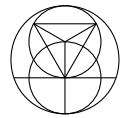
What the Balance Shows Here

Set the brass weights back in their box. The number stamped on each brass weight is the record of an earlier weighing, and the arithmetic of the beam is worked out from stamped numbers and describes your weighing exactly. Mathematics is description of the same kind as the arithmetic of the beam: the finest instrument there is for what is laid out as structure, written out from acts of comparison. Physics is the weighing itself, made from inside the world. The weighing comes first.

The mathematics has properties, such as symmetry, economy and beauty. Each property of the mathematics is a property of the description. Hossenfelder's book *Lost in Math* tells how, for decades, physicists chose new mathematics for the beauty of the mathematics and expected the world to show the particles that the beautiful mathematics required.

The short answer: Physics studies acts of comparison as they happen in the world, while mathematics is the study of structure laid out whole and comes last in the order of depth, after the acts that make it and check it. Mathematics fits the world because mathematics and the world are both made of comparison. Mathematics never becomes the world, because no one, by any comparison, can find anything perfectly symmetric and perfectly continuous at once.

What, then, did physicists actually find when they searched for the beautiful new particles?



Chapter Three

Why Did the New Particles Not Appear?

What this chapter uses

Comparison is setting one thing beside another and finding how the two stand (Preface).

The *Incommensuration Theorem*: symmetry and continuity cannot both be applied, simultaneously and fundamentally, to any event or comparison; and neither can asymmetry and discontinuity. *Symmetry* is being the same under every change of place or setting, and *continuity* is having no gaps, so that a small change of setting gives a small change in what is found; asymmetry and discontinuity are their opposites. The Incommensuration Theorem is a structural fact about the nature of knowing (Chapter Two).

To *exist* is to stand as structure: timeless, the same in every instance, able to be held in view as a whole; to be *real* is to be given in an actual act of comparison: here, now, with the future still open (Chapter Two).

The *order of depth*: metaphysics, physics, computation, mathematics, the deepest field first, each field presupposing the fields before it (Chapter Two).

Physicists promised that the Large Hadron Collider, a great machine for colliding particles, would bring a crowd of new particles, and among the new particles they expected a 'partner' for every known particle. None of the partner particles came. Why did the partners not come? One new particle did come. The story of this chapter begins on the morning when physicists announced the new particle.

Geneva, 4 July 2012

On 4 July 2012 an auditorium was packed at CERN, the European laboratory for particle physics outside Geneva. Some of the people in the auditorium had camped there overnight to be sure of a seat. Peter Higgs and François Englert sat in the audience. Higgs and Englert were two of the theorists who, in 1964, had proposed a new field. A *field* is something spread through all of space, whose smallest ripples are particles. The field that Higgs and Englert proposed came to carry Higgs's name: the 'Higgs field'.

The *Large Hadron Collider* runs under the laboratory: a ring of magnets twenty-seven kilometers around, a hundred meters underground. A 'proton' is the particle at the center of a hydrogen atom. Inside the ring, two beams of protons travel in opposite directions, and physicists make the two beams collide. Great detectors stand at the places where the beams cross, each run by its own collaboration of physicists. The two largest detectors are called 'ATLAS' and 'CMS'. The spokespersons of the two collaborations showed what the two detectors had found, on the morning of 4 July 2012: Fabiola Gianotti spoke for ATLAS, and Joe Incandela spoke for CMS. Each detector had seen a few more collisions than the already known particles could account for. The extra collisions all pointed to something of one particular mass. In each detector, the excess of collisions had reached the strength that physicists require before they speak of a 'discovery'. Incandela said: "This is indeed a new particle".

Physicists measure the masses of particles in a unit called the *billion electron volt*. The mass of the new particle was about 125 billion electron volts. A proton weighs a little under one billion electron volts, so the new particle weighed about as much as a hundred and thirty protons. Each detector had found the new particle on its own, and the two detectors found nearly the same mass: in the full reports that ATLAS and CMS published later in 2012, ATLAS measured 126.0 billion electron volts and CMS measured 125.3 billion electron volts. The *standard model* is the theory that lists every known kind of elementary particle, together with three of the four forces that act among the particles, and gravity, the fourth force, stands outside the standard model. In the standard model, the Higgs field gives the other particles their masses. The new particle was the particle of the Higgs field: the *Higgs boson*. The Higgs boson was the last kind of particle on the standard model's list to be found, and physicists found it forty-eight years after it was proposed.

Many physicists in the auditorium expected the Higgs boson to be the first of a crowd of new particles. They feared one outcome, which a news report in the journal *Science* had named in 2007 in the title of the report: "Physicists' nightmare scenario: the Higgs and nothing else". The Large Hadron Collider ran on, at higher energies than any earlier machine. Nothing new came after the Higgs boson. The known particles of matter come in three *generations*, and each generation is a heavier copy of the generation before. No partner particles came, no new force came, and no fourth generation of matter came. In this chapter, I ask why nothing came after the Higgs boson.

From Hossenfelder's pages

What Sabine Hossenfelder Showed

Sabine Hossenfelder worked for years on physics beyond the standard model. In her book *Lost in Math*, she tells the story of the missing particles from inside particle physics, and she shows why so many physicists were sure that the new particles would appear.

The particles of the standard model come in two families. A particle's *state* is the whole of how the particle stands at one moment, such as where the particle is and how it moves. *Fermions* are the particles of matter, such as the electron and the quarks inside the proton, and no two fermions will share one state. In Hossenfelder's words: "Fermions are extreme individuals". *Bosons* are the carriers of force, such as the particle of light, and any number of bosons can share one state. *Supersymmetry* is the proposal that joins the two families, and Hossenfelder states the proposal exactly:

> Supersymmetry postulates that the laws of nature remain the same when bosons are exchanged with fermions.
>
> (*Lost in Math*, chapter 1, "The Hidden Rules of Physics", section "Invisible Friends")

If supersymmetry were true, every known particle would need a partner from the other family. No two known particles match each other as partners, so the partners would have to be new particles, which are still waiting to be found. Hossenfelder gives a picture: "It's like we have a collection of odd pots and lids and are convinced that certainly the matching pieces must be around somewhere". In Hossenfelder's picture, the 'odd pots and lids' stand for the known particles of the two families. The 'matching pieces' stand for the missing partners.

Why did physicists expect the partners at the Large Hadron Collider in particular? Hossenfelder's answer depends on the mass of the Higgs boson. Every field keeps a restless trembling, even when nothing is there, and physicists call the trembling 'quantum fluctuations'. In the standard model, quantum fluctuations push the mass of the Higgs boson up by a factor of about a hundred trillion. A correction can cancel the push only if the correction matches it to fourteen digits and differs from it only in the fifteenth digit. Physicists call a number like the correction *fine-tuned*, and they call a theory with no fine-tuned

numbers *natural*. Hossenfelder gives the definition in her own words: "Today we call a theory natural if it does not contain numbers that are either very large or very small" (*Lost in Math*, chapter 4, "Where the Numbers Have No Name"). In Hossenfelder's sense, *naturalness* is the expectation that the pure numbers of a theory (numbers with no units, such as the ratio of one mass to another) be neither very large, nor very small, nor very close to one another. Supersymmetry would make the cancellation happen by itself, if the partners were light enough for the Large Hadron Collider to make them. Hossenfelder sums up the reasoning in one line: "This isn't a prediction, it's a wish" (*Lost in Math*, chapter 2, "Why Trust a Theorist?").

Hossenfelder also counts the successes of naturalness as a guide to new particles, and by her count naturalness "scores a total of one prediction" (*Lost in Math*, chapter 4, "Where the Numbers Have No Name"). The one prediction was the charm quark, the fourth kind of quark to be discovered, proposed in 1970. Hossenfelder gives plain advice for the case where a prediction from naturalness fails: "we should note that and move on" (*Lost in Math*, chapter 5, "Naturalness").

Three machines searched for the partners, one after another. A 'positron' is the electron's antiparticle: a particle like the electron in every respect, except that each of the positron's charges is opposite. The first machine was the Large Electron-Positron collider at CERN, which collided electrons with positrons and ran until 2000. The second machine was the Tevatron near Chicago, which ran until 2011. The third machine was the Large Hadron Collider. Each search for the

partners came back empty: no machine found a partner. Hossenfelder watched her fellow physicists answer each empty search by adjusting their models (her word 'superpartners' means the partners):

> Every year the searches for superpartners came back with negative results. Every year the models were updated to accommodate the lack of evidence.
>
> (*Lost in Math*, chapter 3, "The State of the Union", section "It's Going to Be Hard Now")

Hossenfelder states her conclusion carefully, at exactly the strength the data allow:

> This means we know now that if the superpartners exist, their masses must be fine-tuned. Naturalness, it seems, is just not correct.
>
> (*Lost in Math*, chapter 2, "What a Wonderful World", section "Why Trust a Theorist?")

Hossenfelder tells a second story of the same 'shape' as the first: in both stories a theory predicts something new, the searches find nothing, and physicists change the theory to fit the empty searches. The standard model has three forces. The *strong force* holds the quarks together inside the proton, the *weak force* turns one kind of particle into another in some radioactive decays, and we meet the third force, at everyday energies, as electricity and magnetism. In physics a *symmetry* is a set of changes under which the laws stay the same. The word 'symmetry' keeps the sense that Chapter Two gave the word: being the same under every change of place or setting. *Grand unification* is the hope that the three forces are pieces of one larger symmetry, which would hold the changes of all three forces in one set, so that the three forces would act as one force at some very high energy. The first and simplest version of grand unification predicted that protons de-

cay, slowly. Since the mid-1980s, physicists have watched large tanks of water for the decay of a single proton. No one has seen a proton decay, so the simplest version of grand unification is ruled out. Later versions of grand unification predict a proton lifetime too long for any planned experiment to reach, so the later versions are, in Hossenfelder's words, "safe from being experimentally ruled out in the foreseeable future" (*Lost in Math*, chapter 7, "Converging Lines").

Hossenfelder's third story is the one that came closest to a discovery. Hossenfelder writes that on 15 December 2015 she watched a broadcast from CERN, in which ATLAS and CMS presented their first results at the new, higher energy of the Large Hadron Collider. Both ATLAS and CMS reported too many pairs of particles of light whose energies added up to about 750 billion electron volts. Hossenfelder writes that the results of the two detectors, taken together, give "a chance of 3 in 10,000 that the excess is a random fluctuation". She notes that the standard physicists require for a discovery is "roughly 1 in 3.5 million" (*Lost in Math*, chapter 4, "Cracks in the Foundations", section "The Diphoton Diarrhea Begins"). More data came in through the spring and summer of 2016. ATLAS and CMS published the new data on 4 August 2016, as Hossenfelder records. In the new data, the excess was gone.

> In the eight months since its "discovery", more than five hundred papers were written about a statistical fluctuation.
>
> (*Lost in Math*, chapter 10, "Knowledge Is Power", section "The Search Goes On")

What was done: two detectors counted pairs of particles of light from an enormous number of collisions, and then counted again with more collisions. What was found: an excess of pairs at one energy, which faded when more data came in and then was gone. What we now know: the excess was nothing but chance.

From all three stories Hossenfelder draws a larger lesson, which she states in her first chapter: "But for more than thirty years now we have not been able to improve the foundations of physics" (*Lost in Math*, chapter 1, "Failure"). In Hossenfelder's view, data no longer arrive by themselves, so a theory must say where to look, and in her words "mistakes in theory development can lead to a dead end" (*Lost in Math*, chapter 2, the box "IN BRIEF"). Physicists wrote five hundred explanations of a signal that was never there. Hossenfelder concludes from the five hundred explanations that the old standards for judging theories no longer serve: in her words, "To select promising future experiments, we need new rules" (*Lost in Math*, chapter 10, "The Search Goes On").

Hossenfelder is right about the Large Hadron Collider. The particles that physicists expected from naturalness were not there. The argument from naturalness called for the particles, but the argument from naturalness was never evidence about nature.

Content and Context

Why were the partner particles absent? The reason lies in two parts that every act of comparison has. *Comparison* means setting one thing beside another and finding how the two stand. Every measurement is an act of comparison, as Chapter One showed. The balance of Chapter One shows the two parts of every comparison.

Set a pear in the left pan of the balance and brass weights in the right pan. The beam tips, or the beam stays level, and the 'verdict' of the weighing is whether the beam tips: either the pear and the weights weigh the same, or one weighs more. The verdict is about how heavy the pear and the weights are. I call what the verdict of a comparison is about the *content* of the comparison.

Now ask what makes the pear and the weights two things at all. The pear and the weights occupy two places, the left pan and the right pan. I call the respect in which the two things compared are two the *context* of the comparison. On the balance, the context is the two places, together with the floor and the room that hold the two places, and the moment of the weighing: what Chapter Two called the 'setting'. The balance can find the pear and the weights 'the same' in weight or 'different' in weight, but the balance can never find the left pan to be the right pan. So content and context come together in every comparison. Content and context are always two respects, never one. The beam judges one respect: how heavy the two things are. Left and right is a different respect: the respect that makes the pear and the weights two. The beam is free to tip *because* the respect that the beam judges is different from the respect that makes the two things two. Suppose a balance gave a verdict on the very respect that makes the two things two. Then the verdict would be fixed before the weighing, and a verdict fixed in advance is no verdict.

One more part of the balance matters for content and context: the beam. The beam carries the pull of each pan across to the other pan: the pear and the weights meet through the beam. The beam is in neither pan, so the beam is never one of the two things weighed. The beam is part of the setting, and so the beam belongs with the context. The tip of the beam is the result.

In physics, the words 'content' and 'context' have a plain meaning: the content is quantum matter. On my account, the name 'quantum matter' covers every particle found within space and time (light included), with the particle's charges and fields. Quantum matter is therefore wider than the particles of matter in Hossenfelder's two families, which are the fermions alone. In physics, the context is space and time, the 'arena' in which quantum matter is found, and the context also includes the 'setting of possibility': the range of states in which a thing could be found. The word 'content' keeps one sense on the balance and in physics: what the verdict

is about. On the balance, the content is how heavy the pear and the weights are. In physics, the content is the quantum matter found in comparisons.

Look closer, at single particles, and the line between content and context appears a second time inside quantum matter. Think of a hydrogen atom: an electron and a proton held together. The electron and the proton are the two things compared, like the pear and the weights. The electron and the proton meet, and the verdict of their meeting is about the electron and the proton, in the same way as the verdict of a weighing is about how heavy the pear and the weights are. Light passes between the electron and the proton and carries their meeting, as the beam carries the pull of one pan to the other. Light is neither of the two things compared. Like the beam, light belongs with the context. So the particles of matter belong with the content at the scale of single particles: the particles of matter are separate pieces, and no two of the pieces can be in one state at once. The carriers of force belong with the context: a carrier of force carries the act by which one piece of matter meets another piece of matter, and a carrier of the act of comparing is never one of the things being compared. Hossenfelder's fermions, the extreme individuals, are content. Her bosons, which share states freely, are context. The line between the physicist's two families is the line between content and context at the scale of single particles: the two lines are one line, seen from two directions.

Chapter Two set out the Incommensuration Theorem. 'Symmetry' is being the same under every change of place or setting, and *continuity* is having no gaps, so that a small change of setting gives a small change in what is found. 'Asymmetry' and 'discontinuity' are the opposites of symmetry and continuity. In plain words, the Incommensuration Theorem says two things: no single comparison can be perfect in symmetry and in continuity together, and no single comparison can be perfect in asymmetry and in discontinuity together.

Chapter Two found that a comparison held perfectly at its foundation takes one of two forms, and only two. The 'first form' is symmetric and comes in steps, like the box of stamped weights in Chapter Two: every ten-

gram piece in the box is exactly like every other ten-gram piece, and the box holds nothing between ten grams and twenty grams. The 'second form' is continuous and uneven, like the settling beam in Chapter Two: the settling beam passes through every point of its swing with no jump, and no swing repeats the swing before.

In every actual comparison, content 'leans toward' one of the two forms, and context leans toward the other form. I call each of the two ends of the division of comparison a 'pole', and state the division in these words: "Comparison therefore divides into a content pole, which is symmetric and quantized (coming only in whole, separate steps), and a context pole, which is continuous and asymmetric".

Content leans toward the first form: the things found in a comparison come as separate whole pieces. Two pieces of one kind are exactly alike wherever the pieces are found: every electron is like every other electron. Two electrons cannot share one state, because two pieces of content of one kind in one state would be one piece. Context leans toward the second form: the setting runs on with no gaps. Carriers of force in one state add to one another, as light adds to light in one ray. So any number of particles of light can share one state. Content 'taken to perfection' is therefore symmetric and comes in steps, and context taken to perfection is continuous and uneven.

Under the Incommensuration Theorem, the two forms stay apart, and content and context stay apart with the two forms: everything found in a comparison belongs either with content or with context. One line divides content from context: the line is called the *partition*, and the Incommensuration Theorem asserts the partition. The question of the partner particles is decided at the partition.

A List That Is Closed

Picture the table of the chemical elements on a classroom wall. A 'nucleus' is the tiny heavy center of an atom. Chemists can make heavier and heavier nuclei and add the new nuclei at the end of the table, but every one of the new nuclei is still built from the same few constituents. The table can grow, but the list of what things are made of does not grow.

My physics books hold that the list of 'kinds' of elementary particle is closed, like the list of the constituents of the nuclei. A 'neutrino' is a very light particle of matter that passes through almost anything. Every particle of matter has two parts, which physicists call the 'left-handed' part and the 'right-handed' part of the particle. The weak force acts on the left-handed part only. The 'right-handed neutrino' is the right-handed part of each neutrino, the part that lets the neutrino carry its small mass. The *closed list of kinds* is the kinds of the standard model, with a right-handed neutrino in each generation, and no others. A particle built from the known particles, as a proton is built from quarks, is called a *composite*. Colliders may still make heavier composites at higher energies, as chemists make heavier nuclei. But a new kind of elementary particle is not on the list.

Why is the list of kinds closed? Go back to the weighing of the pear: every weighing has three *positions*. The first position is the pear, which is 'the thing compared'. The second position is the weights, which are 'the thing compared against'. The third position is the weighing itself, 'the act of comparing', which joins the pear and the weights. Every comparison has the same three positions, and each of the three forces belongs to one of the three positions. The strong force belongs to the position of the thing compared, the weak force belongs to the position of the thing compared against, and the third force belongs to the act of comparing.

In this paragraph and the next I show where each force has its position, and from the positions I reach the four kinds of matter, and no fifth. Every particle of matter 'stands toward' two positions at once, the thing compared and the thing compared against, and the force of each of the

two positions either acts on the particle or leaves the particle alone. *Color* is the physicists' name for three states a quark can be in, among which the strong force turns the quark. The word 'color' has nothing to do with the colors we see. A particle of matter stands toward the position of the strong force by carrying color or by not carrying color. The *doublet* is a pair of sides between which the weak force turns a particle, and a particle of matter stands toward the position of the weak force by carrying the doublet or by not carrying the doublet. The *label* of a force is the property of a particle that the force acts on. Each force has its position because of its label. The label of the strong force carries the 'mark' of the strong force's position, the label of the weak force carries the mark of the weak force's position, and the balance shows both marks. On the balance, the pear is the thing compared: all of the pear lies in the pan, held whole in view. The weights are the thing the pear is compared against, and the weights stand for the standard that the weights were once matched against, which the weighing 'reaches toward' but does not hold in the pan. Color carries the mark of the thing compared: the three colors stand for the three positions of comparison, held together inside the content, and they are a pattern held whole in view, as the pear is held whole in view in the pan. Each quark carries one of the three colors. A proton is built from three quarks, which sit one at each of the three positions. The doublet carries the mark of the thing compared against: the doublet has one side that faces the act of comparing and one side that does not present itself to the act of comparing. The act of comparing reaches toward the hidden side of the doublet without containing the hidden side, as the weighing reaches toward the standard behind the weights, and being 'reached toward without being contained' is the mark of the thing compared against. The mark of one position never comes from the other position, because the two positions are not interchangeable: the pear is not the weights. The third force acts on a label called the *phase*: an angle, like the angle of a hand on a clock face. The act of comparing touches both positions, and so every particle of matter carries a phase.

Color and the doublet are two labels, each either 'present' or 'absent', so the two labels give four kinds of matter, in the same way as two switches, each on or off, give four combinations and no fifth. The particles of matter with color are the *quarks*. The particles of matter without color are the *leptons*, such as the electron and the neutrino. So the four kinds of matter are quarks with the doublet, quarks without the doublet, leptons with the doublet, and leptons without the doublet. Count the fields of one generation kind by kind. The 'up quark' and the 'down quark' are the two kinds of quark the proton is built from. Quarks with the doublet are the left-handed up and down quarks, the two sides of the doublet, each in three colors: six fields. Quarks without the doublet are the right-handed up and down quarks, each in three colors: six fields. Leptons with the doublet are the left-handed electron and neutrino, the two sides of the doublet: two fields. Leptons without the doublet are the right-handed electron and the right-handed part of the neutrino: two fields. Six and six and two and two make sixteen fields in each generation. The list has a 'slot' for each of the sixteen fields. Every slot is filled, and no slot stands empty for a new kind of matter.

Every particle ever observed belongs to a kind on the list. The *structure of comparison* is what every comparison must contain, and I need one part of the structure of comparison: the three positions and the labels that go with the positions. The Large Hadron Collider found the Higgs boson, which the structure of comparison requires, and found no new kind. The structure of comparison fixes what the Higgs field is, and it also fixes that there is exactly one Higgs field. The account fixes the field and its properties, and the field's mass is measured.

So Hossenfelder and I agree that the Large Hadron Collider found none of the particles that naturalness called for. Hossenfelder and I agree on separate ground. Hossenfelder's ground is that nothing ever gave physicists a reason to expect the particles (in her view, the expectation was a wish), while my ground is the structure of comparison, which has no slot for the particles that naturalness called for. *Extra dimensions* are hidden directions of space beyond the three we know. Physicists made

leading proposals for new particles at the Large Hadron Collider: partners, extra dimensions, and new strong forces. Each of the leading proposals assumed that the known particles are part of a longer list, but the list of kinds is whole. Hossenfelder wrote an opinion piece in *The New York Times* in January 2019. In the opinion piece, she wrote that particle physicists "have no reliable prediction that there should be anything new to find" until far higher energies, about a million billion times above the energies now within reach. I hold that there is no new kind to be found. Set side by side, Hossenfelder's statement and mine agree on every search at the energies within reach.

No Partner Across the Line

There is no supersymmetric partner at all. No partner exists light enough for the Large Hadron Collider to make, and no partner exists at any heavier mass. The result that there is no partner goes further than Hossenfelder's conclusion, which was that the masses of any partners must be fine-tuned.

The reason there is no partner is the line between content and context, and Hossenfelder's pots and lids give the picture. A *transformation* is a rule for putting another thing in place of each thing. For pots and lids, one transformation is this rule: set a lid wherever a pot stood, and a pot wherever a lid stood. A supersymmetry is a transformation of the same kind as the swap of pots and lids, on the fields of nature. Under a supersymmetry, the field of every particle of matter goes to the field of a carrier of force, the field of every carrier of force goes back to a field of matter, and the laws stay the same. In this chapter's words, a supersymmetry takes every field of 'content' to a field of 'context', and every field of context back to a field of content.

'Symmetry' means staying the same under a change, so under a supersymmetry content and context would be the same as each other. Content taken to perfection is symmetric like the box of weights, and context taken to perfection is continuous like the settling beam. Suppose a symmetry

crossed the line between content and context. Then the symmetry would join content and context in one comparison, and so the one comparison would be perfect in symmetry and in continuity together, because content taken to perfection is symmetric and context taken to perfection is continuous. Chapter Two showed what a comparison perfect in symmetry and continuity together would be: a beam that stays level whatever is set in the pans, and so a balance that has stopped weighing. A supersymmetry would perfect symmetry across the very partition that the Incommensuration Theorem asserts. The Incommensuration Theorem forbids the exchange of content with context.

You can see the line between content and context in the simplest thing that particles of the two families do. Swap two identical electrons, and the description of the pair changes sign: the description is multiplied by minus one. Swap two identical particles of light, and the description stays as it was: the description is multiplied by plus one. The partition appears as the difference of sign at the scale of single particles. A sign has no values in between, so no gradual turning carries minus one into plus one. The difference of sign is the picture of the partition. The Incommensuration Theorem is the reason for the partition. I give the argument from the partition in full. The conclusion of the argument is one plain sentence: "There is no supersymmetric partner".

A second book reaches the same result by a separate route: a direct count, made with Hossenfelder's own pots and lids. I derive physics by algebra. I first take stock of the fields of the standard model. Every field that enters the standard model is a field of matter, a carrier of force, or the Higgs field, and there is no fourth sort of field. So any partner would have to be one of the fields of the standard model. I then sort each field by the labels of the field: color, the doublet and the phase. A supersymmetry would have to pair every field of matter with a partner of its own from the other family, and the partner would have to carry exactly the same labels as the field of matter, as each lid must fit its own pot. Only two sets of labels appear in both families. The first set is no label at all. The right-handed part of the neutrino carries no label, and the carrier of the third

force carries no label either. The second set is the set carried by the left-handed electron and neutrino, the two sides of one doublet, and the Higgs field carries the second set too, because the Higgs field also comes as a doublet with the same labels. Nothing in the other family matches the quarks, or the right-handed part of the electron. So no pairing of the standard model's fields is a supersymmetry. The standard model has no other fields, so a partner has nowhere to come from, and so the count settles the question of the partners.

The two routes start from different premises, one from the Incommensuration Theorem and the other from a count of labels. Yet the two routes arrive at the same result. Hossenfelder takes the question as far as the measurements go. Her result is that if there are partners, the masses of the partners are fine-tuned. I take the question to its end, on the ground of the structure of comparison, and my result is that there is no partner, at any mass. Hossenfelder's odd pots and lids are a complete set of two different kinds of thing: the odd pots and lids stand for the known particles of the two families, and the matching pieces were never part of the set.

Three Forces That Were Never One

Hold a die in your hand and turn the die. Each turn shows a different face, one of the six faces of the die, but no turning, however clever, gives the die a seventh face or makes the die a coin. A 'turning' moves a thing within the structure the thing already carries.

The forces of the standard model act on particles as the turning acts on the die. Each force is a set of turnings, a 'symmetry' in the physicists' sense. Each force turns one label, and no force acts on another force's label: the strong force turns color, the weak force turns the doublet, and the third force turns the phase. A quark carries color and a lepton carries none, so no turning can make a quark into a lepton: no turning can give color to a particle that has no color, or take color from a particle that has color.

A carrier of force would have to join a quark to a lepton for a proton to decay in the way grand unification allowed. A 'grand unified theory', a theory of grand unification, has new heavy carriers of force, which would join quarks to leptons. But the structure of comparison has no carrier that joins a quark to a lepton. The three sets of turnings stand side by side, and each set of turnings leaves the labels of the other two sets alone. Grand unification needs a single larger symmetry that is all of one piece, and a symmetry that is all of one piece has no parts that leave one another alone. So the three sets of turnings are not pieces of one larger symmetry, and so no unifying symmetry holds at any energy. The proton therefore has no route to decay through a carrier that joins a quark to a lepton. I give two routes to the conclusion that no carrier joins a quark to a lepton. The two routes arrive at the one conclusion. The first route starts from the turnings that the states of matter allow, none of which acts on color and the doublet together. The second route starts from the forces themselves, which stay three separate sets of turnings at every energy. Physicists have proposed three other routes for a proton to break up: one through hidden extra dimensions, and two through rare events in the strong force and the weak force. I also rule out the three other routes, and conclude: "The proton is stable: no route to decay exists in the structure".

The Super-Kamiokande detector is fifty thousand tons of pure water in the Kamioka mine in Japan. What was done: since 1996, the Super-Kamiokande detector has watched for the flash of a single proton breaking up. About eleven thousand light sensors line the tank of the Super-Kamiokande detector. What was found: no proton has been seen to decay into a positron and a 'pion' (a light particle built from quarks). What we now know, from the report of the Super-Kamiokande detector in 2020: the proton's lifetime for decay into a positron and a pion exceeds twenty-four billion trillion trillion years. Twenty-four billion trillion trillion years is more than a trillion trillion times the present age of the universe. Hossenfelder and I agree on what the empty tank shows: the decay that the simplest unified theory predicted has not come.

The hope behind grand unification has a plain answer: the three forces belong to three distinct positions of comparison, so the three forces were never one force, at any energy. No single larger force splits into the three forces. The weak force and the third force do mix. Light is the one mixture of the carriers of the weak force and the third force that the Higgs field leaves without mass, and the mixing of the two carriers is the joining described by the theory for which the physicist Steven Weinberg shared his Nobel Prize. The mixing joins two carriers, but the mixing makes no larger force from which the three forces split. Hossenfelder herself notes that the theory of the joining "is not a satisfactory unification because it still has two different groups" (*Lost in Math*, chapter 7, "Converging Lines"). In Hossenfelder's sentence, a 'group' is the physicists' word for a set of turnings: a symmetry in the sense of this chapter. Physicists measure the strengths of the three forces at the energies within reach, and then carry the strengths upward in energy by the standard model's own rules for how strengths change with energy. Carried upward, the three strengths draw close to one another. Yet the three strengths meet at no energy. I give one source for both facts: the strengths draw close, and the strengths never meet. The three positions of comparison are 'inseparable', because every comparison has all three positions at once, so no position occurs without the other two. The three positions are also 'distinct', because no one position is another. I join the two reasons in one sentence: "Because the three forces are inseparable, their strengths draw close; because they are distinct, they never become one force". I find no unifying symmetry to test, at any scale.

What an Empty Search Finds

I count the empty searches of the decades since the standard model was finished as 'findings', while Hossenfelder sees the same decades as decades without progress in the foundations of physics.

Start with a measurement that counted kinds of neutrino. A 'Z particle' is a carrier of the weak force. In 1989 the Large Electron-Positron collider at CERN began making Z particles by the million. A Z particle can break up into any kind of 'light' neutrino (a neutrino of small mass). Each kind of light neutrino makes the break-up of a Z particle a little quicker, and a quicker break-up widens the range of energies at which Z particles are made. What was done: from 1989 to 1995, the Large Electron-Positron collider measured how often Z particles were made at energies across the range. In 2019, physicists corrected the calculation of the number of collisions behind the measurements, and the corrected calculation made the count more exact. What was found: a count of kinds of light neutrino that agrees with three, within a margin of less than one hundredth of a kind. Appendix B, For the Specialist, gives the exact value of the count. What we now know: there are three kinds of light neutrino, and not four. Each of the three generations of matter has its own neutrino, so the count of three kinds matches the three generations exactly and leaves no room for a fourth light neutrino.

Now set three more findings beside the count of neutrinos. The searches for partners came back empty, and so did the detectors that physicists built deep underground to catch a particle of *dark matter*, the unseen source of the extra pull that holds galaxies together. I identify the dark matter with 'a ringing of the setting itself': a vibration of context, which is a vibration of the setting of possibility, the range of states in which a thing could be found. The dark matter shows on the balance only as extra pull in the result, and the dark matter is never a thing set in a pan. The dark matter is not matter of any kind on the list of particles. Chapter Twelve explains why I identify the dark matter with a vibration of context. The *graviton* is the particle proposed for gravity on the model of the other

forces. The graviton has never been seen. I call the count of neutrinos and the three other findings "four observations of one fact": the fact that the list of kinds is complete. The list of kinds comes from the structure of comparison, and the list is complete because the structure of comparison is finite and every slot in the structure is filled.

I also name the reason why the empty searches could never settle the question of new particles for physicists: "Our world's method closes cases by finding things. It has no method for closing a case by showing that nothing more is there". A search can show only that it has not yet found something. So physicists can always move a prediction of new particles to the next, larger machine. Hossenfelder advises physicists to note a failed prediction and move on, which is what a 'method of finding' can do. An 'argument from structure' offers more than a method of finding. A physicist who argues from structure closes the case of new particles by counting the kinds. Every search since 1989 has agreed with the count of kinds.

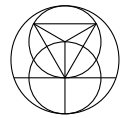
Hossenfelder and I agree on where to look: Hossenfelder holds that physicists must now use theory to decide where experiments look. I build on the same rule as Hossenfelder's, and tell of imagined scientists who follow the rule in this form: "First the argument. Then the instrument". I use the argument from structure to point the instruments at what the structure of comparison leaves to measurement. The instruments point at the masses, the strengths of the forces and the mixings of the known particles, measured ever more finely, and also at the heavier composites built from the known particles.

I offer one practice of my own as an answer to Hossenfelder's call for new rules. I write down predictions and seal the predictions before the measurements that will decide the predictions. Then I leave the sealed predictions alone. The written and sealed predictions make up the *sealed record*, which Chapter Fourteen explains in full. Appendix A, What the Coming Measurements Will Find, gathers what the coming searches will measure and what I say each search will find.

Picture the Large Hadron Collider once more as the balance of Chapter One, built to an enormous reach. In one pan go the collisions. In the other pan go the counts that the known kinds of particle would give. In each search, physicists set the collisions beside the expected counts and look to see whether the beam tips. A new kind of particle would show as extra counts in the first pan. The extra counts would tip the beam at one mass. In December 2015 the beam seemed to tremble at one mass, about 750 billion electron volts, but by August 2016, when more data had come in, the beam hung level again. Everywhere else, the beam has stayed where the closed list of kinds said the beam would stay: level. A beam that stays level is still a result, *because* the level beam has shown how the two pans stand: the collisions match the counts that the known kinds of particle would give.

The short answer: The kinds of elementary particle form a closed list, fixed by the structure of comparison, and the Higgs boson was the last of the standard model's kinds to be found. Supersymmetric partners have no slot on the closed list, and a carrier of force that joins a quark to a lepton has no slot either. So the empty searches since the Higgs boson are findings, *because* the empty searches show that the list of kinds is whole.

No new kind of particle is coming to explain the numbers of the standard model.
Do the numbers of the standard model need explaining at all?



Chapter Four

Do the Unexplained Numbers Need Explaining?

What this chapter uses

The *Incommensuration Theorem*: symmetry and continuity cannot both be applied, simultaneously and fundamentally, to any event or comparison; and neither can asymmetry and discontinuity. *Symmetry* is being the same under every change of place or setting, and *continuity* is having no gaps, so that a small change of setting gives a small change in what is found. The Incommensuration Theorem is a structural fact about the nature of knowing (Chapter Two).

The *content* of a comparison is what the verdict of the comparison is about, and the *context* is the respect in which the two things compared are two; every comparison has three *positions*: the thing compared, the thing compared against, and the act of comparing (Chapter Three).

The *closed list of kinds* is the kinds of the standard model, with a right-handed neutrino in each generation, and no others (Chapter Three).

Physicists have measured some numbers of physics to many digits, and nobody can say why each number has the size it has. Do the measured numbers need explaining, or are the measured numbers simply the numbers our world has? The physicist Sabine Hossenfelder puts the question sharply. She takes three famous puzzles about the sizes of numbers and calls the three puzzles 'aesthetic misgivings': complaints about how

the numbers look, with nothing in the puzzles that contradicts anything. Is Hossenfelder right? And what should anyone do with a number that agrees with the measurements and has no known reason? A schoolteacher in Basel once found a rule that agreed with the measurements for twenty-eight years before anyone knew why the rule agreed.

A Schoolteacher's Rule

Pass an electric current through a thin glass 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, and the glow comes apart into a few sharp lines of color with darkness between the lines. There is one red line, one blue-green line, and two violet lines. Each color of light is a wave with a length of its own, and physicists call the length of the wave the *wavelength*. The wavelength sets the color of the light. The Swedish physicist Anders Ångström had measured the wavelengths of the four lines of hydrogen with great care. A 'nanometer' is a millionth of a millimeter. In nanometers the four wavelengths are about 656, 486, 434 and 410.

Johann Balmer taught at a girls' school in Basel. In 1885, when Balmer was about sixty years old, he looked at Ångström's four numbers and found a rule that produces all four numbers. Put in words, Balmer's rule has three steps. Take a whole number, starting from three. Square the whole number, and divide the square by the square less four. Multiply the result by 364.56. Start with three: three squared is nine, and nine divided by five is 1.8. Then 1.8 times 364.56 is 656.2, the wavelength of the red line. The whole numbers four, five and six give 486.1, 434.0 and 410.1, the wavelengths of the blue-green line and the two violet lines. Four whole numbers gave four lines, and each of the four lines agreed closely with Ångström's measurement.

Then Balmer's rule turned out to give more lines than the four lines Balmer had looked at. The physicist Eduard Hagenbach-Bischoff was Balmer's friend and colleague at the University of Basel. Hagenbach-Bischoff told Balmer that a fifth line of hydrogen had already been observed,

and further lines of hydrogen beside the fifth line. For seven, Balmer's rule produces 397.0, and the observed fifth line lies at 397.0. Balmer had a rule that worked, and nobody knew why the rule worked: no theory of the atom explained the rule, yet the rule kept agreeing with the measured lines for twenty-eight years, one line after another.

Early in 1913 a colleague named H. M. Hansen pointed Balmer's rule out to the young Danish physicist Niels Bohr, who had been asking how an atom holds its electron. Bohr proposed that an atom of hydrogen can hold only certain fixed amounts of energy. Physicists call the fixed amounts the atom's *energy levels*. In Bohr's theory a rule of whole numbers sets the spacing of the energy levels. When an atom drops from a higher energy level to a lower level, the atom gives off light. The energy of the drop sets the wavelength of the light. Balmer's four lines are the drops from the third, fourth, fifth and sixth levels down to the second level. The number four in Balmer's rule is two times two: the square of two, the number of the level that all four drops end at. Bohr worked out the number 364.56 from four quantities: the charge of the electron, the mass of the electron, the speed of light, and Planck's constant, the number that sets the size of the quantum's steps. Bohr's number agreed with Balmer's number. Bohr said later that as soon as he saw Balmer's formula, the matter was immediately clear to him. Bohr published his theory of the atom in July 1913. Balmer's rule had been found by looking at numbers, and through Bohr's theory the rule became one of the doors into quantum theory: one of the starting points from which quantum theory was built.

Remember the twenty-eight years between Balmer's rule and Bohr's reason for the rule. Through all twenty-eight years Balmer's rule agreed with the world, and no one knew why the rule agreed. What should have been written beside Balmer's rule during the twenty-eight years?

From Hossenfelder's pages

What Sabine Hossenfelder Showed

Hossenfelder's book *Lost in Math* is about numbers whose sizes nobody can explain, and about what physicists do with the numbers. Hossenfelder's first case is the Higgs boson. Chapter Three told the story of the discovery of the Higgs boson at CERN, the European laboratory for particle physics. The Higgs field is the field that gives the elementary particles of matter their masses. The Higgs boson is the particle of the Higgs field. A 'GeV' is a billion electron volts, the unit of mass that Chapter Three used. The mass of the Higgs boson is about 125 GeV, while a proton weighs a little under one GeV.

The standard model has a peculiar trouble with the mass of the Higgs boson. The quantum fluctuations add a huge contribution to the mass of the Higgs boson. If nothing canceled the contribution, the contribution would make the Higgs boson heavier than measured by a factor of a hundred million million. Physicists can repair the standard model by subtracting a second term, which the physicists choose to cancel the contribution of the quantum fluctuations. The contribution and the second term must then agree for fourteen digits and differ in the fifteenth digit. When two terms must cancel to fourteen digits, physicists call the cancellation 'fine-tuning'.

> Physicists call a number that seems to require explanation "fine-tuned", while a theory that has no fine-tuned numbers is "natural".
>
> (*Lost in Math*, chapter 2, "Why Trust a Theorist?")

In Hossenfelder's sense, *naturalness* is the expectation that the pure numbers of a theory be neither very large, nor very small, nor very close to one another.

Hossenfelder answers the case of the Higgs mass directly. If two numbers had been drawn from a bowl of lottery tickets, a fourteen-digit match between the two numbers would look suspicious. But no one draws the laws of nature from a bowl.

> We have only these laws and we have no way of telling how likely or unlikely they are. That the Higgs mass requires explanation, therefore, is indeed feeling, not fact.
>
> (*Lost in Math*, chapter 2, "Why Trust a Theorist?")

If you want to call a number 'unlikely', you need a rule that says how likely each possible value of the number would be. Mathematicians call the rule a *probability distribution*. Hossenfelder points out that physics supplies no probability distribution for the constants of physics, and that picking a probability distribution is itself a choice: "the reference to chance itself already requires a choice" (*Lost in Math*, chapter 5, "Naturalness"). In *Existential Physics*, Hossenfelder makes the point about probability for all the constants of nature at once. Physicists have only ever measured each constant at the one value the constant has, so there is no sample of other values to count.

> There's nothing quantifiably unlikely, and therefore there's nothing in need of explanation.
>
> (*Existential Physics*, chapter 7, "Imagine No Religions")

Hossenfelder also notices which numbers physicists complain about. Physicists fret over the masses of the particles and over the mixing angles. Each particle that the weak force acts on is a blend of particles of different masses, and the 'mixing angles' say how far each particle that the weak force acts on is a blend. Physicists fret over the amount of 'dark matter', the unseen source of the extra pull that holds galaxies together. Physicists fret over the amount of the energy of empty space

too. Physicists also fret over how weak gravity is beside the other forces. Hossenfelder objects to singling out a few numbers: "I merely object to the idea that some numbers are in particular need of explanation while other problems fall by the wayside" (*Lost in Math*, chapter 5, "Naturalness").

Hossenfelder sets a different kind of problem beside the complaints about numbers. When two accepted theories contradict each other, Hossenfelder calls the problem an 'inconsistency'. Special relativity is Einstein's theory of space and time for bodies in steady motion. Special relativity contradicted Newton's theory of gravity, and the repair was general relativity, Einstein's theory of gravity as the curving of space and time. Special relativity also contradicted quantum mechanics. The repair was quantum field theory, the quantum theory of fields in which the standard model is written. Hossenfelder shows from the history of physics that, wherever two accepted theories contradicted each other, mathematical deduction led physicists to a new theory.

Then Hossenfelder names three famous puzzles about numbers, and the first puzzle is the fine-tuning of the Higgs mass. The second puzzle is about the strong force, which binds quarks into protons and into neutrons, the uncharged partners of protons in the nucleus of an atom. A particle's 'antiparticle' is like the particle in every respect, except that each charge of the antiparticle is opposite to the particle's charge. Matter made of antiparticles is called 'antimatter', which Chapter Three met. The strong force could treat a process differently from the process's mirror image with matter swapped for antimatter. Physicists write the amount of the difference as an angle. The letter 'C' stands for swapping a particle for its opposite charge. The letter 'P' stands for swapping a particle for its mirror image, and CP stands for doing both swaps. Measurement finds the angle so small that Hossenfelder calls the angle "offensively small" (*Lost in Math*, chapter 4, "Making Problems"). Physicists call the puzzle of the small angle the *strong CP problem*. Einstein's equations of gravity have one constant

term, the energy of empty space itself, which physicists call the *cosmological constant*. The third puzzle is that the cosmological constant is small: physicists usually estimate the cosmological constant from quantum theory, and the usual estimate is larger than the measured value by a factor of a one followed by 123 zeros. Of all three puzzles Hossenfelder writes: "these are not inconsistencies; they are aesthetic misgivings" (*Lost in Math*, chapter 10, "Lost in Math").

Hossenfelder is right that the three puzzles are aesthetic misgivings and not inconsistencies. Two facts support her case: no measurement can produce a probability for the laws of nature, and a feeling that a number is the wrong size is no evidence about the world.

The Same Result, on Other Ground

I reach the same result about fine-tuning as Hossenfelder. On my account, only a reason, once found, explains an agreement of numbers, and I never count an agreement of numbers, by itself, as evidence for any particular reason, such as a new particle. I take every number at the size that one of three sources gives the number: the structure of comparison, a stated step, or a measurement. I give no number a 'natural' size that the number ought to have had.

Every number carries a stated answer to one question: where does the number come from? A number can come from the structure of comparison, from the structure of comparison with one stated step, from measurement, or from my account and measurement both. I call the stated answer the *standing* of the number, and there are four standings, each with its own picture.

First, a number can be set by the structure of comparison. A chessboard has sixty-four squares: you check the number of squares by counting, and you never measure the number of squares. Several numbers of physics have the first standing. One is the electric charges of the quarks,

which come in thirds of the electron's charge. Another is the number of 'generations': the particles of matter come in three copies, and each copy is a generation. Another is the strong force's own angle, which is zero.

Second, a number can be set by the structure of comparison once a stated step is taken. A surveyor's deed says that a lot of land runs a hundred feet north from the iron stake at the lot's corner. If you take one particular iron stake to be the corner stake of the deed, every line of the lot follows from the deed. Only the land itself can answer whether the particular stake is the corner stake of the deed. The arithmetic of the deed cannot answer the question. In the picture, taking the stake to be the corner is the 'stated step'. I name each stated step at the place where I take the step. The self-coupling of the Higgs field has the second standing, and I come to the self-coupling later in this chapter.

Third, a number can be measured. A tailor's pattern gives every proportion of a coat, but the one thing the pattern cannot give is the size of the person who will wear the coat, so the tailor measures the person. The mass of the electron has the third standing: the mass of the electron is measured. Other masses are read in units of the mass of the electron. The 'strength of light' is how strongly light acts on electric charge. The strength of light is measured too, and so are a few other numbers.

Fourth, a number can be reached by my account and found by measurement, while the reason for the agreement is still a question. Picture two clocks in different rooms of a house. The builder of the house left a note saying that the two clocks will keep the same time, with no word of how the two clocks will keep the same time. You look at the two clocks week after week, and the two clocks keep the same time to the second. You find by looking that the two clocks agree, but why the two clocks agree is a good question. You keep the clues to the answer beside the question, and here is one clue: perhaps both clocks run on the same wall current. In the picture, the builder's note stands for my account, which reaches the value, and your looking stands for measurement, which finds the value. When I

reach a value and measurement finds the value, I call the value a *measured agreement*, and a measured agreement carries the question of why the value agrees with measurement.

The four standings are four different relations between a number and the world. In the same way, one person has four different facts: an address, a phone number, a birthday and a height. Among the particles there are twenty-six numbers to account for: nineteen in the standard model, and seven more for the neutrinos. Each of the twenty-six numbers carries one standing. I set out the twenty-six numbers one by one and divide the numbers more finely, into six standings. I group the twenty-six numbers into the four standings of this chapter. Every step of my account rests on the structure of comparison, on a stated step or on a measurement, and no step of my account rests on a probability distribution over the constants, or on a sense of what size a number should have. So Hossenfelder and I agree on one result: a feeling that a number is unlikely is no evidence about the world. Hossenfelder's ground is that no one can measure a probability for the constants. The ground of my account is that every number has its standing.

A Value That Lands

What should someone write beside a number that agrees with measurement when no one knows why the number agrees?

When a number agrees with measurement before anyone knows why, I call the number a *value that lands*. A value that lands is a question, "why does it land?", and the value is also evidence of a reason not yet known: evidence that a reason exists, before anyone knows what the reason is. The agreement is explained once someone finds the reason. So I write the question "why does it land?" beside every value that lands, and I count the agreement as evidence of a reason not yet known. Balmer's rule shows the answer at work.

Picture the two-pan balance that returns in every chapter of this book: a beam on a pivot, with a pan at each end. Suppose you weigh pebbles from a stream against a set of small stamped weights. The first pebble levels the beam at exactly three of the smallest weights. The next pebble levels the beam at exactly seven, the next pebble at exactly five, and so on through the whole bag of pebbles. You could write "luck" in your notebook and close the notebook. Or you could write a question in the notebook: why does every pebble land on a whole number? The question already contains a clue: the whole numbers are a clue that something inside the pebbles comes in grains of one size. When a weighing lands on a value that calls for a reason, the question of why the weighing lands there is the notebook entry that keeps the work going.

Balmer's rule held a clue of the same kind as the whole numbers of the pebbles. Balmer's rule used whole numbers and the square of two. Balmer himself guessed that the squares of other whole numbers would give other families of lines. The whole numbers and the square of two were clues that something in the atom comes in whole steps, counted one, two, three. Bohr found the reason for Balmer's rule in the whole steps of the atom: the energy levels. Physics has a second case in which the clues of an agreement led physicists to the reason for the agreement. Two quantities stand in the same proportion in every body ever tested, whether gold, wood, water or wheat: how hard the body is to set moving, and how strongly gravity pulls on the body. Einstein asked why the two quantities stand in the same proportion, and Einstein's answer became general relativity. The agreement came first in Balmer's case and in Einstein's case. The clues in each agreement then led physicists to the reason for the agreement.

I use one word, 'fitted', to separate a value that someone chose from a value that landed. When someone chose a value to make the value match, the value is *fitted*, like a dial turned until the needle points where the needle should, and the match of a fitted value has a reason: the turning of the dial. Even for a fitted value, a question stays: why does the world need the dial at that position? Balmer chose the form of his rule and one num-

ber, 364.56, by looking at four lines. Balmer did *not* choose that so simple a rule produces all four lines as closely as Ångström measured the four lines, nor that the rule produces the fifth line and the lines found after the fifth line. Balmer's rule agreed with the lines, and the agreement came from the world: the agreement 'landed'.

Hossenfelder writes that there is nothing in need of explanation, and I write the question in place of her sentence, with every clue to the reason gathered beside the question. The entry "coincidence" says that an agreement has no reason, as the entry "luck" in the pebble notebook does. Before anyone finds the reason for an agreement like Balmer's, all that anyone has shown is that the reason is not yet known. Balmer's rule was held as a question, and so the rule became a door into quantum theory: a starting point from which quantum theory was built.

I go one step further: I hold that every pure number among the particles has a reason, whether or not anyone has yet found the reason. The reason for each pure number is one of two things: a law that fixes the number, or a proof that no law fixes the number. I aim at one of two ends for each pure number among the particles, in the way that a carpenter can close a question about a frame in one of two ways. The carpenter can prove that the two diagonals of a square frame must be equal. Or the carpenter can prove that nothing in the plan fixes the color of the paint. Then the carpenter writes the color once on the work order. Either way, the carpenter has fully accounted for the frame. In the same way, a pure number is either derived through the number's law, or shown by argument to be a number that no law fixes. A number derived through its law is like the equal diagonals, and a number that no law fixes is like the color of the paint: an argument shows that no law fixes the number, and the number is then read once from measurement. The strength of light is a number of the second kind: an argument shows that no law fixes the strength of light, and the value of the strength of light is read once from measurement. The argument, which I give in Chapter Five, is that nothing a world must contain fixes the strength of light. Some numbers have reached their end already. If a number has not yet reached either end, the number car-

ries the question that would settle the number. Hossenfelder and I each reject a verdict that someone reaches before finding the reason. Hossenfelder rejects the verdict that a number needs a new explanation because the number looks unlikely. I reject the verdict that an agreement is a 'coincidence'.

The Strong Force's Angle

Take Hossenfelder's second puzzle first: the strong CP problem. On my account, the strong force's own angle is zero, and the reason is the structure of comparison.

Chapter Three found two parts in every comparison. The first part is what the verdict of the comparison is about, and Chapter Three calls the first part the *content* of the comparison: on the balance, the content is how heavy the thing in the pan is. The second part is the respect in which the two things compared are two. On the balance, the context is the two places that the two things occupy, the left pan and the right pan, together with the floor and the room that hold the two places, at the moment of the weighing. In physics, the content is the matter that is found, and the context is the arena of space and time in which the matter is found, together with the setting of possibility. Chapter Two used a setting to say what symmetry and continuity mean. The word 'symmetry' means that what is found stays the same when the setting changes. The word 'continuity' means having no gaps, so that a small change of setting gives a small change in what is found. The setting of Chapter Two is the context of a comparison.

Now look at a weighing in a mirror. Suppose a pear is weighed against known weights, as in Chapter Three. In the mirror, the pear sits in the other pan. The verdict in the mirror is the same: the pear and the weights weigh what they weighed. The mirror changed one part of the setting: which pan is on the left and which pan is on the right. The mirror left the content as the content was. Symmetry means that the content stays the same when the setting changes. When what is found differs as the setting

changes, the difference is an 'asymmetry'. One example of an asymmetry is a thing and the thing's mirror image behaving differently. Asymmetry belongs to context.

The context of a measurement has three measures: space, time and possibility. The two 'swaps', P and C, each reverse one of the three measures, and P reverses space, as a mirror does. C reverses possibility, because swapping a particle for its antiparticle reflects the range of states the particle could be found in: every charge the particle could be found with turns to the opposite charge, as a mirror turns left into right. Because asymmetry belongs to context, a force can treat a process differently from the process's mirror image with matter swapped for antimatter only if the act of the force reaches the context. To reach the context, the act of the force must carry a state of matter across: out of the content, where everything stays the same when the setting changes, into the context, where differences belong, and back again.

The 'doublet' of Chapter Three is a pair of sides between which the weak force turns a particle, and the act of the weak force turns a particle across the particle's doublet. The turning carries the state of the particle out of the content into the context and back, so the weak force cannot treat a state and the mirror image of the state alike. As Chapter Three said, the weak force acts on the left-handed part of a particle only. When a force's own form treats a process differently from the swapped process, the force 'breaks' the swap. The weak force is the one force whose own form breaks a swap. The weak force's form breaks P taken alone and C taken alone, but the form keeps CP, the two swaps taken together. Some weak decays do show a difference between a process and the process's mirror image with matter swapped for antimatter, and the difference in the weak decays comes from one 'further angle' in the mixing of the quarks, beside the mixing angles. The mixing of the quarks can carry the further angle only because the quarks come in three generations, and without the further angle the weak force would treat a process and the process's mirror image with matter swapped for antimatter alike.

The act of the strong force keeps every state in the content. The strong force turns a quark among the quark's three 'color' states, as a hand turns a die among the die's faces in Chapter Three, and everything the strong force turns stays content. So the strong force has no form of its own that could tell a process from the process's mirror image with matter swapped for antimatter, and therefore the strong force's own angle is zero.

A second argument for the zero angle starts from the rules by which the turnings of the strong force combine. The second argument is about one part of the strong force: the part that could tell a process from the process's mirror image with matter swapped for antimatter, made of the turnings of the strong force in which the difference between the process and the mirror image would have to lie. The second argument shows that the part is 'closed on itself': when turnings of the part are combined, the combination gives only turnings of the same part, and the turnings of the part carry nothing of the part into the rest of the strong force. Suppose an effect tells a process from the process's mirror image with matter swapped for antimatter. Then the effect cannot pass from the closed part to the rest of the strong force. The two arguments are independent of each other. The two arguments arrive at one result: the strong force keeps the symmetry CP because of the structure of comparison. No number was adjusted to make the strong force keep CP. I give the first argument. I give the second argument.

The masses of the quarks carry an angle with them, called the quarks' *phase*. The angle that experiments measure is the strong force's own angle plus the quarks' phase. The quarks' phase is a different angle from the further angle in the mixing of the quarks, which some weak decays show, and a different angle again from the phase of Chapter Three, which the third force turns. Physicists measured the 'whole angle', the strong force's own angle plus the quarks' phase, with neutrons. A neutron has no overall charge, but if the whole angle were not zero, the angle would give the neutron a slight lopsidedness of charge inside, which physicists call an 'electric dipole'. A team held very slow neutrons in steady magnetic and electric fields at the Paul Scherrer Institute in Switzerland. Each neutron

spins like a tiny top, and in a magnetic field the axis of the neutron's spin turns steadily around. The team watched whether the electric field changed the rate of turning, because the electric field would change the rate for a lopsided neutron. In 2020 the team reported that the electric field did not change the rate, within a limit finer than any limit reached before. We now know that the strong force's whole angle is less than about two ten-billionths of a radian (a 'radian' is an angle of about fifty-seven degrees).

The structure of comparison allows the quarks' phase two values, zero and a half turn, and at either of the two values the strong force would treat a process and the process's mirror image with matter swapped for antimatter alike. The phase takes zero or a half turn according to signs that the quark masses carry. A 'halving' is a step down by a factor of two in mass, and the rungs are counted in halvings below the heaviest quark. I count one comparison, with the comparison's two outcomes, as one halving. In the working, each mass is a number with a sign, plus or minus. Measurement finds the size of each mass, and the sign of a mass enters only the quarks' phase: each minus sign adds a half turn to the phase, as a person who turns to face the other way has made a half turn. I take the quark masses as the ladder sets out the quark masses, and the ladder has one minus sign among the three quarks with charge plus two thirds and one minus sign among the three quarks with charge minus one third. The two minus signs add two half turns to the phase. Two half turns make one whole turn, and one whole turn brings the phase back to zero. Zero, and not a half turn, is also the value that measurement supports. The structure of comparison sets the strong force's own angle at zero, so the whole angle is the quarks' phase alone. The measured whole angle is small, and the small size shows that the phase lands on zero. The zero of the phase is a measured agreement: I reach zero through the two minus signs of the ladder, and measurement finds zero. I write the question of the measured agreement beside the zero: why do the quark masses add no angle to the strong force's own angle, whose zero the structure sets?

In 1977 and 1978 physicists proposed a new light particle whose work would be to drive the strong force's angle to zero. Physicists call the proposed particle the *axion*. The structure of comparison needs no axion: the angle that the structure sets is already zero, and Chapter Three's closed list of kinds of particle has no slot for an axion.

The Higgs Mass

Hossenfelder's first puzzle is the Higgs mass, and on my account each number of the Higgs puzzle has its standing.

The Higgs field acts on itself, and how strongly the Higgs field acts on itself is called the 'self-coupling' of the Higgs field. The Higgs field comes as a pair: a doublet in the sense of Chapter Three, two sides between which the weak force turns the Higgs field. Each side of the doublet carries a number that marks the side: plus one half for one side, and minus one half for the other side. The size of the number, one half, is called the 'doublet's half', and the structure of comparison sets the doublet's half. I identify the self-coupling with half the square of the doublet's half. One half squared is one quarter, and half of one quarter is one eighth. So the self-coupling is one eighth at the first level of calculation, before the corrections that the quantum fluctuations add, and the value of one eighth is derived given my one identification.

Physicists call the corrections that the quantum fluctuations add the 'loop term'. Add the loop term, and take one measured number: the value at which the Higgs field settles in empty space. I then reach a Higgs mass of 125.17 GeV. Measurement finds the same mass, within the measurement's stated uncertainty, so the Higgs mass of 125.17 GeV is a measured agreement. A measured agreement is the standing of the two clocks and the builder's note: I reach the value, measurement finds the value, and the question of why the value lands is kept beside the value.

Then, the Higgs puzzle comes down to two numbers, each with its standing. The self-coupling is derived given one stated identification, while the mass is a measured agreement that carries the question of why the mass lands.

Why the Cosmological Constant Is Not a Free Number

Hossenfelder's third puzzle is the energy of empty space, and for the energy of empty space the measurement came first. In the 1990s two teams of astronomers set out to measure how fast the expansion of the universe was slowing down. Saul Perlmutter led one team, and Brian Schmidt led the other team with Adam Riess. The teams used a kind of exploding star called a 'Type Ia supernova', whose true brightness is nearly the same in every case. So astronomers can read the distance of a Type Ia supernova from the supernova's apparent brightness, as a candle across a football field looks dimmer than the same candle at arm's length. The distant supernovae were too dim for any universe whose expansion was slowing down. In 1998 the teams found that the expansion is speeding up. We now know that empty space carries an energy of its own, and the energy of empty space is small: about the mass of three or four hydrogen atoms in each cubic meter of space.

In general relativity, the energy of empty space enters as the cosmological constant. Hossenfelder states the usual standing of the cosmological constant: "In general relativity, the cosmological constant (CC) is a free parameter" (*Lost in Math*, chapter 9, "Feeble Fields and Fifth Forces"). A 'free parameter' is a number left open in a theory, to be filled in by measurement. The cosmological constant is not a 'free number': the value of the cosmological constant rests on steps of mine, and I state each step in the first person where I make the step. The central step is an identification, and the central step comes in the first of the four steps below. The *particle horizon* is the edge of everything whose light has reached us. Once my steps are taken, three things set the value of the cosmological constant: the

structure of comparison and two measured things, the strength of gravity and the size of the particle horizon. I reach the value in four steps, and at the fourth step I set the value beside measurement.

First, you measure empty space from inside empty space. When you measure a table, you are not part of the table. But when you measure empty space, you are made of the very fields whose lowest energy you are measuring, like a fish trying to measure the water the fish swims in. Every field keeps a trembling in empty space, and the trembling is the lowest energy of the field. Physicists call the trembling summed over all the fields the *vacuum energy*. When physicists reckon the total of the vacuum energy in the usual way, the total is the estimate that comes out larger than the measured energy of empty space by a factor of a one followed by 123 zeros. A measurement made from inside empty space receives only a share of the total vacuum energy, as a cup dipped in the sea holds real sea water and never holds the sea. I identify the cosmological constant with the 'share' of the vacuum energy that a measurement made inside empty space takes in, as distinct from the total.

Second, what bends space is what a comparison finds, and no comparison finds the total vacuum energy. Space and time bend under what comparisons find in space and time, in proportion to the energy found, so energy that no comparison ever finds bends nothing. A measurement takes in only a share of the total, as the cup holds only a share of the sea. So no measurement takes in the whole total. The total, taken whole, also has a shape that no comparison finds. The total is the same at every place, and the total is the same for everyone moving steadily, whatever the speed of each one. When you run through still air, you feel a wind, but through empty space there is no wind at any steady speed. The total has no break anywhere. So the total, taken whole, would be perfectly *symmetric*, the same under every change of place or setting, and perfectly *continuous*, with no gaps, so that a small change of setting gives a small change in what is found. The Incommensuration Theorem, met in Chapter Two, says that no comparison finds anything perfect in symmetry and in continuity

at once. Therefore no comparison finds the total, so the total bends no space, whatever the size of the total, and the factor of a one followed by 123 zeros needs no canceling.

The share is found in another way: as a count. What a measurement takes in comes in whole pieces, and each piece is either taken in or not, as a marble is either in the cup or not, with no smooth smear between three marbles and four marbles. A count that is the same everywhere is symmetric and comes in steps. The box of weights in Chapter Two has the same pairing: symmetric and in steps. The Incommensuration Theorem allows a finding to be symmetric and in steps at once, so the share is found, and the share bends space.

Third, the share has a size, and the size of the share is a count. Begin with the edge of what has reached us. Picture a vast dark plain on which lanterns were all lit at one moment, long ago. From where you stand, you see only the lanterns whose light has had time to reach you, and the farthest lanterns you see mark a ring around you, a ring that widens each night as more light arrives. Our particle horizon is the ring of lanterns for the universe: the edge of everything whose light has reached us since the expansion began. Our particle horizon now lies about forty-six billion light years away, because space has stretched as the light traveled.

Next comes the count of 'tiles' on the edge. A 'black hole' is a region of space whose gravity lets nothing out. In the 1970s the physicists Jacob Bekenstein and Stephen Hawking found that the edge of a black hole carries a count. The 'Planck length' is the length built from the strength of gravity, the speed of light and Planck's constant. Picture the edge of a black hole tiled like a floor, with one tile for every four tiny squares a Planck length on a side. Each tile stands for one independent way in which what lies inside the edge can hold energy or vary, as each string of a piano can ring on its own. I assign the same count of tiles to the particle horizon, because the particle horizon bounds everything that a present measurement has compared. Our particle horizon carries about two and three tenths times ten to the power one hundred twenty-three tiles.

Then comes the vacuum energy that the tiles share. The total vacuum energy, reckoned as a whole, has two parts. The first part is the energy of all the fields at their lowest, at the smallest scale there is. The 'Planck density' is the energy packed into a volume at the scale built from the strength of gravity, the speed of light and Planck's constant. I take the first part to be the Planck density, and Newton's constant (the measured strength of gravity) fixes the Planck density.

The world has six small dimensions besides the three dimensions of space and the one dimension of time, and the six small dimensions are the same in size and shape at every place. The second part of the total comes from the six small dimensions. The shape of the six small dimensions fixes what kinds of particle there can be. The shape fixes the closed list of kinds of Chapter Three. The six small dimensions differ from the extra dimensions that physicists proposed for the collider of Chapter Three: the proposed extra dimensions would have added new particles to the list, while the six small dimensions fix the list and add nothing to the list. I return to the six small dimensions in later chapters. The shape of the six small dimensions bends away from flat, as the surface of a ball bends. How far a shape bends away from flat is called the *curvature* of the shape. The curvature of the six small dimensions holds an energy of its own, and the energy of the curvature has the sign that draws space together, the sign opposite to the sign of the first part. So the energy of the curvature counts against the first part. The energy of the curvature takes away about twelve hundredths of the Planck density.

Picture an estate to be shared equally among a great many heirs, from which a fixed charge is taken before the sharing. The curvature of the six small dimensions is the fixed charge. The structure of comparison sets the size of the six small dimensions, and the size of the six small dimensions fixes the charge. What remains after the charge is a little under nine tenths of the Planck density, and what remains is called the 'trimmed total'. The trimmed total is what the tiles share. Each tile holds an equal part of the

trimmed total, because the total is the same at every place and nothing makes one tile different from another, as heirs whom nothing tells apart receive equal parts.

Last comes the number of channels. Every measurement registers three kinds of thing: a pattern, laid out in space; a force, acting in time; and a probability, spread over what could be found. Empty space reaches a measurement through *channels*, and I identify the channels with the three kinds of thing that a measurement registers. The structure of comparison sets the number of kinds of thing that a measurement registers at three, so a measurement has three channels. I take each channel to take in one whole tile. I take the tile of each channel to be a different tile, because the three things the channels carry are distinct. Do a telescope and a thermometer, used together, take in six tiles? A telescope and a thermometer used together take in three tiles: the one who measures stands at one place, and the tiles taken in are counted once for the place where the one who measures stands, and not once for every instrument carried to that place. So a measurement takes in three tiles out of all the tiles on the edge.

Now put the steps together. Divide the trimmed total into as many equal parts as the particle horizon has tiles, and the cosmological constant is three of the equal parts, as three heirs' shares are three parts of what remains of the estate, out of as many parts as there are heirs. So three tiles hold about one part in a one followed by 123 zeros of the trimmed total.

Fourth, the number can be found in two ways. Put the measured size of our particle horizon into the share, and the share then gives an energy of empty space that agrees with the measured energy of empty space to within about two percent. Appendix B, For the Specialist, gives both values in the units particle physicists use. There is a second way to find the energy of empty space, and the two ways must agree. Picture two surveyors sent to measure one field: one surveyor walks the edge of the field with a measuring chain, and the other surveyor works from a hilltop with angles and a map. The two surveyors measure one field, so the answers of the two surveyors must agree, and when two answers must agree, the agreement can tell you something that neither surveyor could find alone.

The share is the first way to find the energy of empty space, and the second way is the astronomers' way, through an equation that the physicist Alexander Friedmann found from Einstein's theory in 1922. The space of our universe has no overall bend on the largest scales. Friedmann's equation says that, for a universe with no overall bend, the rate of the expansion fixes how much energy each volume of the universe holds. The energy in each volume has three parts: matter, ordinary and dark together; the energy of empty space; and a thin sliver of light and other fast particles. The dark matter is not matter of any kind on the list of particles, but the dark matter still counts in the matter part, by the weight of the dark matter. The three parts make up the whole of the energy in a universe with no overall bend, and the sliver of light is measured.

The expansion itself sets a unit of distance, the 'unit of the expansion': the distance at which the expansion carries things away at the speed of light. Now count the size of the particle horizon in the unit of the expansion. When the size of the horizon is counted in the unit of the expansion, the rate of the expansion enters the share through the size of the horizon. The rate enters the share as the square of the rate, because the count of tiles on the edge grows as the square of the size of the edge, and the rate also enters Friedmann's equation as the square of the rate. The strength of gravity enters the share and Friedmann's equation in the same way. Set the share beside Friedmann's equation, and the rate of the expansion and the strength of gravity both drop out. What is left is one statement in pure numbers, a relation between two quantities: the first quantity is the size of the horizon, counted in the unit of the expansion, and the second quantity is the part of the energy of the universe that belongs to empty space.

The horizon lies as far away as light has traveled since the expansion began. When the distance to the horizon is counted in the unit of the expansion, the distance depends only on how the expansion ran over the history of the universe. How the expansion ran depends only on how the energy has been divided among the three parts, because matter and light thin out at different rates as space grows, and the energy of empty space does not thin out at all. So the statement has one unknown: the part of the

energy of the universe that is matter. The statement gives the 'matter part' as about three tenths. The measured matter part agrees with the value from the statement, within the measurement's stated uncertainty. The energy of empty space and the matter part are one measured agreement, seen in two ways. In the same way, the answers of the two surveyors are two measures of one field.

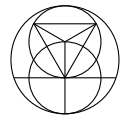
Now count what was left free in the share. The structure of comparison sets the count of three channels. The structure of comparison sets the part that the six small dimensions take away. The share itself is my identification, made in the steps above: three parts out of the count of tiles. Two more identifications of mine go with the share: the count of the edge of a black hole, assigned to the particle horizon, and the channels, identified with the three things a measurement registers. Two further steps are mine as well, and I stated each step where I took the step: taking the first part of the total to be the Planck density, and taking each channel to take in one tile. The strength of gravity is measured, and so is the size of the particle horizon. Every number in the share is fixed by the structure of comparison, by one of my stated steps, or by measurement, and each number is fixed before the share is set beside the measured energy of empty space. The energy of empty space is small *because* the edge of what has reached us is large.

The particle horizon grows a little every year, as light from farther away arrives. The cosmological constant stays one number all the same: the cosmological constant is fixed once. Our *epoch* is one whole span of the universe's history, the span that began at the Big Bang. Einstein's equations require their constant term to be one number throughout one geometry, and the one geometry of our epoch is the one shape of space and time that holds the whole history of our epoch. The requirement is a theorem of the geometry, and the theorem uses no measurement. A road carries one speed limit along the whole length of the road, posted once. One geometry carries its one constant in the same way. The one value of the cosmological constant is fixed by the present measurement, made here and now from inside the world. Picture an astronomer who lived when

the universe was half its present size: the astronomer's records reach us now, in the one history that we rebuild from the present measurement, and the astronomer's records carry the same constant that we measure. Some physicists have proposed that the speeding up is driven by a field whose strength changes over time. The one constant drives the speeding up of the expansion, and the constant is the same at every place and every time of our epoch. No field whose strength changes over time drives the speeding up.

The short answer: Every number of physics has a standing. When a number agrees with measurement and no one knows why, the number is a question, "why does it land?", and evidence of a reason not yet known. Every pure number among the particles has a reason, whether or not anyone has yet found the reason: a law that fixes the number, or a proof that no law fixes the number.

Since every pure number among the particles has its reason, was our universe tuned for us, or is ours one of many universes?



Chapter Five

Was the Universe Tuned for Us, or Is Ours One of Many?

What this chapter uses

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 Two).

To *exist* is to stand as structure: timeless, the same in every instance, able to be held in view as a whole; to be *real* is to be given in an actual act of comparison: here, now, with the future still open (Chapter Two).

The *standing* of a number is the stated answer to where the number comes from: from the structure of comparison, from the structure of comparison with one stated step, from measurement, or from my account and measurement both; a *value that lands* is a number that agrees with measurement before anyone knows why, and it is a question, "why does it land?" (Chapter Four).

The world has *six small dimensions* besides the three dimensions of space and the one dimension of time, the same in size and shape at every place, and the shape of the six fixes what kinds of particle there can be (Chapter Four).

A familiar argument runs as follows. Change certain constants of nature a little, one at a time, and there would be no stars, no carbon and no people like us. If the argument is right, what follows from the argument? Did someone set the constants with care? Is ours one universe among a great many? Or does neither follow?

The laws of physics use certain fixed numbers that the laws do not supply themselves. Physicists call the fixed numbers the *constants of nature*. Three examples are how strongly gravity pulls, how strongly electric charges pull on one another, and how heavy each particle is. In this chapter I answer *only* the physics of the question. I leave to philosophy the older question of why there is something rather than nothing.

Copernicus's Birthday in Kraków

In September 1973 astronomers met in Kraków, in Poland, for a symposium of the International Astronomical Union. The meeting honored the five hundredth birthday of Nicolaus Copernicus, the astronomer who moved the Earth out of the center of the heavens. The subject of the meeting was how well the theories of the universe as a whole agreed with what telescopes had found. One of the speakers was the physicist Brandon Carter, whom the physicist John Wheeler had asked to put on record some ideas that Carter had first suggested at a meeting in Princeton in 1970 and had never written up.

Carter began his talk with Copernicus. In the talk as printed the next year, Carter wrote that "Copernicus taught us the very sound lesson that we must not assume gratuitously that we occupy a privileged central position in the Universe". Then Carter turned the lesson around. Our place in the universe need not be central, but our place cannot be just anywhere either. We can only find ourselves in a place, and at a time, where beings like us can live. Carter wrote that "what we can expect to observe must be restricted by the conditions necessary for our presence as observers".

Carter gave a name to the idea that our own presence limits what we can observe. Carter called the idea the *anthropic principle*, from the Greek word for a human being. Carter gave the anthropic principle two forms. The first form, which he called "weak", says that "our location in the universe is necessarily privileged to the extent of being compatible with our existence as observers". The second form, which he called "strong", says that "the Universe (and hence the fundamental parameters on which it depends) must be such as to admit the creation of observers within it at some stage". Carter's 'fundamental parameters' are the constants of nature.

Carter added one more idea. He wrote that a prediction made from the strong form could be promoted to an explanation "by thinking in terms of a 'world ensemble'". By a 'world ensemble' Carter meant "an ensemble of universes characterised by all conceivable combinations of initial conditions and fundamental constants": a whole collection of universes, each universe started in its own way, each with its own settings. Carter offered the step from prediction to explanation only, in his own words, "as a last resort, when no stronger physical argument is available".

So the two ideas of this chapter arrived together, in one talk given in honor of Copernicus. The first idea is that our own presence limits what we can find. The second idea is that ours may be one universe among a great many. Today the collection of universes is called the *multiverse*, and the anthropic principle still has the name Carter gave it.

From Hossenfelder's pages

What Sabine Hossenfelder Showed

Sabine Hossenfelder takes up both of Carter's ideas, in *Lost in Math* and again in *Existential Physics*. Hossenfelder begins with the argument from *fine-tuning*: the claim that the constants sit in a narrow

band that allows life, a band so narrow that the constants look as if someone had set the constants with care. Hossenfelder gives the argument a picture:

> Imagine God sitting in front of a big panel with knobs.
>
> (*Existential Physics*, chapter 7, "Imagine No Religions")

Each knob on the panel carries the name of one constant. Turn a few knobs away from our settings, and the stars fail to light, and we are gone. The fine-tuning argument then says that our settings are very unlikely, and so need an explanation. Those who make the fine-tuning argument offer two explanations: either a designer set the knobs, or there is a multiverse, in which every setting occurs somewhere and we live in a universe whose setting allows us.

Hossenfelder answers the word 'unlikely' directly. You need a *probability distribution* to call a setting unlikely. A probability distribution is a rule that says how often each setting would turn up over many draws. A fair die is one example: thrown many times, a fair die shows each face one time in six. For the constants of nature, there has only ever been one draw. No one will ever measure a constant at a value other than the value the constant has. So Hossenfelder concludes:

> There's nothing quantifiably unlikely, and therefore there's nothing in need of explanation.
>
> (*Existential Physics*, chapter 7, "Imagine No Religions")

Hossenfelder's picture for a single draw is a bag: you reach into the bag without looking and pull out one slip of paper, with a long number written on the slip. You know nothing about what else is in the bag, so the one pull tells you nothing about how likely your number was. In the same section, Hossenfelder gives her verdict on the two ex-

planations, the designer and the multiverse: "While a creator or a multiverse is not ruled out by science, science does not require their existence either".

In *Lost in Math*, Hossenfelder shows that the multiverse and naturalness share one difficulty. Both the multiverse and naturalness need a probability distribution for the constants, and the probability distribution has to come from yet another theory. Hossenfelder puts the difficulty this way:

> (*Lost in Math*, chapter 5, "Cosmic Poker")

Hossenfelder grants the anthropic principle one use: as a limit on what we can find, the anthropic principle is sound. If you see someone walking down the street with a coffee cup, you can conclude that there is a coffee shop somewhere nearby. Hossenfelder also reports a story about the astronomer Fred Hoyle, who is said to have reasoned from carbon: carbon is central to life on Earth, so stars must be able to make carbon. The properties of carbon that Hoyle predicted were then found. Hossenfelder sums up the proper use of the anthropic principle:

> The anthropic principle, therefore, is a constraint on our theories that enforces agreement with observation.
>
> (*Lost in Math*, chapter 5, "Cosmic Poker")

When someone uses the anthropic principle as a constraint, the value of no constant follows from the principle, because physicists have found other combinations of the constants that would still allow a chemistry rich enough for life. Hossenfelder writes in the same section that "our universe isn't all that special".

In *Existential Physics*, Hossenfelder draws the same line again, between a constraint and an explanation. Hossenfelder defines her own two forms of the anthropic principle, a weak form and a strong form, in chapter 7, in the section "Do We Live in the Best of All Possible Worlds?". Hossenfelder's weak anthropic principle says that the constants of nature "must allow for the existence of life", and she writes that the weak form "is merely an observational constraint on our theories". Hossenfelder's strong anthropic principle says that the constants are what they are because the universe gave rise to life, and she writes that the strong form, "taken at face value, is wrong". Hossenfelder's weak form says what Carter's second form says, so the two writers give the names 'weak' and 'strong' to different statements.

Hossenfelder sorts multiverses into several kinds. *Inflation* is a proposed burst of very fast expansion in the first moments of the universe. In *eternal inflation*, the burst never stops everywhere at once, and bubble universes keep forming inside the inflating space. *String theory* is an attempt at one theory of all the forces, gravity included. The *landscape* of string theory is the vast range of possible worlds that string theory allows, each world with its own particles and constants. The *many-worlds interpretation* of quantum theory says that every possible outcome of a measurement happens, each outcome in a world of its own.

Hossenfelder grants two things. A theory may contain parts that no one can observe, and a few kinds of multiverse can be tested. In eternal inflation, for example, our bubble universe might once have collided with another bubble. The collision, if it happened, would have left a mark on the oldest light in the sky. Hossenfelder reports of the search for the collision mark, in *Lost in Math* (chapter 5, "Endless Possibilities"): "It's been looked for and hasn't been found". In most kinds of multiverse, no signal from the other universes can ever reach

us, and the reason is in how the theory behind each of those kinds of multiverse is built. Hossenfelder writes of universes that no signal can ever leave:

> Hence, assuming that these other universes are real is ascientific.
>
> (*Existential Physics*, chapter 5, "The MultiWorse")

Hossenfelder takes the word *ascientific* from the physicist Tim Palmer: an ascientific belief is a belief that science can neither confirm nor rule out, and that is not needed to describe anything we observe. In the same section of *Existential Physics*, Hossenfelder gives her colleagues short advice: "If you want to talk about it, fine, but don't pretend it's science".

Hossenfelder also names where multiverses come from. In *Lost in Math* (chapter 5, "Endless Possibilities") she writes, "Since every theory requires observational input to fix parameters or pick axioms, every theory leads to a multiverse when it lacks input". In the same section she calls the multiverses "the mathematical artifacts that I think they are": by-products of the mathematics.

On string theory, Hossenfelder reports two facts: string theory has made discoveries in mathematics and in the physics of black holes, the regions of space whose gravity lets nothing out, but string theory has no experimental evidence. On the beauty of string theory she is direct, in *Lost in Math* (chapter 8, "String Theory and Its Discontents"): "mathematics is full of amazing and beautiful things, and most of them do not describe the world".

The philosopher Karl Popper proposed a test for science: a theory belongs to science when some possible observation could show the theory false. Hossenfelder reports, in *Lost in Math* (chapter 2, "Why Trust a Theorist?"), that Popper's test has "long been an outdated philo-

sophy". In practice, she says in the same section, "we 'implausify' them": physicists patch a theory again and again, the theory grows awkward, and in the end people lose interest in the theory.

Four of Hossenfelder's results matter most for the question of this chapter. First, the anthropic principle limits what we can find and explains no value. Second, a probability distribution over the constants is a guess that no measurement can check. Third, science says nothing either way about universes that no one can ever observe, so a belief in such universes is ascientific. Fourth, beauty in mathematics is no evidence about the world.

I push this idea around for a while, but I still can't see how guessing a probability distribution for a parameter is any better than guessing the parameter itself.

A Row of Worlds

All four of Hossenfelder's results also follow in my account (the Immanent Metaphysics, together with the physics that I work out from the Immanent Metaphysics) from my own ground, which is *comparison*: setting one thing beside another and finding how the two stand. Every measurement is an act of comparison.

The first picture is this. Imagine a long row of worlds, set side by side. The worlds differ in the value of one constant and in nothing else. The row is a picture in thought, and nothing in the picture says that the worlds are real. In each world, the things the world holds can stand together in many ways: an electron held by a proton, for example, or two charges some distance apart. Call each way that things can stand together an *arrangement*. Now compare the worlds by asking three questions of every arrangement in every world: is the arrangement 'possible' in that world, 'impossible', or 'certain'?

Comparing the worlds by the three questions has three possible results.

In the first result, the answers stay the same all along the row. Then no answer of possible, impossible or certain depends on the value of the constant. The constant is then independent of comparison, and so the value of the constant has to be measured.

In the second result, the answers change only at a few isolated values of the constant, and then the isolated values are impossible for the constant, while every other value stays possible.

In the third result, only one value of the constant gives a world the arrangements that the very idea of the constant requires. Then the constant is fixed, and comparing along the row also says how to compute the value of the constant. Pi is a number fixed in the way of the third result, by the idea of a circle. Draw a circle of any size on a flat page. Divide the distance around the circle by the distance across the circle, and you always get the same number: pi. Anyone can compute the digits of pi, one by one, with no measurement.

Take the *strength of light*: the number, about one part in one hundred and thirty-seven, that sets how strongly light and electric charge act on each other. Picture the row of worlds that differ only in the strength of light: in every world along the row, the same arrangements are possible, the same arrangements are impossible, and the same arrangements are certain. Changing the strength of light changes *only* how often things happen, and how strongly. So the strength of light has the first result. Nothing that a world must contain fixes the strength of light, so the strength of light has to be measured. I start the argument from the rule that the circle shows, that a constant fixed by its idea is fixed as pi is, and the step of the argument is that every comparison has the same structure at every value of the strength of light.

Hossenfelder reaches a neighboring result from chemistry: other combinations of the constants would still allow a chemistry rich enough for life, so life does not single out the values we have. I reach the result for the

strength of light from the structure of comparison instead (from what every comparison must contain), by a step that has nothing to do with life.

I show why no value follows from the anthropic principle. Suppose that our being here is what picks out a value: then no one can predict the value, or work the value out from the basic laws. The value is no longer a consequence of law. The value then becomes what I call "an accident of location".

A probability distribution has a second limit as well: a rule that covers every time at once cannot say which time is now. Think of a calendar on the kitchen wall. The calendar lists every day of the year, and every day on the calendar is printed the same way. The calendar cannot tell you which day is today: only the morning itself tells you which day is today.

I give the two words 'exist' and 'real' exact meanings, and the calendar and the morning show both meanings.

I state the calendar's point for the whole history of the universe. Picture a rule stated from outside the universe, a rule that covers the whole history of the universe at once. A *comparer* is anything that makes a comparison. The rule from outside can say how likely a comparer is to stand at each time in the history, but the rule from outside cannot single out any one time as real. The rule could single out one time as real only by taking the present of every time as given together, as if every day on the calendar were today at once. Hossenfelder found that a probability distribution does not explain the value we see. I give two separate reasons for her result: the first, that a value picked out by our being here is no longer a consequence of law, and the second, that a rule from outside cannot single out which time is now.

I also give a reason for Hossenfelder's result that multiverses are artifacts of mathematics. In mathematics, a circle can be perfectly smooth and exactly the same under every turn, both at once. No one, by any comparison, ever finds a thing in the world that is both perfectly smooth and exactly the same under every turn. The reason is the Incommensuration

Theorem, set out in Chapter Two: symmetry and continuity cannot both be perfected in one comparison, and neither can asymmetry and discontinuity.

In mathematics, symmetry and continuity can be written down together, both perfect and at once. The reason is that mathematics contains no one who compares, and no time. I quote the sentence of another that states the point exactly: "In a domain from which temporal comparison is removed, symmetry and continuity can be written down together. Such a domain is not a real world, precisely because the real world has a temporal element and that domain does not". So mathematics can describe structures that no one could ever find by comparison. Suppose no one could find a structure by comparison: then the structure exists in the way the circle exists, as structure, but the structure is not real, because no act of comparison gives the structure. Suppose no one could ever find a collection of universes by comparison. Then the collection is a structure of the same kind as the circle: in mathematics the whole collection is laid out at once, with no one comparing inside the collection, and no act of comparison gives the collection. So the collection exists as structure, and the collection is not real.

Carbon shows what the anthropic principle can do when someone uses the principle as a limit on what we can find. In 1953 the astronomer Fred Hoyle argued from one observed fact: there is carbon in the world. In stars, carbon is made when three nuclei of helium join into one nucleus of carbon. Carbon can have an *excited state*: a level of energy above the lowest level of carbon. Three helium nuclei join often enough to make all the carbon there is only if carbon has an excited state at just the right height. So Hoyle said that carbon must have the excited state, and he said at what height. Later in 1953, Ward Whaling and his colleagues found the excited state at the height Hoyle had given. Whaling and his colleagues worked at the California Institute of Technology. In 1957 Cook, Fowler and the two Lauritsens reported further measurements of the excited state. Today the excited state is called the 'Hoyle state'. I tell Hoyle's step as an inference

from carbon, with no appeal to life. So Hoyle's step is the anthropic principle in the one use Hossenfelder grants the principle: a limit on what we can find.

The cosmologist George Ellis holds that a collection of universes that cannot be tested should not be called physics. I agree with Ellis and with Hossenfelder, and I add a reason of my own. My account has one world, with one settled state of empty space. So there is no collection of worlds from which our world could be selected.

One Valley

A hilly country with many valleys shows what one settled state of empty space means. Set a ball at the bottom of one valley and nudge the ball. The ball rolls a little way up the slope and settles back where the ball was. Now drop a ball onto the country from the sky. The ball can come to rest in any valley. Which valley the ball rests in is a fact about where the ball fell, and not a fact about the shape of the country.

Empty space, too, settles into a state: the state with the least energy that empty space can have nearby, as the ball settles at the bottom of a valley. Physicists call the settled state of empty space a *vacuum*, and each valley of the picture stands for one vacuum. In string theory, the world has ten dimensions: one of time, three of space, and six more, curled up far too small to see. Call the six extra dimensions the six small curled dimensions, or simply 'the six'. In string theory, the six have holes in their shape, as a ring has a hole through it. A *field* is something spread through space with a value at every point, and a field can wind through each hole of the six a whole number of times: once, twice, three times, and so on. Physicists call the number of times a field winds through one hole a *winding number*. Each set of winding numbers gives a different valley. Physicists estimate the number of valleys at ten to the five hundred, a one followed by five hundred zeros, or more. In string theory, our world is one valley among the many, and string theory contains no principle that fixes which valley we live in.

I also have ten dimensions, with six curled small, and on my account each count of dimensions comes from the structure of comparison. The six of my account have *one* valley.

The first reason is that no field winds through the six of my account: in my account, gravity comes from the geometry of space and time alone, so my account has no field that could wind through the six. When no field winds through the six, there are no winding numbers to choose among. The six of my account carry whole numbers of one kind only: counts of the shape of the six. No smooth stretching can change a count of a shape, just as no stretching changes the number of holes in a ring, so each count of the shape of the six has one value.

The second reason is that the shape of the six is found twice, by two separate routes. Picture two walkers who set out from different towns and reach the same summit by different roads. Neither walker chose the summit from a list. In the same way, two routes that start from different premises arrive at one and the same shape for the six. One route is set out, and the other route in another. On neither route is the shape picked from a list of candidates. So there is no range of shapes for a landscape to spread over.

The six have one shape and one valley, so the energy of empty space has one value. There is no spread of valleys from which to choose the value. The *cosmological constant* is the energy of empty space as gravity feels the energy. I set out the identification in Chapter Four. I derive the value of the cosmological constant. The derived value agrees with the measured value to within about two percent. For this chapter, one fact about the derivation matters: no selection among universes took part in the derivation.

One Beginning for the Whole Sky

The whole sky comes from one beginning. My account has no eternal inflation, and so no bubble universes, just as the six small dimensions of my account have no landscape of valleys. Physicists proposed inflation to

explain several puzzles. One puzzle is why regions of the sky that no signal could ever have joined have one and the same temperature. I answer the temperature puzzle without inflation, from how our history began. The regions of the sky have the same temperature because all the regions come from one beginning, in the same way that two towns founded by settlers from one place can share an accent although the people of the two towns have never spoken to each other. The shared accent is like the shared temperature, and the one place the settlers came from is like the one beginning. I describe the beginning in Chapter Eleven. I also answer, without inflation, the other puzzles that inflation was introduced to solve.

I take one more step, using an identification that I make in Chapter Eleven. The oldest light in the sky has faint differences, slightly warmer in one place and slightly cooler in another. I identify the faint differences with a pattern carried over, averaged together, from the epoch before ours (an *epoch* is one whole span of the universe's history, and our epoch is the span that began at the Big Bang). Suppose a burst of inflation had lasted long enough to stretch out the lengths we observe today: then the burst itself would have made the faint differences, out of the trembling of empty space as space inflated. So, with the identification, I exclude a long burst of inflation. Endless inflation would be the longest burst of all, and endless inflation is also the kind of inflation that would bud off other universes. So endless inflation does not happen, and no other universes bud off.

One World, Compared from Inside

Hossenfelder holds that science can settle neither answer to the question of whether the other universes are real (*Existential Physics*, chapter 5, "The MultiWorse"). In her view, a statement that the other universes are real is ascientific, and so is a statement that the other universes are not real. I answer the question from the structure of comparison. Every comparison is made from somewhere inside a world: something that is there sets one thing beside another. Suppose someone wanted to lay out a col-

lection of whole universes side by side, each universe with its own settings: the person would have to stand where every universe could be seen at once, outside all of the universes. No comparison is made from outside every universe, because every comparison is made from inside a world. So it follows from the structure of comparison that there is one world, and that the constants of the world are fixed. A collection of other worlds could be laid out only from a place where no comparison can be made.

No one could ever find, by comparison, the other universes of the string landscape or of eternal inflation. So the other universes of both kinds are not real. The other universes have no place in the structure of my account either, because the structure of comparison allows one shape, one valley and no long inflation, and no other universes. The other universes exist as the mathematics of string theory, in the way the perfect circle exists.

The Far Regions of Our Own Universe

Hossenfelder writes of what lies beyond what we can observe: "Science doesn't say anything about whether it exists or doesn't exist" (*Existential Physics*, chapter 5, "The MultiWorse"). Some parts of our own universe lie beyond what we can see now, and some parts lie beyond what we can ever see. Some regions of space lie beyond the particle horizon, the edge of everything whose light has reached us so far, and some regions lie even beyond our *event horizon*, because the expansion of space is speeding up. Our event horizon is the boundary past which no event, now or at any later time, can ever send us a signal, and I call the regions beyond our horizons the *far regions*. Think of villages along a very long road. Each village trades with the villages next to it. No one walks the whole road, and no goods from the far end of the road ever reach our village. The far villages are still villages on the same road.

The far regions are what the villages show: parts of the one arena, related to their own neighbors as our region is to ours. The 'arena' is the one space and time that holds the far regions and our region. Each region in-

teracts with the regions next to it, as each village trades with the villages next to it, and so the far regions belong to our one world and are not another universe. Comparisons happen in the far regions all the time, wherever one thing there interacts with another, and so, wherever a comparison happens in the far regions, the far regions are real.

The Many Worlds of Quantum Theory

The many worlds of quantum theory are a multiverse too. The Incommensuration Theorem shows that the other worlds of the many-worlds account are not real. The many-worlds account describes a whole world fixed completely by one law, with every outcome of every measurement happening in some *branch* of the world, where a branch is one of the many worlds. A world fixed completely by one law needs two things, both perfect, at once. First, the same law must carry every state into the next state, everywhere and always. The sameness of the law everywhere and always is symmetry perfected. Second, every state must be fixed at every point, so that each state passes into the next state with nothing unfixed between the two states: a passage with no gap is continuity perfected. Perfect continuity is the continuity of the settling beam of Chapter Two, which passes through every position with no jump. The settling beam is the beam of the balance swinging toward rest. Perfect continuity holds without exception, so the law leaves no gap anywhere. A whole world completely fixed by a law perfects symmetry and continuity together, whichever account describes it, and the theorem forbids that pairing. So, when the many-worlds account is taken as an account of a whole world, the Incommensuration Theorem excludes the many-worlds account. The other branches exist as structure in the mathematics of the many-worlds account, but no one ever finds the other branches by comparison, and so the other branches are not real.

Hossenfelder finds that the many-worlds account makes the same predictions as the standard interpretation of quantum theory (*Existential Physics*, chapter 5, "Many Worlds"). The 'standard interpretation' is the

interpretation that most textbooks teach: the quantum description gives the odds of each result, and one result is found. I set the many-worlds account beside my account, and the two accounts differ on whether the other branches are there, a difference that no measurement can detect. So my reason for excluding the other branches is the structure of comparison, and no experiment.

One Form, and a Reason for Every Number

I answer Carter directly with one more result of my account. I show that the form of physics could not have been otherwise. The form of physics includes the kinds of force and the shape of the six. The universe has the form it has because any form that supports comparison must have this form, not because observers must exist, but because comparison must be self-consistent and there is exactly one self-consistent comparison structure. The anthropic principle is a selection effect. A *selection effect* is an explanation of what we see by what our being here lets us see. My result is of another kind: there is exactly one self-consistent structure of comparison, and so one form of physics.

I also hold that every pure number among the particles has a reason. A *brute constant* is a number with no reason. No pure number among the particles is a brute constant. Each pure number among the particles has a reason of one of two kinds: either a law fixes the value of the number, or a proof shows that no law fixes the value of the number. The strength of light has a reason of the second kind, from the row of worlds. A number whose reason is not yet found carries one question: which of the two kinds of reason does the number have? Hossenfelder concludes that there is nothing in need of explanation, because no unlikelihood can be measured. On my account, each number has a reason, and finding the reason means answering one question, which has two possible answers: a law that fixes the number, or a proof that no law fixes the number. No probability is part of the question.

I first gave the name in Chapter Four. I hold that a value that lands "is a question, and it is evidence of a reason not yet known". Hossenfelder's slip of paper is drawn once from the bag, so the slip tells us nothing about what else is in the bag. I ask a different question of the slip: which law fixes the number written on the slip, or what proof shows that no law fixes the number?

What String Theory Found

In string theory, each point-like particle is replaced by a tiny vibrating string, and each kind of particle is one way the string can vibrate. I give the findings of string theory first, and only then name where the landscape comes from. *Quanta* are separate pieces, each exactly like the others. The founding discovery of string theory was that string theories, in their consistent forms, describe gravity by quanta: the particle of gravity is one of the ways the string vibrates.

In 1996 Andrew Strominger and Cumrun Vafa used string theory to count the hidden states of a class of idealized black holes. Earlier, Jacob Bekenstein and Stephen Hawking had given each black hole an *entropy*, set by the area of the black hole's surface. The entropy of a black hole is a count of the states inside the black hole that no comparison from outside can tell apart. The count by Strominger and Vafa matched the entropy of Bekenstein and Hawking exactly. I call the founding discovery of string theory and the count by Strominger and Vafa "two of the most striking results in modern physics".

Another result of string theory is a match between gravity inside a region of space and a quantum theory on the boundary of the region, and Hossenfelder calls the match the biggest breakthrough in the foundations of physics in recent decades. I describe the match as two exact descriptions of one system, joined by a dictionary that translates each description into the other: this is correspondence, not emergence. 'Emergence' would mean that one description arises out of the other description, while 'correspondence' means that each description translates exactly into the other.

Then I name where the landscape comes from: the first step of string theory is to begin from quanta and to build space and time, the arena in which everything happens, out of quanta. Picture trying to build a smooth hillside out of identical bricks. However the bricks are stacked, the bricks make steps, and countless different stackings look alike from far away. The bricks are like the quanta, and the smooth hillside is like the smooth arena of space and time. The countless stackings that look alike are like the many possible worlds.

A discrete starting point, however rich, has fixed no single smooth world; that is what multiplicity means. The many valleys of the string landscape are the difficulty predicted by the first step of string theory, which is building space and time out of quanta. The Incommensuration Theorem shows why building space and time out of quanta gives many valleys. Quanta have the character of 'sameness with gaps': each piece is exactly like the others, and there is a gap between one piece and the next. The arena of space and time has the character of 'smoothness': no gaps anywhere. Suppose one description built the smooth arena exactly out of identical quanta. The description would have to carry both characters together, both perfect: the sameness of the pieces, which is symmetry, and the smoothness of the whole, which is continuity. The Incommensuration Theorem excludes perfect symmetry and perfect continuity together in any event or comparison. I quoted the statement of the theorem earlier in this chapter. In mathematics, the two characters can be written down together, as the perfect circle is written down, but then, as with the circle, the mathematics describes no world that anyone could find by comparison.

I describe a different line of research, one that starts the other way round, and I call the line of research 'the different line': researchers on the different line follow three rules. First, gravity stays the arena, the space and time in which everything happens. Second, no single description is asked to carry both characters. Third, space and time are never treated as made of quanta, because quanta would give space and time a smallest step.

I name three difficulties. Each difficulty comes from a different first step, and in the next paragraphs I show that the different line, which takes none of the three first steps, has none of the three difficulties.

The first difficulty is many possible worlds, with no principle that fixes which world is ours, and the first difficulty comes from starting with pieces and building the smooth arena out of the pieces, as the bricks stacked into a hillside showed.

The second difficulty is an equation of change that does not give back the changing world, and the second difficulty comes from starting with the smooth arena and dividing the arena directly into quanta. Change is described against the arena, the way a ledger records each sum against a date in the margin of the ledger. Make the dates into entries of the ledger, and the ledger still holds every number but no longer says which entry came first. In the picture, the margin of dates is the arena, and making the dates into entries is dividing the arena into quanta.

The third difficulty is the need for a further principle, and the third difficulty comes from giving up one of the two characters, smoothness or sameness with gaps, and hoping to rebuild the lost character from the other character. Square tiles can come close to a circle, but nothing in the tiles says that a circle is wanted, so something besides the tiles has to say that a circle is wanted, and that something is the further principle.

Researchers on the different line take none of the three first steps, so the research on the different line has none of the three difficulties, and the research on the different line has no landscape, because the string landscape is the first difficulty. My account is research on the different line. So the string landscape comes from one particular first step: the attempt to build space and time out of quanta. The Incommensuration Theorem excludes building space and time exactly out of quanta. Hossenfelder sees the landscape as one case of a general pattern: any theory that lacks input from observation leads to a multiverse.

On beauty, Hossenfelder and I agree: beauty, like symmetry or economy, is a property of a mathematical description, and a property of a description is no evidence about the world the description describes.

A Test Kept in Its Place

Can Popper's test apply to a question about universes that no one can ever reach? I keep Popper's test and state where the test applies: a test can settle something only where the outcome of the test can be compared again, by another person, at another time, and along another route.

When four conditions are true of an outcome, I call the outcome *objective*, as I do. First, the outcome comes from an actual comparison. Second, the outcome can be compared again in each of the three ways: by another person, at another time, and along another route. Third, every finding from the repeated comparisons is consistent with the other findings. Fourth, the outcome could have come out against what was expected. A test applies exactly where the outcome of a comparison can be objective, and nowhere else. Where an outcome can be objective, the test "is a valid and powerful tool".

Popper's test cannot apply to an 'unreachable' universe: a universe that no one could ever find by comparison. A test needs an outcome to compare, and an unreachable universe gives no outcome, so no test can confirm an unreachable universe, and no test can rule an unreachable universe out. My answer about the other universes rests on the structure of comparison, because no test can apply to an unreachable universe. I keep Popper's test for the claims I make about the world. Appendix A, "What the Coming Measurements Will Find", states what each coming measurement will measure and what I say each measurement will find.

I also name three ways in which anything can be validated: measurement, agreement among people, and proof. Measurement and proof validate truth, while agreement among people does not: agreement among people validates nothing by itself. *Only* measurement and proof can show whether a theory is true. Physicists sometimes lose interest in a theory, as

Hossenfelder describes, and losing interest is a change in the physicists. The theory is exactly as true, or as false, as the theory was before the physicists lost interest. I discuss the three ways of validation in full in Chapter Fourteen.

What Can Be Set on the Pan

Come back to the two-pan balance of the earlier chapters: a beam rests on a pivot, with a pan hung from each end. You set a thing in one pan and known weights in the other, and the beam tips toward the heavier pan, or stays level.

In this chapter, the balance shows one more step. A thing can be weighed *only* if the thing can be set on a pan of this world. Every interaction that leaves a mark is a comparison, even when no one watches the interaction. In Chapter Six, a print left in sand will show an interaction that leaves a mark with no one watching. The far regions beyond our horizons interact with neighboring regions all the time, so the far regions are weighed all the time, on the pans of their own neighborhoods, and the far regions belong to this world. Suppose a universe can never be set beside anything in our universe. Then no weighing of the universe gives any result at all.

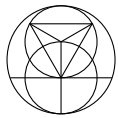
Hossenfelder also offers a thought about creation, and I answer her thought, too, with the rule that a thing can be weighed only if the thing can be set on a pan of this world. Hossenfelder allows that one could place a moment of creation at "a moment at which the math becomes real", a suggestion she makes in *Existential Physics*, in the brief answer that closes her interview with Tim Palmer, "Is Math All There Is?". I keep the two words 'exist' and 'real' apart, as the kitchen calendar and the morning showed earlier in this chapter. A law exists; a measurement is real.

So the pattern of the law stands as structure. What is real is each weighing, made now, in which the pattern is found. Mathematics does not turn into the world at some first moment.

Carter's two ideas now each have an answer, and so does the question of the numbers of our world. First, the anthropic principle is a true limit on what we can find, and the anthropic principle explains no constant. Second, Carter's world ensemble has no range of universes from which the members of the ensemble could be made. There is one shape, one valley and one world. Third, each number of our one world has a reason: a law that fixes the number, or a proof that no law fixes the number. Where neither reason is yet found, the number carries one question: which of the two reasons does the number have? There is one world, so every question in the chapters ahead is a question about this world: a question about what happens in this world, or about what we find when we compare.

The short answer: There is one world, with one form and one settled state of empty space. The structure of comparison fixes the form of the world. I call on no designer and on no multiverse to explain any constant.

Since there is one world, what happens in the one world when a quantum system is measured?



Chapter Six

What Happens When a Quantum System Is Measured?

What this chapter uses

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 Two).

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

The *content* of a comparison is what the verdict of the comparison is about, and the *context* is the respect in which the two things compared are two (Chapter Three).

There is one world, with one settled state of empty space; the other universes of the landscape and of eternal inflation are not real (Chapter Five).

What does a measurement do? Sabine Hossenfelder reports three things about quantum mechanics, the physics of atoms and light. Quantum mechanics works, and nobody likes quantum mechanics. Physicists have several explanations of what the mathematics of quantum mechanics means. A physicist she interviews calls the choice among the

explanations "an aesthetic choice". Quantum mechanics is right every time, so you may ask what is left to understand about the moment when something is measured.

A Cat in a Steel Chamber

On 29 November 1935 the weekly journal *Die Naturwissenschaften* printed the first part of a long paper by Erwin Schrödinger, writing from Oxford. The title of the paper was "Die gegenwärtige Situation in der Quantenmechanik", "The Present Situation in Quantum Mechanics". Schrödinger was one of the founders of quantum mechanics: in 1926 Schrödinger had written down the equation that tells how the quantum description of a system changes in time, and the equation still bears Schrödinger's name. Earlier in 1935, Albert Einstein, Boris Podolsky and Nathan Rosen had published a paper. In the paper, the three authors doubted that quantum mechanics gives a complete description of the world. Schrödinger's paper cites the paper of Einstein, Podolsky and Rosen.

Schrödinger set out a picture in the fifth section of his paper, under the heading "Are the Variables Really Blurred?". A cat is shut in a steel chamber. Beside the cat is a 'Geiger counter', a tube that clicks when a single atom breaks apart. A tiny amount of radioactive material sits with the counter, and the atoms of the radioactive material break apart now and then, each atom at a moment no one can foretell. When an atom breaks apart, physicists say that the atom 'decays'. John Trimmer translated Schrödinger's paper into English in 1980. Trimmer's translation says that the amount of radioactive material is chosen "so small, that perhaps in the course of one hour one of the atoms decays": the hour is just as likely to pass with no atom decaying. If an atom does decay, the counter fires, a hammer falls, and a small flask of poison breaks.

Leave the cat, the counter and the radioactive material alone in the chamber for an hour, and ask what the quantum description of the chamber says. Schrödinger answered that the description of the whole system would have in it

> the living and the dead cat (pardon the expression) mixed or smeared out in equal parts.
>
> (Erwin Schrödinger, "The Present Situation in Quantum Mechanics", 1935, section 5, "Are the Variables Really Blurred?", translated by John D. Trimmer)

Schrödinger introduced the cat as one of the "quite ridiculous cases" that anyone can set up in quantum mechanics. Schrödinger's point was that, in quantum mechanics, an uncertainty at the scale of atoms passes up to the scale of a thing you can see. Schrödinger wrote: "It is typical of these cases that an indeterminacy originally restricted to the atomic domain becomes transformed into macroscopic indeterminacy, which can then be resolved by direct observation". You open the chamber, and the cat is alive, or the cat is dead. Schrödinger added that, because one look settles whether the cat is alive or dead, the case of the cat "prevents us from so naively accepting as valid a 'blurred model' for representing reality". Schrödinger said that a blurred photograph of a sharp thing is a different thing from a sharp snapshot of a bank of fog. In the picture, the cat that one look finds is the sharp thing. The smear in the quantum description is the blur of the photograph.

The cat puts the question of this chapter in its plainest form. Follow the description of the world forward in time by Schrödinger's own equation, and the description gives a smear, the living cat and the dead cat mixed, but when anyone looks, the world gives one outcome: one cat, alive or dead. What happens between the smear and the one outcome, when the measurement is made?

From Hossenfelder's pages

What Sabine Hossenfelder Showed

Sabine Hossenfelder starts from the success of quantum mechanics, and she states the success at its full strength.

> Quantum mechanics has been right, right, and right again. But despite this, or maybe because of this, nobody likes it.
>
> (*Lost in Math*, chapter 6, "Everything Is Amazing and Nobody's Happy")

Hossenfelder is right about the success of quantum mechanics: no experiment has ever contradicted the predictions of quantum mechanics.

Hossenfelder explains what a measurement is in a few plain steps. In quantum mechanics, a piece of mathematics called the *wave function* describes each system. Physicists compute the odds of each possible result from the wave function, but no one ever observes the wave function itself. When someone measures a system and gets one result, we "have to update the wave function", as Hossenfelder puts it, so that the result found has odds of one in one. Physicists call the change in the wave function the *measurement update*, and physicists also call the measurement update 'collapse' or 'reduction'. Hossenfelder chooses among the words 'collapse', 'update' and 'reduction' with care:

> (*Existential Physics*, chapter 1, "Eternal Information")

Hossenfelder also says who, or what, does the measuring. A small thing, such as an atom, has different possibilities. The possibilities of a small thing combine with one another. Physicists call the effects by which the possibilities combine the 'quantum behavior' of the thing. Large objects, such as cats, do not show quantum behavior in everyday life, because the surroundings of a large object destroy the

quantum behavior too quickly. Hossenfelder writes that a measurement is "any interaction that is sufficiently strong or frequent to destroy the quantum behavior of a system". Physicists calculate how quickly the surroundings of a system destroy the quantum behavior of the system. Hossenfelder writes of the calculations: "Most important, these calculations show that a measurement in quantum mechanics does not require a conscious observer" (*Existential Physics*, chapter 1, "Eternal Information"). A stray molecule of air can do the measuring.

Hossenfelder gives the reason why no one ever finds a cat that is both alive and dead: the quantum behavior of a thing fades as the surroundings of the thing keep touching the thing. Physicists call the fading *decoherence*. A cat is warm and wiggling, and the surroundings of the cat always touch the cat. The touches scramble the 'quantum links' between the parts of the cat. The quantum links are the links by which the possibilities of the parts combine with one another. The touches scramble the quantum links so quickly that the cat behaves as an ordinary object. Hossenfelder writes: "The cat isn't both dead and alive; there's just a 50 percent probability that it's dead". Hossenfelder is exact about how much decoherence explains:

> But decoherence does not explain how after measurement the probability distribution updates to a distribution that has a probability of 1 for what we observed. So decoherence solves part of the riddle, but not all of it.
>
> (*Lost in Math*, chapter 6, "Everything Is Amazing and Nobody's Happy")

Hossenfelder also argues that quantum mechanics is less strange than quantum mechanics is often said to be. Add two possible states of Schrödinger's equation together, and the equation gives a new state, which physicists call a *superposition*. Schrödinger's description of the chamber is a superposition: the living cat and the dead cat, added to-

gether. Hossenfelder writes: “And that’s what a superposition is: A sum. That’s it” (*Existential Physics*, chapter 5, “Many Worlds”). In the same section she writes: “But I want you to know that much of the supposed weirdness of quantum mechanics just comes from forcing it into everyday language”.

Hossenfelder describes a link between two particles that once met: when the two particles are measured, their results agree more closely than any ordinary link allows, however far apart the particles are. The link is called *entanglement*. When the agreement of a link holds between places far apart, Hossenfelder calls the link ‘nonlocal’, while a link made in one place, where the two particles meet, is ‘created locally’. Hossenfelder writes: “While entanglement is indeed nonlocal, it is still created locally” (*Existential Physics*, chapter 8, “Size Matters”). Nobody can use the link to send a message, and in the same section Hossenfelder gives the reason: “However, no information can be sent with this measurement, because the outcome is random”. In *Lost in Math*, Hossenfelder tells of an experiment made in the Canary Islands in the summer of 2008. The group of Anton Zeilinger made linked pairs of ‘photons’, particles of light, on La Palma, and the group sent one photon from each linked pair to a receiver on Tenerife, 144 kilometers away. The agreement between the results held.

An *interpretation* of quantum mechanics is an explanation of what the mathematics of quantum mechanics means: what the wave function is, and what happens in a measurement. The best known interpretation is the *Copenhagen interpretation*. Hossenfelder notes that the Copenhagen interpretation is also called the ‘standard’ interpretation, because the Copenhagen interpretation is the one most commonly taught. In the Copenhagen interpretation, the wave function is a tool for computing the odds of results. A second interpretation is the *many-worlds interpretation*, in which there is no update at all. Every possible result happens, each result in its own branch of the world. A third interpretation is the ‘pilot wave’. In the pilot wave, each particle

follows one definite path, and the wave function guides the particle along the path. Hossenfelder reports a judgment of the physicist Chad Orzel: no one can at present name an experiment that would give one result for one interpretation and a different result for another interpretation. For his example, Orzel compares the many-worlds interpretation with the pilot wave, and Orzel concludes: "And in the absence of this it's an aesthetic choice" (*Lost in Math*, chapter 6, "Quantum Mechanics Is Magic"). Chapter 6 of *Lost in Math* ends with an "In Brief" box, in which Hossenfelder adds: "In the foundations of quantum mechanics too, it is unclear what is the actual problem that requires a solution". Hossenfelder also holds a view about what is real. In her view, different mathematics can describe the same observations: one theory can be written in several formulations. So Hossenfelder concludes that "we can't assign 'reality' to any particular formulation of a theory" (*Existential Physics*, chapter 3, "Brains. In Empty Space").

Hossenfelder also says what she expects of the measurement update:

> (*Existential Physics*, chapter 1, "Eternal Information")

'Deterministic' means fixed in every detail by what came before. 'Time-reversible' means able to run backward as well as forward. No physical process lies beneath the measurement update.

I find the word collapse misleading because it suggests a physical process that quantum mechanics doesn't contain, so I will stick with update or reduction. I myself think it's likely the measurement update will one day be replaced by a physical process in an underlying theory, and it might come out to be both deterministic and time-reversible again. I hold a different view: the measurement update is a change in what has been found.

A Mark Left Where No One Is Watching

Imagine a hoof pressing into wet sand at the edge of a beach. The sand takes the shape of the hoof and not another shape. Hours later someone walks by and reads the print: a horse went this way.

The print in the sand comes from two events, and each event is a comparison: the act this book began with, setting one thing beside another and finding how the two stand. In the first event, the hoof was set against the sand. The sand took one shape out of all the shapes the sand could have taken. By taking one shape, the sand registered how the hoof and the sand stood. The sand is matter, and at the moment the hoof pressed, the sand found a sameness or a difference, with no one present, so the sand's taking one shape is a comparison. The second event came hours later: someone read the print. Reading the print is a second comparison, made on the record that the first comparison left: the print. The first event did not wait for the second event.

I derive quantum mechanics from the act of comparison, in plain words. I say what counts as a finding in exactly the terms of the print in the sand, and define a *finding* as any comparison that lays down a record. A finding is an interaction after which some part of the world carries a record of the outcome. A 'comparer' is whatever makes a comparison. The finding is made by the comparer that finds, the screen or the counter, as an interaction, and no mind is needed. The comparer is a role, and that a mind, an instrument or a thermostat can fill the role.

A fact of physics is the ground for the claim that no mind is needed. In 1932 the mathematician John von Neumann studied the chain of instruments that runs from a measured system to a final record. Von Neumann showed that the line between the measured system and the instruments can be drawn at any link of the chain, and that wherever the line is drawn, every predicted count comes out the same. So nothing special happens at the last link, where a person looks. What makes an interaction a finding is that the interaction lays down a record, and nothing else.

Hossenfelder reaches the same result as my account: a measurement needs no conscious observer. Hossenfelder's ground is the calculation of how quickly the surroundings of a system destroy the quantum behavior of the system, while the ground of my account is the structure of comparison itself: what every comparison must contain. Every finding is an act of comparison, and any interaction that lays down a record is a finding. So two routes, from two starting points, arrive at one result.

The two-pan balance of the earlier chapters now pictures one more step of this chapter's answer. Picture a balance left alone overnight in a locked shop: a small pen sits on the end of the pointer of the balance, and the pen rests on a strip of paper. Late in the evening, someone sets a parcel in one pan and weights in the other pan. The shop is locked before the beam has settled. During the night the beam settles and tips. In the morning the mark is on the paper, whether or not anyone watched the beam move. The beam tips and leaves a mark whether or not anyone watches, so what the beam shows is a record.

I use the same picture of a balance, with an apple on each pan, to show the parts of every comparison. The Preface pictured, and Chapter Three set out, one way to divide every comparison: into the content of the comparison and the context of the comparison. The 'content' is what the result of the comparison is about, such as how heavy the things in the pans are. The 'context' is the setting of the comparison: on the balance, the two pans, the beam that joins the pans, the floor and the room that hold the pans, and the moment of the weighing. I also divide every comparison in a second way, separate from content and context: every comparison has a side from which the comparison is made and a side about which the comparison is made. On the balance, the side about which the weighing is made is the apples. The side from which the weighing is made is the instrument itself, together with whoever reads the instrument. I call the side from which the weighing is made "the balance and whoever reads it". On the side from which the weighing is made, the instrument alone is enough: in the locked shop, the beam tips and the pen marks the paper with no one there to read the mark.

What the Surroundings Do

The surroundings of a thing keep leaving marks too, as the pen in the locked shop does. In 2003 a group in Vienna worked with molecules of 'carbon seventy', each molecule a closed cage of seventy carbon atoms. The Vienna group was Klaus Hornberger, Markus Arndt, Anton Zeilinger and their colleagues. The Vienna group sent the molecules through an instrument that splits a beam into paths and brings the paths back together. When two possible paths combine, a striped pattern appears, and physicists call the striped pattern *interference*. The Vienna group pumped a chamber nearly empty of gas, and in the chamber the molecules built up bands of interference. Then the Vienna group let a little gas into the chamber, and as the pressure rose, the bands faded. Molecules of gas struck some of the cages. Each molecule of gas that struck a cage carried away a trace of which path the cage had taken. The Vienna experiment shows that decoherence happens, and other experiments like the Vienna experiment show the same. The experiments also show that decoherence works as quantum mechanics says decoherence works.

I give decoherence a plain picture: think of the surroundings of a system as a notebook that each possibility of the system writes in. If two possibilities leave the notebook exactly the same, then nothing records which possibility happened, and the two possibilities keep their interference in full. If instead the two possibilities leave two notebooks that differ on every page, then no measurement of the system alone can show any interference between the two possibilities. A cat is warm and breathes, and light and air strike the cat every instant, so the living cat and the dead cat leave two notebooks in which countless pages differ at once.

I then reach Hossenfelder's result on decoherence, in the words "Decoherence stops short of one outcome": decoherence alone does not explain how a measurement comes to one result. Schrödinger's cat has a living possibility and a dead possibility, and the two possibilities stop interfering long before anyone opens the chamber. From then on, each possibility carries its own record, written into the air, the light and the walls of the

chamber. The finding made when the chamber is opened determines which of the two records the opened chamber will show. So decoherence prepares the measurement, and the act of comparison completes the measurement, with one outcome.

I reach two more of Hossenfelder's results, on ground separate from hers. One result is about the strangeness of quantum mechanics, and the other result is about entanglement. Hossenfelder says that much of the strangeness of quantum mechanics comes from forcing the mathematics of quantum mechanics into everyday words. I reach the same result. I find the cause of the strangeness one step before the words: in the 'classical picture' from which the everyday words are taken.

Start from the classical picture, in which each thing has a definite position and a definite speed, each path is fixed in advance, and each cause acts only where the cause is. Then look at the world, and find that the world does not behave as the classical picture says: the result is surprise. The weirdness is an artifact of the starting point, and not a feature of quantum mechanics. The surprise is a fact about the expectations that the classical starting point produces. I start instead from the act of comparison, and show, chapter by chapter, that superposition, entanglement and the odds of outcomes each follow from the act of comparison. For someone who starts from comparison, nothing in superposition, entanglement or the odds is left to surprise.

Entanglement is one example: entanglement is no surprise for someone who starts from comparison. If two particles meet and interact directly, while each particle still shows quantum behavior, then the states of the two particles become linked: the two particles are entangled. Hossenfelder's words "created locally" describe entanglement made when two particles meet. I reach the same result from the fact that an interaction is a comparison. After the two particles part, the results measured at each place, taken alone, are random, while the agreement between the results appears only when someone brings the two records together, by signals that travel no faster than light. Nothing passes between the two places to make the agreement, so nothing can carry a message from one

place to the other. Here again, Hossenfelder reaches the same result as my account: entanglement is a link made by meeting, and the link carries no signal.

What Changes When the Outcome Is Found

Hossenfelder expects the measurement update to be replaced one day by a physical process. I hold that the measurement update is a change in what has been found, the same for everyone who has the outcome, and that no process lies beneath the measurement update.

Picture a weather forecast. The forecast is smooth: a seventy percent chance of rain at noon, falling to forty percent by evening. What you find when you go outside comes in steps: rain falls on you, or rain does not fall on you. Once you are wet, nobody rewrites the clouds: finding the rain changes nothing in the sky. What changes is what has been found, and so what the next forecast starts from changes too.

The *quantum state* is another name for the wave function of Hossenfelder's explanation, and the quantum state is like the forecast in one respect and unlike the forecast in another respect. Like the forecast, the quantum state is smooth and gives odds. Unlike the forecast, the quantum state cannot be sharpened by further knowledge, because there is no hidden state underneath the quantum state.

I state what the measurement update is: when a measurement is made, a comparison has occurred, and the result of the comparison now belongs to the record of the system. The 'record of the system' is what has been found about the system, laid out for anyone who has the outcome, and the measurement update is a change in the record of the system. In that plain-words book I am exact about the sense in which the measurement update is a change in what is known. What changes is the laid-out record, "which is shared, and the same for everyone who has the outcome", and not one person's 'degree of belief', that is, one person's private confidence in one

result or another. A 'law of motion' is a rule for how things change in time. The measurement update is neither a physical process nor an extra law of motion added to quantum mechanics.

Why does the measurement update look like a physical process to so many people? The usual framework of quantum mechanics is narrower than my account. The usual framework has only the states of a system and the rules for changing the states. Inside the usual framework, the step from many possibilities to one result can only be written as a change of state. The name for the change of state is 'collapse'. The collapse is a feature of the usual framework. Hossenfelder declines the word 'collapse', because the word suggests a physical process that quantum mechanics does not contain. So Hossenfelder already treats the measurement update as no physical process, within quantum mechanics as quantum mechanics stands today.

Why is the outcome a matter of chance at all? Look again at the counter in Schrödinger's chamber. Quantum mechanics gives the odds that one atom of the radioactive material breaks apart within the hour, but the counter clicks at a moment that nothing in the quantum description fixed. I find the reason for the chance in the Incommensuration Theorem, which Chapter Two set out. 'Symmetry' is being the same under every change of place or setting. A description that fixed every finding exactly would need two things at once. First, the description would need one law that carries every state into the next state, the same everywhere and at every time: symmetry made perfect. Second, the description would need every state fixed at every point, with no gap anywhere in what the law fixes: continuity made perfect. The first clause of the Incommensuration Theorem means that perfect symmetry and perfect continuity cannot hold together, so in every 'lawful' description (every description that has a law), something is left over that the law of the description does not fix. In Schrödinger's chamber, the moment of the click is what is left over. The fate of the cat is left over with the moment of the click. The chance of the outcome belongs to comparison itself. There is no hidden layer beneath the quantum state, so no hidden layer can remove the chance.

The Incommensuration Theorem also sets a limit on how close any description can come to a finding: the smooth mathematics of quantum mechanics comes as close to each finding as any measurement can resolve, but the smooth mathematics never contains the finding itself. The Incommensuration Theorem guarantees the gap between the continuous description and the definite finding, and no future theory removes that gap.

A finding also runs one way: from many possibilities to one result, and never back. Hossenfelder states herself that the measurement update runs one way: once a particle has been measured, she writes, "we cannot infer what the wave function was prior to measurement" (*Existential Physics*, chapter 1, "Eternal Information"). I give the reason, using the cat. Before the chamber is opened, there are two possibilities, a living cat and a dead cat, but the opening of the chamber is one act, and the one act gives one cat. Each act like the opening of the chamber leaves its mark, and many of the acts add up to one record. In the same way, the pen in the locked shop leaves its marks night after night. The marks add up to one strip of paper. If the step from the two possibilities to the one cat ran backward, the step would go from the one record to the many possibilities: from the one cat found back to both cats. The backward step can be written down, as a relation between the record and the possibilities, but no act of comparison runs backward, because every act of comparison ends in one result. So the passage from possibility to result cannot be undone.

So, I hold three things about the measurement update. First, the measurement update is the change of the shared record when a comparison has occurred. Third, a finding runs one way.

The Problem, Named Exactly

Hossenfelder writes that it is unclear what problem in the foundations of quantum mechanics needs solving. I name the problem: two different things go by the one name 'the measurement problem'.

The first thing called ‘the measurement problem’ is a clash among the textbook rules of quantum mechanics. One rule says that a system left to itself changes smoothly, so that a sum of possibilities stays a sum, while another rule says that a measurement makes the state jump to one result. Apply the first rule to the atom, the counter and the cat together, and you get Schrödinger’s smeared cat. Apply the second rule, and you get one cat.

I show where the clash came from. The rules of quantum mechanics came from six separate traditions, of mathematics and of physics, over about twenty-five years, from 1906 to 1932, with refinements in 1935 and 1951. Physicists kept the rules together because the rules predict the right answers. But the rules were assembled from the six traditions, and no one ever derived the rules from one starting point. The measurement problem is the scar left by that assembly. I derive the same rules from one source, the act of comparison, and when the rules are derived from the act of comparison, each rule turns out to describe a different thing. The rule of smooth change describes the range of what is possible before any finding, while the ‘jump’ is the act of finding itself. The two rules are said of two different things, so the two rules do not clash.

The second thing called ‘the measurement problem’ is the gap between a smooth description and a finding that comes in a step. I described the gap in the section before this one, “What Changes When the Outcome Is Found”: the smooth mathematics comes as close to each finding as any measurement can resolve, and never contains the finding itself. The gap is no contradiction. The rule for the odds is the rule by which physicists compute the odds of each result from the wave function. The rule for the odds applies at the gap: from the smooth description, the rule for the odds determines how often each finding comes.

Now each interpretation of quantum mechanics can be placed, by the part of a comparison that is missing from the interpretation. Picture a three-legged stool. Saw off one leg, and the stool tips over, toward the place where the missing leg stood. Show someone a fallen stool, and the person can tell from the direction of the fall which leg is gone.

Every comparison stands on three legs of its own: every comparison has three parts, as the stool has three legs. The first leg is the 'act of finding', here and now. The second leg is the 'record' that the act lays down, which anyone can read. The third leg is the place from which the question is asked, with the range of possible answers to the question. In Schrödinger's chamber, the act is the opening of the chamber. The record is the cat as found, with every mark the cat leaves. The place from which the question is asked is the chamber as set up, with the atom, the counter, the flask and the two outcomes the chamber allows. Each leg stands only together with the other two legs, and no leg can do the work of another leg. I sort each interpretation by the leg missing from the interpretation, and find the known difficulty of each interpretation exactly where the missing leg belongs. In the same way, the direction in which a stool falls shows which leg is gone.

Two interpretations show the pattern: the Copenhagen interpretation and the many-worlds interpretation. The Copenhagen interpretation includes the act and the record. In the Copenhagen interpretation, measurement is the starting point. I keep the same order, with the act first. The Copenhagen interpretation says nothing about the range of possible answers. So the Copenhagen interpretation cannot say where the line between the measured system and the measuring instrument falls. From the beginning, people who doubt the Copenhagen interpretation have asked where the line falls. The many-worlds interpretation includes the smooth change, but the many-worlds interpretation has no act of finding, because in the many-worlds interpretation every result happens. The difficulties of the many-worlds interpretation are two questions: which branches there are, and what the odds mean. Choosing how to divide the world into branches is choosing which outcomes count as having happened, and odds need someone who faces outcomes and weighs the outcomes, so each of the two questions needs the act of finding, the leg that the many-worlds interpretation removed. Each interpretation is a par-

tial view: as a description of the part that the interpretation includes, an interpretation is not wrong, but as an explanation of the whole, an interpretation is missing one leg.

So I reach a result different from Orzel's "aesthetic choice". Each interpretation is placed by structure: by which part of every comparison is missing from the interpretation. I keep all three parts of every comparison, so my account needs none of the interpretations.

What Is Real

Hossenfelder will not call any formulation of a theory 'real', because many formulations fit the same observations. I agree with Hossenfelder that no formulation of a theory is to be called 'real'. I also give the word 'real' an exact meaning. With the exact meaning, I can say what is real without claiming that any theory is real.

Think of a train timetable and a train arriving. The timetable is laid out whole, the same in every copy, and the timetable holds even when nobody is on the platform. The arrival happens here, now, and once. To *exist* is to stand as structure: timeless, the same in every instance, able to be held in view as a whole, as the timetable is. The mathematics of a physical theory exists; its findings are real.

We can sort out Schrödinger's cat at once with the two words, 'exist' and 'real'. In the exact sense of 'exist', the smeared description of the cat exists: the smeared description is the laid-out range of what the opened chamber could show, with the odds of each result. In the exact sense of 'real', the cat you find is real. The other branches of the many-worlds interpretation exist as structure in the mathematics, but no one ever finds the other branches, so the other branches are not real in the exact sense of 'real' that I give in my account.

The Mark on the Paper

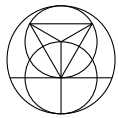
Go back to the locked shop. The balance tipped in the night, and the pen left its mark. No one watched, and the mark is there all the same. In the morning you look at the mark: looking is a second comparison, made on the record that the first comparison left. Nothing happened to the beam when you looked: what changed was what you had found.

Hossenfelder was right on four points: no mind is needed for a measurement, 'collapse' is the wrong word for the measurement update, decoherence stops short of one result (decoherence alone does not give one result), and entanglement is made by meeting and carries no message. So every measurement told in the chapters that follow is a mark laid down in the world. What the beam shows does not wait for anyone to look.

Hossenfelder keeps open another possibility: a theory beneath quantum mechanics, in which the physical process that Hossenfelder expects to replace the measurement update might come out deterministic, so that each outcome would be fixed by what came before. She writes: "Some argue that quantum mechanics is just not the right theory and has to be replaced with something better. This is a possibility I have worked on myself" (*Existential Physics*, chapter 5, "Many Worlds").

The short answer: A measurement is any interaction that lays down a record, whether or not anyone watches. The one outcome of a measurement is found in the act of comparison, by a chance that belongs to comparison itself. What changes is the shared record of what has been found. The change in the shared record is the whole of the measurement update.

Could the outcome have been fixed all along, together with the experimenter's choice of what to measure?



Chapter Seven

Could Everything, the Experimenter's Choice Included, Have Been Fixed in Advance?

What this chapter uses

The *Incommensuration Theorem*: symmetry and continuity cannot both be applied, simultaneously and fundamentally, to any event or comparison; and neither can asymmetry and discontinuity. *Symmetry* is being the same under every change of place or setting, and *continuity* is having no gaps, so that a small change of setting gives a small change in what is found. The Incommensuration Theorem is a structural fact about the nature of knowing (Chapter Two).

A *finding* is any comparison that lays down a record; the measurement update is the change of the shared record of what has been found, and the change of the shared record is the whole of the update (Chapter Six).

Every comparison has three parts, as a stool has three legs: the act of finding, here and now; the record that the act lays down, which anyone can read; and the place from which the question is asked, with the range of possible answers to the question (Chapter Six).

Could the outcome of an experiment have been fixed from the start, together with the experimenter's choice of what to measure? Sabine Hossenfelder has worked on a theory that would lie beneath quantum

mechanics. In that theory, the outcome of an experiment is fixed together with the 'settings' of the experiment, the experimenter's choices of what to measure.

A Way Out, Named on the Radio

The question became sharp in the work of one man, John Bell. Bell was an Irish physicist who had worked since 1960 at CERN, the European laboratory for particle physics near Geneva. Bell spent a year's leave at American universities. After the leave, in 1964, Bell sent a short paper called "On the Einstein-Podolsky-Rosen Paradox" to the journal *Physics*. The paper contained the theorem now called Bell's theorem, which sets a limit on how closely two measurements made far apart can agree when each particle carries its answers with it. I call the limit Bell's limit, and I picture Bell's limit in the next two sections of this chapter. Experimenters spent the following decades putting Bell's limit to the test, and in 1982 the physicist Alain Aspect and his colleagues carried out one of the tests in France and found what quantum mechanics predicts.

A few years later, the physicist Paul Davies and the producer Julian Brown made a program for BBC Radio 3 about what experiments like Aspect's mean, and they called the program *The Ghost in the Atom*. Davies and Brown put their questions to Bell for the program, and Cambridge University Press printed the conversations in 1986, in a book also called *The Ghost in the Atom*. In a 'deterministic' universe, every event is fixed by what came before the event. Bell was asked whether anyone could still hold, after the experiments, that the universe is deterministic: the experiments had found that two particles far apart agree more closely than any answers fixed in each particle at the start could make the particles agree. Bell answered that there was one way to keep determinism. Bell said that one of the ways of understanding the experimental results "is to say that the world is super-deterministic". In a 'super-deterministic' world, the experimenters are fixed in advance along with the rest of nature: the experimenters feel that they choose which experiment to run, but their choices

too are fixed in advance. Bell said that the difficulty raised by the experimental results disappears when the experimenter's choice is fixed in advance as well.

Bell's way out is now called 'superdeterminism': a world fixed in advance in every detail, the experimenters' choices included. To see what superdeterminism requires, we need three things, in this order: one simple picture, then Bell's theorem, and then Hossenfelder's own statement of the case for superdeterminism.

A Coin, Two Cups and a Fair Test

Suppose a friend tells you she can taste the difference between tea made with water straight off the boil and tea made with water left to cool. You want to find out whether she can taste the difference, so you make one cup of each kind, out of her sight. Before each round you flip a coin: if the coin falls 'heads', you hand her the cup made with boiling water, and if the coin falls 'tails', you hand her the cup made with cooled water. She tastes the tea and names the cup, and after twenty rounds you count how often she was right.

What makes the count of right answers mean anything? The coin makes the count mean something, *because* the coin made your choice of which cup to hand her, and the fall of the coin had nothing to do with which answer she leaned toward before tasting. The fall of the coin may have causes of its own, but the test needs *only* one thing: whatever settled the fall of the coin had nothing to do with what was in her before she tasted. So, if she is right nineteen times out of twenty, the score tells you about her tongue.

Now suppose something against all likelihood. Suppose some cause, shared by your coin and your friend, had arranged the fall of the coin and her answers together beforehand: then, in every round, the coin fell on the side for the cup she was about to name. Then nineteen right answers out

of twenty would tell you nothing about her tongue, *because* the score would be a product of the arrangement. The taste of the tea would never have entered into the score.

A *setting* is the choice of what to measure, as the coin chose the cup. The *hidden state* of a measured thing is whatever the thing carries that the experimenter cannot see, as your friend's leaning toward one answer was in her before she tasted. Every experiment needs its settings chosen the way the coin chose the cup: by something that has nothing to do with what the measured thing carries before the measurement. So every experiment has a requirement: the settings of the measuring devices must be independent of the hidden state of the things measured. Physicists call the requirement of independent settings *statistical independence*.

Two Rooms and an Answer Sheet

Bell's theorem is about pairs of particles prepared together, so that quantum mechanics describes each pair as one whole. When quantum mechanics describes a pair of particles as one whole, physicists call the pair *entangled*. One particle of each pair flies to a laboratory on the left, and the twin of the first particle flies to a laboratory on the right. In each laboratory a dial on the instrument is turned to one of a few positions, and the position of the dial sets which question the instrument puts to the particle. The instrument records one of two answers, 'plus' or 'minus'.

Picture the same experiment with people in place of particles: a pair of twins is led into two separate rooms. In each room a card is drawn at random from a short pile of questions. The twin in the room answers the question on the card 'yes' or 'no'. Once the doors are shut, the twins cannot speak to each other, and after thousands of rounds the two lists of answers are set side by side and compared, question by question.

An 'answer sheet' is the plainest way for the twins to agree often: before the twins part, the twins settle what each twin will say to every question that could be drawn. Bell showed that answer sheets have a limit. However the twins write the answer sheets, the agreements across the dif-

ferent pairs of questions cannot together pass a certain score. The score that the agreements cannot pass is Bell's limit. When particles carry their answers with them, as the twins carry a sheet, physicists call the carried answers *local hidden variables*. The answers are 'hidden' because the quantum description does not contain the answers, and the answers are 'local' because each particle carries its own answers and nothing passes between the rooms faster than light. Quantum mechanics predicts that entangled particles pass Bell's limit. Experiment after experiment has found that entangled particles *do* pass Bell's limit.

Bell's limit depends on an assumption. The assumption is that the cards drawn in the two rooms have nothing to do with the answer sheets. The assumption is statistical independence: the requirement that the coin satisfied when the coin chose the cup in each round of the tea test. Suppose the cards to be drawn were fixed in advance together with the sheets. Then each sheet could be written for exactly the questions that would come, and so the twins could reach any score at all.

In the picture of the twins, Bell's way out fixes the cards in advance together with the sheets. Take a complete description of the world at one moment, and carry the description forward by one law that is the same everywhere. *Determinism* is the thesis that the description, carried forward by the law, fixes the world at every other moment. *Superdeterminism* is determinism with one clause added: the settings the experimenters choose are fixed along with everything else, together with the hidden state of the particles that the experimenters measure. In a superdeterministic world, statistical independence fails, so Bell's limit no longer applies, and physicists can keep a theory in which each particle carries its own answers and nothing travels faster than light.

From Hossenfelder's pages

What Sabine Hossenfelder Showed

Hossenfelder sets out her work on superdeterminism in papers written for physicists, but she leaves the work aside in her two books for the general reader, *Lost in Math* and *Existential Physics*. In *Existential Physics*, Hossenfelder mentions her own work on replacing quantum mechanics in a single passage:

> Some argue that quantum mechanics is just not the right theory and has to be replaced with something better.
>
> (*Existential Physics*, chapter 5, "Many Worlds")

The endnote to the passage names the paper in which Hossenfelder sets out her work: "Rethinking Superdeterminism", which she wrote with the climate physicist Tim Palmer, and which was published in 2020 in the journal *Frontiers in Physics*.

Hossenfelder and Palmer begin the paper with what they call one serious shortcoming of quantum mechanics: "it lacks a physical description of the measurement process". A measurement turns a spread of possible outcomes into one outcome that is found. Physicists call the question of what physically happens during a measurement the *measurement problem*. Hossenfelder and Palmer hold that the measurement problem indicates one of two things: at the least, that quantum mechanics is incomplete, or, more radically, that quantum mechanics is in need of a complete overhaul. They hold that superdeterminism may supply the completion or the replacement.

Hossenfelder and Palmer then state exactly which assumption fails in a superdeterministic theory:

> A superdeterministic theory is one which violates the assumption of Statistical Independence (that distributions of hidden variables are independent of measurement settings).
>
> (S. Hossenfelder and T. N. Palmer, "Rethinking Superdeterminism", *Frontiers in Physics* 8, 2020, abstract)

Classical physics is the physics of the centuries before quantum mechanics. A *linear system* is a system whose response to two causes acting together is the sum of the system's responses to each cause alone. Hossenfelder and Palmer hold that the usual doubts about superdeterminism come from experience with classical physics and with linear systems. They hold that experience with classical physics and with linear systems misleads the people who doubt superdeterminism. *Non-locality* is the way that particles far apart seem to act on one another faster than light could carry any signal. Hossenfelder and Palmer write: "Superdeterminism is a promising approach not only to solve the measurement problem, but also to understand the apparent non-locality of quantum physics".

Hossenfelder and Palmer give one part of their paper to free will. Superdeterminism is often taken to be a denial of the experimenter's free will. Hossenfelder and Palmer answer that the question of free will is beside the point. "In summary", they write, "raising the issue of free will in the context of Superdeterminism is a red herring".

Hossenfelder and Palmer also answer a charge against superdeterminism: the charge that giving up statistical independence would invalidate the method of science itself. They state the charge as follows: in a deterministic theory, someone can take any outcome and work back by the law to the starting state that would have produced the outcome, and the person can then claim to have explained the outcome.

Hossenfelder and Palmer write that accepting an explanation made by working back from the outcome "would seemingly invalidate the science method in general". Their answer is that "just by knowing a theory violates Statistical Independence one cannot tell anything about its explanatory power": to judge the 'explanatory power' of a theory, they write, "one needs to study a concrete model".

Hossenfelder and Palmer also answer a second form of the charge, which their paper calls the 'tobacco company syndrome'. Suppose statistical independence could fail in Bell's experiments. Then, the charge says, a tobacco company could claim that a trial linking smoking to lung cancer was spoiled, and could blame a hidden link between the random sorting of the patients and the illness measured. The answer of Hossenfelder and Palmer is that the habit of assuming statistical independence was formed on classical systems, and they write that "the whole reason we are having this discussion is that classical physics is not sufficient to describe the systems we are considering". Hossenfelder and Palmer add that, in the tobacco trial, nothing suggests that the random sorting could not be carried out again and again. Hossenfelder and Palmer write that differences between classical and quantum theories "can emerge" only where physicists, to describe an experiment, must reason about measurements that were never made. For example, no one measures the answer that a twin would have given to a card that was not drawn. Hossenfelder and Palmer judge that the tobacco analogy "raises the impression that the assumption of Statistical Independence is more outlandish than it really is".

Hossenfelder has also proposed a way to look for a superdeterministic theory in the laboratory. In 2011 she published the paper "Testing Super-Deterministic Hidden Variables Theories" in the journal *Foundations of Physics*, and the paper sets out an experiment in which systems are put into the same starting state each time and measured one measurement after another.

First, Hossenfelder and Palmer identify the assumption of statistical independence exactly. So a reader knows which step of Bell's argument fails in a superdeterministic theory. Second, Hossenfelder and Palmer propose tests of statistical independence, in Hossenfelder's paper of 2011 and again in their joint paper of 2020, and with the tests experimenters can study the question of statistical independence in the laboratory.

This is a possibility I have worked on myself, but because it's both speculative and somewhat off topic, I don't want to go into this here. Hossenfelder and Palmer state her position at full strength in the paper, so I take her position from the paper. In Appendix A, "What the Coming Measurements Will Find", I gather what tests of superdeterminism will measure and what I say experimenters will find in the tests; of her test, I say that the measurements will settle to the weights of the Born rule (the rule of quantum theory that states the chance of each outcome), at every sensitivity and every interval, with no correlation in time beyond those weights. I credit two things in the work of Hossenfelder and Palmer, and I share a third. Third, my argument later in this chapter assumes nothing about free will, like the argument of Hossenfelder and Palmer.

What the Experiments Did

Physicists call a *loophole* any way by which an answer sheet might still explain the agreements. The tests of Bell's limit left loopholes for decades after Bell's paper. The first loophole was that the detectors might miss so many particles that the particles caught were an unrepresentative sample. The second loophole was that the settings might be chosen so slowly that a signal at the speed of light could carry the setting of one room to the other room.

A team of physicists closed both loopholes in one experiment, early in the summer of 2015. The team worked on the campus of Delft University of Technology in the Netherlands. Ronald Hanson led the team, and Bas

Hensen was the first author of the paper that reported the experiment. The team set up two laboratories 1.3 kilometers apart. In each laboratory, a single electron sat at a flaw in a small chip of diamond. The team asked each electron about its 'spin', the tiny magnetic direction that the electron carries, and each electron sent out a particle of light to a third station, which had two detectors. The two electrons were entangled whenever the third station caught two particles of light, one in each of the station's two detectors. Each catch of two particles of light began a round of the experiment. In each laboratory a fast generator of random numbers chose the question, and the laboratory recorded the answer before any signal at the speed of light could have arrived from the other laboratory. The team ran the experiment for 220 hours over 18 days and gathered 245 rounds. The answers in the two laboratories agreed more closely than Bell's limit allows. In the same year, two more teams closed both loopholes with entangled light. Marissa Giustina and her colleagues worked in Vienna, and Krister Shalm and his colleagues worked in Boulder, Colorado. Both teams also found that the agreements passed Bell's limit. We now know that no answer sheet carried by the particles can explain the agreements, so long as the settings are independent of the answer sheets.

One way out remained: the settings might not be independent of the answer sheets. So the experimenters turned to how the settings themselves are chosen. On 30 November 2016 about a hundred thousand people played an online game, pressing keys to make a stream of choices. The choices of the players were sent to twelve laboratories on five continents, where the choices set the dials of thirteen experiments. The BIG Bell Test Collaboration published the results in *Nature* in 2018. The results passed Bell's limit again. Experimenters in Vienna took the settings from the color of light arriving from stars of our own galaxy, in work published in 2017, and the light from the nearer of the stars had left the star about six hundred years before the experiment. In 2018 two large telescopes on the island of La Palma gave the settings for another test, taking the settings from the light of *quasars*, the blazing centers of distant galaxies. The

light from the quasars had set out more than seven point eight billion years before the experiment. In all three tests, the agreements passed Bell's limit.

What do we now know? Suppose some cause, shared by the settings and the particles, fixed both together: then, in the quasar test, the shared cause would have to lie more than seven point eight billion years in the past. In the BIG Bell Test, the shared cause would have to fix the choices of a hundred thousand people. Hossenfelder and Palmer write that the experiments "merely rule out that the observed correlations in Bell-type tests were locally caused by events in the distant past" (the observed correlations are the agreements between the answers in the two laboratories). The result of Hossenfelder and Palmer also follows in my account, from ground of its own: in a superdeterministic world, every result is fixed together with everything else, the settings included. So no result of an experiment can rule out a superdeterministic world. The experiments make superdeterminism very costly: superdeterminism now needs a shared cause that lies billions of years in the past and that also fixes the choices of a hundred thousand people. The experiments constrain superdeterminism, but the experiments do not exclude superdeterminism by logic.

Two options remain, and plain reasoning about which option needs less already decides between the two options. On the first option, the whole past was arranged at every scale: the arrangement fixed the settings taken from starlight, from quasars and from a hundred thousand players together with the hidden state of the particles. On the first option, too, the arrangement left no trace anywhere else. On the second option, some of what happens is not fixed by anything that came before. A 'prior specification' of an outcome is a full description of everything that came before the outcome, down to the last detail. When no prior specification fixes an outcome, however complete the prior specification is, I call the outcome *hard randomness*. The second option is simpler than the first option by a very large margin. The margin is enough by itself for me to accept hard

randomness in my account. I also have a deeper ground for hard randomness. From the deeper ground I show whether the world is fixed in advance, before any laboratory is built.

What Every Comparison Leaves Open

Every measurement is an act of *comparison*: setting one thing beside another and finding how the two stand. Chapter Two set out the *Incommensuration Theorem*, the theorem that holds for every comparison: no comparison can have two particular kinds of perfection together. In the Incommensuration Theorem, *symmetry* means being the same under every change of place or setting. Both meanings use the 'setting' of a comparison, as Chapter Two named it: the places, the moment and the conditions in which the comparison is made, as distinct from the setting of an experiment's dial. I argue against superdeterminism from the Incommensuration Theorem, in three steps.

The first step is about determinism itself. Picture a player piano, whose paper roll fixes every note before the first key is struck. Under determinism, the world is like the paper roll. Determinism requires two things at once. First, determinism requires one law to carry every state into the next state, the same in every place and at every time: that is symmetry, made perfect. Second, determinism requires the law to fix every state at every point, with no gap anywhere: that is continuity, made perfect. The continuity that determinism requires is the continuity of Chapter Two, held without exception. Perfect continuity says: where the setting is the same, what is found is the same. So the law fixes the state at every place and at every moment. The Incommensuration Theorem forbids exactly the pair of perfect symmetry and perfect continuity, so determinism is 'unreachable' as a matter of structure. Being unreachable as a matter of structure is different from being false as a matter of fact.

The second step is short. Superdeterminism requires everything that determinism requires, and more: superdeterminism also includes the settings of every experiment among the things that are fixed. Suppose a posi-

tion needs the pairing that the Incommensuration Theorem forbids. The position does not become possible by needing the same pairing over more of the world. Whatever cannot be had for the particles cannot be had for the particles, the apparatus and the experimenter together. Suppose a promise cannot be kept for one room of a house. Then the promise cannot be kept for the whole house. In the picture, the one room stands for the particles, and the whole house stands for the particles, the apparatus and the experimenter together. So the Incommensuration Theorem excludes superdeterminism, for the same reason that the Incommensuration Theorem excludes determinism. The reason is about comparison, and *not* about quantum mechanics.

In the third step, I exclude a determinism that holds only in part. Determinism is a guarantee that covers everything, and a single exception breaks a guarantee that covers everything. In the third step, a 'scale' is a level of size, such as the size of particles or the size of dials. A scale is completely fixed only if the smaller things that make up the scale are completely fixed too, because the small makes up the large. The dials that the experimenters set are made of particles, and so are the experimenters themselves. Suppose nothing fixed the outcome of one particle. Then the dials are unfixed too. So a failure of determinism among the particles is a failure of determinism at every larger scale. There is no partial determinism, and so there is no partial superdeterminism either.

Physics also shows how one particle's outcome, which nothing fixed, can come to affect the dials. A double pendulum is two rods hinged end to end. Release a double pendulum twice, from starting positions too close to tell apart. Within seconds, the two swings bear no resemblance to each other. Processes like the swing of a double pendulum make a difference grow, starting from a difference too small for any instrument to record, until the difference is large enough to matter to people and to their instruments. The difference made by a particle's outcome that nothing fixed can grow in the same way, so that in time the very dials that the ex-

perimenters set can depend on the outcome. Suppose determinism held only nearly, at the scale of particles. Then there would be no determinism at the scale of the experimenters either.

I set out the whole argument against superdeterminism in one essay, on the structural impossibility of superdeterminism. I set out the third step in chapter 3, section VI. In that section, I first rest the third step on how the small makes up the large, and then I show small differences growing, as the swings of the double pendulum do, until the differences are large enough to affect the settings.

A Choice Is Not a Cause in Disguise

Superdeterminism is determinism with one clause added, the clause that fixes the settings, and the added clause fails in a way of its own. The way the added clause fails shows that choice, the part of an event that is new, is part of every event. Every real event contains three things, bound together. Picture one round of a Bell test. One law fixes how often each answer comes over many rounds, and the law is the same in every round. The particle arrives at the instrument, and the instrument clicks, but nothing before the round fixes which answer comes in this one round. Each event has a pattern that repeats: the same kind of cause followed by the same kind of effect, again and again. The pattern that repeats is called *causation*. The law of the rounds is a case of causation. Each event also has a happening, the actual passage from one state to the next: the happening itself is called *change*, and the click of the instrument is a case of change. Each event also has something new, something that was not contained in what came before: what is new in an event is called *choice*, and the answer in this one round is a case of choice. Causation, change and choice are distinct, but the three never come apart, and none of the three can do the work of another.

The word 'choice' names the part of an event that no pattern fixes, described from inside. The word 'choice' applies at every scale. The phrase 'from inside' means from the position of the process that the part came

from. The same part of the event can also be described from outside, from the position of law, and from outside the same part is hard randomness: an outcome that no prior specification fixes, however complete. Chapter Eight shows how the same part of an event, seen from inside by the one from whom the part comes, is what a person knows as choosing.

The Incommensuration Theorem shows why every event always has a part that is choice: symmetry is the pattern that repeats, the same law in every place, and continuity is a specification of every state with no gaps. Symmetry and continuity cannot both be total. So something is always left over that the pattern does not fix, and I call what is left over 'choice'. The Incommensuration Theorem says that the 'leftover' is never empty. Superdeterminism says that the leftover is empty, in the act of measuring as in everything else. The Incommensuration Theorem excludes *exactly* an empty leftover.

The claim of the Incommensuration Theorem is about every comparison, whoever or whatever makes the comparison. My argument against superdeterminism assumes nothing about free will, so with my argument I answer Hossenfelder and Palmer on their own terms. Hossenfelder and Palmer call the issue of free will a 'red herring'. My argument does not raise the issue. Whatever selects a setting draws on the leftover, the part that the pattern leaves unfixed, in the same way that the particle draws on the leftover. The dial can be turned by a person, by a machine that generates random numbers or by the light of a star, and in each case whatever turns the dial draws on the leftover in the same way.

You may ask whether the leftover is only what we do not yet know: perhaps, you may think, the hidden details of the early universe would fix the leftover, if anyone could learn the hidden details. When something is only 'not yet known', a complete description of the thing is there to be had. We do not yet have the description. The Incommensuration Theorem says something different: every description of a comparison leaves something over. A world is what comparisons are of: whatever is found in a world is found by setting one thing beside another. So a description with nothing left over describes no comparison, and so describes no world.

Suppose a description fixed every state without gap and held every law without exception. The description would leave nothing to be measured, and in the description nothing would happen. A description in which nothing happens cannot be the description of what happens in a laboratory.

I agree with Hossenfelder on one conviction: quantum mechanics is not the final word. My account has its own reason for the conviction. What lies beneath quantum mechanics is the act of comparison itself, and not a deterministic mechanism.

When the Pan Is Chosen with the Weight

One more ground against superdeterminism depends on Hossenfelder's own standard. Hossenfelder criticizes the appeal to beauty in physics because she demands that physics answer to evidence. Every experiment presupposes that the settings of the experiment are independent of what the experiment measures. The independence of the settings makes a result evidence about the thing measured. Without the independence, a result would be one more product of whatever produced the setting. Superdeterminism is a thesis about *all* events. So, in a superdeterministic world, no setting anywhere is independent of what the experiment measures. In a superdeterministic world, no observation could count as evidence for superdeterminism. No observation could count as evidence for anything else either. Hossenfelder and Palmer answer the charge against the method of science on two other matters: the explanatory power of a given theory, which a concrete model must show, and how far beyond classical systems a habit formed on classical systems applies. The ground I state in this section is about something else: what makes any result evidence about the thing measured, in a world where superdeterminism holds of every event.

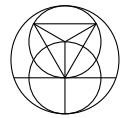
Think of the two-pan balance once more. You set a stone in one pan, choose known weights for the other, and watch the beam tip. The tip of the beam tells you about the stone because you chose the weights apart

from the stone. In the picture, the stone stands for the thing measured, the choice of weights stands for the setting, and the tip of the beam stands for the result. Suppose your choice of weights were fixed together with how the beam tips. Then every weighing would tell us nothing about the stone. The tea test showed the same point with a coin: a coin that fell together with your friend's answers told you nothing about her tongue. Every result in physics has depended on the independence of the settings, from the first weighing to the latest Bell test.

Why does the independence of the settings matter for the whole book? Measurement can teach us anything only in a world where the setting and the answer were not written together beforehand. Our world is a world in which the setting and the answer were not written together beforehand, because of the structure of comparison, and so an experiment can teach us about the thing the experiment measures.

The short answer: The world is lawful and open at once. Every act of comparison leaves something that no law fixes. So the experimenter's choice and the particle's answer were never written together in advance. Each measurement is a question that the world answers at the moment the question is asked.

Since the world is not fixed in advance, what is left of free will?



Chapter Eight

Has Physics Ruled Out Free Will?

What this chapter uses

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 Two).

When no prior specification fixes an outcome, however complete the prior specification is, I call the outcome *hard randomness* (Chapter Seven).

What is new in an event, not contained in what came before, is called *choice* (Chapter Seven).

The measurement update is the change of the shared record of what has been found (Chapter Six).

Sabine Hossenfelder writes that, under the established laws of physics, the past fixes the future, with one exception (occasional quantum events that no one can influence), and she concludes, for herself, that "free will does not exist". Does physics show a future fixed by the past, apart from quantum events, with no free will in it? Chapter Seven found that the world is not fixed in advance. Chapter Seven also found that the experi-

menter's choice of a setting and the particle's answer were never written together in advance. In this chapter, I ask what a world not fixed in advance leaves for you when you choose.

An Intelligence That Knows Everything

In 1814, in Paris, the mathematician and astronomer Pierre-Simon Laplace published a book on chance, the *Essai philosophique sur les probabilités* (*A Philosophical Essay on Probabilities*). Early in the book, Laplace described a mind of a particular kind: a mind that would know, at one instant, every force at work in nature and the position of every thing that nature is made of. The mind would also be vast enough to work all of the knowledge through by calculation, and Laplace wrote that, for the mind, the motions of the largest bodies in the universe and of the lightest atom would stand together in one formula.

Laplace closed the sentence with these words:

> rien ne serait incertain pour elle, et l'avenir comme le passé serait présent à ses yeux.
>
> (Pierre-Simon Laplace, *Essai philosophique sur les probabilités*, Paris, 1814, section "De la probabilité")

In English: nothing would be uncertain for it, and the future, like the past, would be present before its eyes. Later writers named Laplace's imagined knower 'Laplace's demon'. In the same pages, Laplace says what probability measures: probability, he writes, is relative partly to our ignorance and partly to our knowledge. We lack the demon's knowledge, so we count chances. In Laplace's picture, 'chance' is the measure of what we do not know. The demon knows everything, so the demon would never need to count a chance. The demon would also find every novel dull, because the demon would know the ending of each novel before opening the first page.

Hossenfelder quotes the same passage of Laplace in the first chapter of *Existential Physics*, where she asks whether the past still exists, and her chapter on free will uses Laplace's picture, with one change. In the chapter on free will, she writes that what you do today follows from the state of the universe yesterday, which follows from the state the day before, and so on, all the way back to the Big Bang. Her one change is an exception, wherever a random quantum event makes a difference. Since Laplace, physicists have learned one large new thing: the laws of the very small include chance that no knowledge removes. So I ask two questions: what becomes of Laplace's picture once the chance of the very small is counted in, and what does the picture then leave for a person who chooses?

From Hossenfelder's pages

What Sabine Hossenfelder Showed

Hossenfelder first states what the established laws of physics say about the future, without using the words 'free will' at all. She needs two terms, and the first term is *determinism*, which she defines in her opening chapter: "The idea that all events in the future can in principle be calculated from any earlier time is called determinism". The second term is 'quantum mechanics': the theory of matter and light at the scale of atoms, in which single outcomes come by chance, such as the moment one atom breaks apart. Hossenfelder uses the two terms, determinism and quantum mechanics, to state what the established laws say, in two sentences:

> The currently established laws of nature are deterministic with a random element from quantum mechanics. This means the future is fixed, except for occasional quantum events that we cannot influence.
>
> (*Existential Physics*, chapter 6, "A Quagmire of Evasion")

The weather is one system in which tiny differences at the start grow into large differences later. Physicists call the behavior of systems like the weather *chaos*. Hossenfelder adds that the future of a chaotic system is just as fixed. In her words, "Chaotic laws are still deterministic; they are just difficult to predict".

Hossenfelder draws her own conclusion about free will from laws that fix the future, apart from quantum events that no one can influence:

> (*Existential Physics*, chapter 6, "A Quagmire of Evasion")

Hossenfelder's reason is an old one, which she takes from the philosopher Friedrich Nietzsche. A will that is free should not be caused by anything else, *but* a will caused by nothing was not caused by you either. So, with Nietzsche, Hossenfelder calls free will a contradiction. She puts computation in the place of free will: our brains evaluate input and arrive at the best decision they can. She notes that her phone makes 'decisions' too, every time the phone works out which notifications to show on its lock screen.

Hossenfelder then turns to the view that free will can be defined so as to fit with determinism. Philosophers call the view *compatibilism*. Compatibilism is the dominant view among professional philosophers, by the survey Hossenfelder cites. She accepts the compatibilist definitions of free will as definitions, "neither right nor wrong, merely more or less useful". The worry she addresses is the one that ordinary people have about free will when they learn physics. She holds that the compatibilist definitions leave that worry untouched: the definitions do not answer the worry. Hossenfelder gives her answer to the question of her chapter:

> Has physics ruled out free will? No, it has merely ruled out certain ideas about free will.
>
> (*Existential Physics*, chapter 6, "Life without Free Will")

Hossenfelder names one opening that she can see: large systems might have properties that cannot be derived, even in principle, from the laws of the particles the systems are made of. She calls the possibility 'strong emergence'. She writes that strong emergence could happen if the calculation that leads from the small to the large ran into a *singular point*: a point beyond which a calculation cannot be continued. She calls strong emergence "a long shot" that is "compatible with all we currently know".

In a later chapter, Hossenfelder asks whether people are predictable, and she sharpens the question. She writes that, under quantum chance, what can be predicted are the probabilities of decisions. Hossenfelder sums up the part of her argument about prediction in one sentence:

> In summary: we have no reason to think human behavior is unpredictable in principle, but good reason to think it's very difficult to predict in practice.
>
> (*Existential Physics*, chapter 9, "The Limits of Math")

Hossenfelder also records the point that the physicist David Deutsch made in her interview with him: the growth of knowledge cannot be predicted. She puts Deutsch's point in one line, in her brief answer to the interview: "If you could predict the growth of knowledge, your knowledge wouldn't grow". And she holds that people can live and judge well without free will. She calls "silly" the worry that society would fall apart, because whatever has made moral responsibility work so far will go on working.

Hossenfelder is right that the equations of physics carry each state into one next state, and she is right that, under the established laws, nothing that came before a quantum event fixes the single outcome of the event. She is right that renaming 'free will' leaves the ordinary

worry where the worry was (a new name does not answer the worry), and she is right that a prediction of new knowledge would already be the new knowledge.

Personally, I would just say this means free will does not exist and put the case to rest.

Where the Two Accounts Meet

Every measurement is an act of comparison.

First, the future is very largely fixed by the past. The first result: the laws of physics are reliable, experiments repeat, and the future is very largely fixed by the past. Drop a cup, and the cup falls, every time. The whole success of physics lies in regularities like the falling cup. I keep all of the regularity that physics has found.

Second, nothing that comes before a single quantum outcome fixes the outcome. Picture a Geiger counter on a bench beside a lump of radioactive rock. Every so often the counter clicks, because an atom in the rock has broken apart and sent a particle through the counter. A large batch of radioactive atoms breaks apart at a rate that is among the best-measured regularities in physics, *but* nothing predicts the moment at which one single atom breaks apart.

Compare a roulette wheel. Details that no one measured may settle where the ball comes to rest. Two of the unmeasured details are how hard the wheel was spun and how the ball was thrown. We call the result 'random' because we do not know the details. I call randomness of the roulette kind *soft randomness*: a limit of what we know, which better knowledge could shrink. The randomness of the atom is of another kind, because however fully someone described everything that came before the moment the atom breaks apart, the description would not settle the moment. In plain words, a 'prior specification' is a full description of

everything that came before the outcome. Hard randomness is a fact about the world, and the single outcome of a quantum measurement is the plainest instance of hard randomness.

Hossenfelder reaches the unfixed single outcome through quantum mechanics, as physicists have established quantum mechanics. I reach the unfixed single outcome from the structure of comparison. Every comparison has what I call a 'remainder', an outcome that nothing before the outcome fully fixes, and the remainder is hard randomness. The Incommensuration Theorem, set out in the next section, guarantees that every comparison has a remainder. Hossenfelder's ground is quantum mechanics, and the ground of my account is the structure of comparison. The two grounds are separate, and the two separate grounds give one result.

Third, Hossenfelder and I both set aside the old quarrel over compatibilism. Hossenfelder sets the quarrel aside because the compatibilist definitions of free will do not answer the worry of ordinary people. Both sides of the quarrel take a fixed world to be at least possible, *but* the structure of comparison shows that a fixed world is impossible, by the Incommensuration Theorem, which I set out in the next section. So the question of free will becomes a new question: what is choice, in a world that is full of causes and not fixed in advance?

Fourth, the probability of each outcome can be known in advance, and the single outcome cannot. If someone knew everything that came before an outcome, completely, the person could know the probability of each possible outcome and nothing more, so the person could not predict which single outcome will occur. Hossenfelder states that the probabilities of decisions can be predicted, and her statement agrees with the fourth result of my account.

Fifth, some things cannot be predicted because of what the things are. Deutsch states the fifth result for knowledge: a prediction of the growth of knowledge would already be the knowledge, so nothing would have

grown. We know that we cannot predict choices; if we could, they would be causes and not choices. Deutsch and I reach statements of one form from two different starting points.

Two Perfections That Cannot Meet

No world is purely and completely deterministic, because every world has pattern and every world also has a part that nothing earlier fixes. The name of the theorem, 'Incommensuration', says that two kinds of perfection have no common measure. No act of comparison can have the two kinds made perfect together.

The theorem uses four words: 'symmetry', 'continuity', 'asymmetry' and 'discontinuity'. Chapter Two found each of the four words in the balance. *Symmetry* is being the same under every change of place or setting: set one ten-gram piece from the box of weights against another, in this town or on another continent, and the beam rests level. Watch the beam settle after a weighing: the beam swings through every position between one end and the other, with no jump. *Asymmetry* is the opposite of symmetry, and *discontinuity* is the opposite of continuity. Each swing of the settling beam is a little smaller than the swing before, so no swing repeats the last: the swings show asymmetry. The pieces in the box of weights come in steps, a ten and a twenty with nothing between: the steps show discontinuity.

Now look at what Laplace's demon needs. First, the demon needs one law that carries every state into the next state, the same everywhere and at every time. One law, the same everywhere and at every time, is symmetry, made perfect. Second, the demon needs every state specified at every point, with no gap, so that each state passes into the next state without a break, and a specification with no gap anywhere is continuity, made perfect. Perfect continuity is the continuity of the settling beam, held without exception. Under perfect continuity, what the law fixes has no gap anywhere, at any scale, however small. Determinism needs symmetry and

continuity perfected together, but the first clause of the theorem states that symmetry and continuity cannot *both* be perfected in any event or comparison, so no world is purely and completely deterministic.

The second clause of the theorem states that the opposite extreme is impossible as well. An outcome with nothing at all accounted for would be *pure randomness*, and pure randomness would be asymmetry and discontinuity perfected together. The second clause forbids asymmetry and discontinuity perfected together, so every actual world lies between determinism ('the clockwork') and pure randomness ('the noise'). Every actual world has cause together with hard randomness. The word 'cause' names pattern found again and again, and hard randomness is a part that nothing earlier fixes.

The equations of physics remain exactly as they are under the result of the theorem. If an equation carries each state into exactly one next state, the equation is 'deterministic' as mathematics, and mathematics is a description. A perfectly exact fence does not make the field inside it exact. A surveyor can set the fence posts to the width of a hair. The grass inside the fence still grows in its own way. Hossenfelder finds determinism in the established laws of physics. In the picture, the determinism of the laws belongs to the 'fence', which is the mathematics. The 'field' inside the fence stands for the world that scientists measure. In the field, scientists find causal law, one comparison at a time. A *causal law* is a pattern seen again and again by an observer in time.

In her chapter on whether people are predictable, Hossenfelder also finds practical uses in knowing where prediction fails: heading off a hurricane before the hurricane grows, or heading off an instability in a fusion reactor before the instability grows. I name two uses of science. In one use, scientists narrow what could happen, and in the other use, scientists widen what could happen. Scientists sometimes narrow what a device can do to what the device is meant to do, and the narrowing is called 'engineering'. Scientists sometimes find possibilities that no one had seen, and

the finding is called 'discovery'. Heading off a hurricane is 'engineering' in this sense. In both uses, what scientists establish is causal law, and *never* the complete specification that determinism would require.

One Exception Reaches Every Scale

Hossenfelder's position allows exceptions: she writes that the future is fixed, except for occasional quantum events. In this chapter, a *scale* is a level of size, such as the size of particles or the size of people. I show that a determinism with exceptions is no determinism at any scale. Determinism is a promise about everything, and just as there is no partial guarantee of everything, there is no 'partial determinism'. The small makes up the large. A failure of determinism also passes from the large to the small: the free will theorem shows the passage, and I give the theorem in full at the end of this section. The theorem states: if no earlier information available to the particle fixes the experimenter's setting, nothing that came before fixes the particle's answer. The experimenter's setting belongs to the scale of people, and the particle's answer belongs to the scale of particles. So one failure of determinism anywhere is a failure at every scale.

Physicists have shown how a small difference grows until the difference matters at a large scale, and one famous case was found by accident. In 1961 the meteorologist Edward Lorenz was running a simple model of the weather on a computer at the Massachusetts Institute of Technology, with twelve numbers standing for temperature, wind and the like. Lorenz wanted to repeat part of a run, so he typed in one of the numbers as .506, where the machine had held .506127. The small change from .506127 to .506 changed the whole pattern of two months of simulated weather, and in 1963 Lorenz published what he had found: "slightly differing initial states can evolve into considerably different states". We now know that the weather magnifies small differences in the way Lorenz found, and so does a great deal else in nature.

Hossenfelder agrees that nature magnifies small differences, and she counts the magnifying as part of a deterministic world, *but* we can follow the magnifying downward, toward smaller and smaller differences, as I do. Imagine the differences that settle the outcome of a magnifying process made smaller and smaller, until in the end the differences fall below the finest difference that any interaction at all can register. Quantum physics sets a limit on the finest difference that any interaction can register: below a certain fineness, no interaction can tell apart the differences that would fix both where a particle is and how the particle is moving. Every measuring tool is itself an interaction, so no tool that could ever be built can reach below the limit. Every way of telling two states apart is an interaction, so if no interaction could tell two states apart, the two states cannot be told apart in any way at all. What cannot be told apart in any way is the same, so the two states are one state. And yet the system that magnifies the differences still produces an outcome. Whatever happens below the limit settles the outcome. What happens below the limit is hard random, as seen from anywhere inside the range where measuring works. Hard randomness rises through every process that magnifies what the process cannot resolve: hard randomness seeps upward, the way groundwater rises wherever it finds a path.

You can build a chain of magnifying steps yourself, in imagination. Wire a Geiger counter to a small rocket, so that if the counter clicks within the next minute, the click launches the rocket. The rocket nudges a small asteroid. In time, the new path of the small asteroid shifts a larger asteroid, which in a longer time shifts a larger asteroid still. After the first link, every link of the chain is ordinary gravity and motion, *but* the first link was a click that nothing beforehand fixed, so the occasional quantum events leave the large-scale future open, given time and a path to travel by.

There is a second route to the result that what happens is not fixed in advance, and the second route uses physics alone. In 2006 the mathematicians John Conway and Simon Kochen proved what they called the 'free will theorem'. The free will theorem uses the established laws of quantum mechanics and relativity. The theorem states that if no earlier in-

formation available to the particle fixes the experimenter's choice of a 'setting' (the direction along which an instrument measures), then nothing that came before the particle's answer fixes the answer. Conway and Kochen published a second paper in 2009, and in the paper of 2009 they add that the proof is still valid when a computer program picks the settings, so long as the particles have no access to the program. So the theorem needs one freedom in the experimenter: the 'statistical independence' of Chapter Seven. The term 'statistical independence' means that the settings are independent of the hidden state of what is measured. Every experiment already assumes statistical independence, and Chapter Seven showed that statistical independence is what makes a result evidence about the thing measured. Chapter Seven described a 'tea test'. A friend said she could taste the difference between two kinds of tea, and a coin chose which cup to hand her. The tea test assumed the same independence, in the coin. The fall of the coin had nothing to do with what was in the taster before she tasted. The assumption of independent settings uses nothing from the Incommensuration Theorem. So the ground of the second route is separate from the ground of the first route. The two routes start from separate grounds and give one result, and each route alone is enough for the result: what happens is not fixed in advance, at the scale of particles and therefore at every scale.

From Outside, Chance; From Inside, Choice

So the world has a part that nothing earlier fixes. What is the unfixed part of the world, for you?

Picture a friend about to say the next word of a sentence. From outside, no one can predict the word: nothing your friend has said so far fixes the next word. From inside, your friend means the word. Both descriptions describe the same word.

I hold that hard randomness and choice are one event described from two positions. When the outcome that nothing fixed is described 'from outside', from the position of law, the outcome is hard randomness. Hard

randomness is something no law specifies, with no pattern and no meaning. When the same outcome is described 'from inside', from the position of the one engaged, the outcome is choice. The choice is significant to the process the choice came from, and the choice bears the nature of the process. When an outcome is significant to the process the outcome came from, the outcome has *meaning* for the process. From outside, randomness; from inside, choice: one event, two descriptions, both correct, neither complete.

If you watch a person instead of a particle, you find the same pairing of randomness and choice. People are fairly predictable: a good deal of what anyone will do can be foreseen. A program that shrinks computer files writes down every pattern in a stream of data. Now write down, in the same way, everything about a person that can be predicted. However good the program, some part of the person's behavior will not shrink, and the leftover part cannot be told apart from randomness, and yet the leftover is the part the person regards as their own choosing.

Now I can answer Nietzsche's argument, which Hossenfelder adopts. Nietzsche's argument has three steps. A determined act was not chosen, a random act was not chosen either, and so the words 'free will' name nothing coherent. Nietzsche's argument depends on an assumption: the world is either fully determined or purely random. The Incommensuration Theorem shows that neither world is possible: no world is fully determined, by the first clause of the theorem, and no world is purely random, by the second clause. Choice lies between the completely random, which would be mere noise, and the completely determined, which would be the mere playing out of a script.

Hossenfelder's phone also has a place in my account: the phone decides which notifications to show on its lock screen. I keep two words apart: 'decision' and 'choice'. A *decision* is a selection from a set of possibilities already laid out, made by cutting away the others. The phone decides, and so do we, and causes explain a great deal of deciding. A *choice* can bring about something that was open but on no list at all. Someone with a free evening picks among a film, a dinner and an early night, giv-

ing up two to have one. The person has made a 'decision'. Then a friend calls with an idea that was on no list: a walk by the river at sunset. The evening becomes something that none of the options was, and taking up the walk is a 'choice'.

On my account, the word 'choice' names the part of an event that physicists record as hard randomness, seen from inside. I leave aside the will beyond law and chance that Hossenfelder rejects. I neither defend a will beyond law and chance nor assume one. Every experiment gives the same numbers under Hossenfelder's description and under the description of my account, because the quantum chance of the established laws, as Hossenfelder describes the laws, is the hard randomness of my account.

Two of Hossenfelder's particular claims have a different form in my account. First, Hossenfelder looks for one rare opening, a singular point, where the calculation from the small to the large breaks down, while I find the room for choice at *every* scale. The reason is the Incommensuration Theorem: no deterministic description, at any scale, can be complete. In principle, no description, however refined, contains everything that the description describes. In practice, exact calculation from the laws of particles already gives out at chemistry, the first step up: exact calculation succeeds only for the simplest systems, such as the hydrogen atom, and every method used for the chemistry of anything larger approximates. The practical limit shows how early calculation stops on the way up from the small to the large. *But* the room for choice rests on the limit in principle. Second, Hossenfelder holds that, apart from quantum chance, there is no reason to think human behavior unpredictable in principle. I hold that most behavior is predictable, and that the part of behavior that is choice cannot be predicted in principle, because a choice that could be predicted would be a cause. To everyone else, the part that is choice looks exactly like randomness.

What the One Who Chooses Owns

If you choose, are you responsible for what follows? Hossenfelder says that responsibility keeps working, and I reach the same result. The ground of my result is the structure of choice itself. A choice has three parts: a range of what is open, the selection, and the consequence. A choice without its consequence is not yet a choice. Because the world is causal, what is chosen goes on to have effects; because it is not determined, the one who chose could have chosen otherwise.

Cause and choice are present together in what you do, in a proportion that changes from act to act. A 'habit' is a choice made so often that the choice runs almost wholly as cause. Your hand reaching for the light switch is a habit. A 'turning point' in a life is a run of causes bent almost wholly by choice. Most acts lie between a habit and a turning point. The life of a person is the movement of the proportion of cause to choice in the person's acts. Choice and causality are conjugate: each can be held more fully only as the other is held less fully, and neither comes before the other.

Hossenfelder also refuses the step from "no free will" to "nothing matters". In her words: "Free will or not, we are here, and therefore we matter". She warns that some experiments on belief in free will prime people to take the step, which she calls 'fatalism', and I refuse the same step, for a reason of my own.

In this chapter, 'meaning' is significance to the process an outcome came from. Every line that marks where meaning stops is itself drawn by a comparison, made from where someone or something stands. The comparison is significant to the one who makes the comparison. So the comparison has meaning for the one who makes the comparison, in the sense just given. So meaning is present wherever comparison occurs, and it cannot be removed. Suppose someone declares that nothing matters, that nothing has meaning: to make the declaration, the person weighs things for their worth. Weighing things for their worth is an act of comparison, so the declaration itself has meaning, in the sense just given.

Hossenfelder gives her own advice: "Instead of thinking of ourselves as selecting possible futures, I suggest we remain curious about what's to come and strive to learn more about ourselves and the universe we inhabit". I keep in full the curiosity Hossenfelder asks for. I also hold that the 'selecting' is real: each time you choose, you are a place where the future is selected, from what was open and sometimes from what was on no list.

A Beam Balanced to a Hair

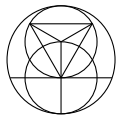
Come back to the two-pan balance, which in every chapter has stood for an act of comparison. Set a weight in each pan, matching the two weights as closely as you can, and let go. The beam trembles, balanced to within a hair. Which way does the beam tip?

Every act of comparison has a part that nothing earlier fixes, and the weighing is an act of comparison too, so a beam balanced to within a hair shows the unfixed part plainly: which way the beam tips is not written in advance. Laplace's demon would claim to know the tip already, from every draft of air and every speck of dust, *but* by the Incommensuration Theorem there is no world in which the demon's knowledge could be complete. The weighing still has its law (the heavier pan goes down, every time), and the law of the heavier pan is the kind of regularity that the whole success of physics lies in. The tip at the hair's breadth is found *only* in the weighing. Now suppose the one weighing is you: you set one possibility beside another and find how the two stand for you. Causes fix much of the result, as causes fix much of a decision. You call the part of the tip that nothing fixed your 'choice'.

The act of comparison is the subject of this book's question. So the act of comparison shows a world in which every comparison has a part unfixed. The world has an 'open future': the world is full of causes and never fixed in advance.

The short answer: Physics and the structure of comparison together show two things: the future is very largely fixed by the past, and no world is fixed completely, at any scale. The part that nothing fixes in advance is hard randomness. Hard randomness is choice, seen from inside by the one from whom the hard randomness comes.

What, then, is the one who chooses: a bag of atoms, a pattern that could be copied, a program?



Chapter Nine

Are You Only a Bag of Atoms?

What this chapter uses

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 Two).

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

Hard randomness is an outcome that no prior specification fixes, however complete (Chapters Seven and Eight).

Hard randomness is choice, seen from inside by the one from whom the hard randomness comes (Chapter Eight).

If you are made of nothing but particles, are you then nothing but the pattern your particles make: a pattern that could be copied, uploaded into a machine, or run as a program?

A Pack of Neurons

In 1994 the scientist Francis Crick gave one answer to the question, as bluntly as anyone has. In 1953 Crick and James Watson had found the double helix of DNA. In 1976 Crick moved to the Salk Institute in La Jolla, California, and Crick gave the rest of his working life to the brain and to *consciousness*, the fact that experience happens to someone.

Crick's book on the brain and consciousness is *The Astonishing Hypothesis*. In the book Crick states his idea in one sentence and then makes a joke of the idea.

> The Astonishing Hypothesis is that "You", your joys and your sorrows, your memories and your ambitions, your sense of personal identity and free will, are in fact no more than the behavior of a vast assembly of nerve cells and their associated molecules. As Lewis Carroll's Alice might have phrased it: "You're nothing but a pack of neurons".
>
> (Francis Crick, *The Astonishing Hypothesis*, chapter 1, "Introduction")

Crick's joke is in the last words, "a pack of neurons". The joke comes from Lewis Carroll's book *Alice's Adventures in Wonderland*, where at the end of the book the court of the Queen of Hearts turns on Alice, and Alice cries, "You're nothing but a pack of cards!" The whole pack of cards rises into the air and comes flying down on Alice. Then Alice wakes on the bank beside her sister. In Crick's joke, Alice says of you what Carroll's Alice said of the cards: you are nothing but a pack.

Sabine Hossenfelder quotes Crick's sentence in *Existential Physics*. She notes that Crick phrased the sentence sharply on purpose, and her own answer adds a claim that Crick's sentence does not make. She holds that you are the arrangement of your particles, and that some other material could carry the arrangement of your particles. She writes that uploading yourself to a computer is compatible with all we know, and that belief in

copies of you elsewhere conflicts with nothing in science. In this chapter I answer the question that her readers carry away: is a person a pattern, which could be copied, uploaded or simulated?

From Hossenfelder's pages

What Sabine Hossenfelder Showed

Hossenfelder asks the question in the title of her fourth chapter: "Are You Just a Bag of Atoms?" She begins the chapter with a picture. Take a person apart into chemical elements, and you have mostly water, then a big jar of carbon, some nitrogen, a few smaller jars of calcium and phosphorus, and pinches of the rest.

Then Hossenfelder gives her result, as a particle physicist:

> the available evidence tells us that the whole is the sum of the parts, not more and not less.
>
> (*Existential Physics*, chapter 4, "More Is More")

The constituents of an object are the parts the object is made of. Hossenfelder holds that "the behavior of an object can be deduced from" the properties, behavior and interactions of the object's constituents. She calls the view *reductionism*, and she counts reductionism among the best-established facts about nature, because no one has ever found a molecule, drug or material that behaves otherwise than its atoms allow. Hossenfelder also shows how physicists pass from small things to large things. Picture a map of hill country so detailed that the map shows every pebble in the meadows. For a hike, you lay a grid over the map and keep one average height for each square of the grid, and so you throw away detail too fine to matter at the size you care about. Physicists call averaging that throws away detail too fine to matter *coarse-graining*. Coarse-graining gives a simpler description, which Hossenfelder calls an *effective model*. Some things appear only in an effective model, such as the temperature of a gas or the con-

ductivity of a metal. Hossenfelder calls the things that appear only in an effective model *emergent*. The fine details at short distances barely matter for what happens at large distances. Physicists call the fact that the fine details barely matter the *decoupling of scales*. Hossenfelder notes that nobody knows why the scales decouple. In *Lost in Math*, Hossenfelder adds a caution of her own: "reductionism does not imply a steady increase of simplicity toward smaller scales" (chapter 10, "Lost in Math").

Then Hossenfelder turns from atoms and materials to you. Scientists dated the cells of adult bodies by the carbon in the cells, in a study published in 2005, and the scientists found the average cell only about seven years old. Hossenfelder compares a body to the ship of Theseus. The ship of Theseus was kept in a museum and repaired plank by plank, until none of the ship's first planks was left. The cells of a body are replaced as the planks of the ship were, and Hossenfelder says that the arrangement of the parts stays: "What makes you you is this entire arrangement" (chapter 4, "One Bit at a Time"). She tells a thought experiment from 1980 by the philosopher Zenon Pylyshyn. Replace one *neuron* (one nerve cell) in your brain with a silicon chip that does exactly what the neuron did. Then replace the next neuron, and the next, until your brain is all chips. Hossenfelder argues that the material underneath can be exchanged while the working of the whole brain stays the same, because the details at short distances decouple from what happens at large distances: the decoupling of scales.

Her conclusion:

> The information that makes you you can be encoded in many different physical forms. The possibility that you might one day upload yourself to a computer and continue living a virtual life is arguably beyond present-day technology. It might sound entirely crazy, but it's compatible with all we currently know.
>
> (*Existential Physics*, chapter 4, "One Bit at a Time")

Hossenfelder's fifth chapter has a question for its title: "Do Copies of Us Exist?" The *many-worlds interpretation* of quantum theory says that every possible outcome of a measurement happens, each outcome in its own branch of a world that keeps on splitting, and so, somewhere, a copy of you takes every road that you did not take. Hossenfelder finds that the many-worlds interpretation predicts exactly what the standard interpretation predicts. The standard interpretation is the interpretation that most textbooks teach, in which each measurement has one result. She writes that the difference between the two interpretations "is one of belief". The belief is about whether the other branches are, in her words, "as real as ours". When science says nothing either way about a belief, Hossenfelder calls the belief *ascientific*. She takes the word 'ascientific' from the physicist Tim Palmer. She writes that belief in infinitely many copies of you "doesn't conflict with anything we know. It's a science-compatible belief system" (chapter 5, "Many Worlds").

In the same fifth chapter Hossenfelder takes up the *simulation hypothesis*. The simulation hypothesis is the proposal that our world is a program running on a computer in some other world. The philosopher Nick Bostrom published the best-known argument for the simulation hypothesis in 2003. The usual complaint against the simulation hypothesis is that nobody knows whether consciousness can be simu-

lated. Hossenfelder sets the usual complaint aside and presses a complaint about physics instead. Of Bostrom she writes: "He implicitly claimed it's easy to reproduce the foundations of physics with something else" (chapter 5, "Do We Live in a Computer Simulation?"). An *algorithm* is a step-by-step recipe that a computer follows. Nobody knows an algorithm that reproduces general relativity (Einstein's theory of gravity) and the standard model (the theory of the known particles and forces) with all the symmetries of the two theories. Physicists have looked for signs that nature proceeds step by step, like computer code. Hossenfelder reports that the physicists have found no sign that nature proceeds step by step. So Hossenfelder concludes that the simulation hypothesis is no serious scientific argument, and that believing the simulation hypothesis takes faith.

In her eighth chapter Hossenfelder asks whether the universe thinks. The web of galaxies looks something like the network of connections in a brain. But signals cross the universe at no more than the speed of light. By Hossenfelder's count, neighboring clusters of galaxies could have traded only about a thousand signals so far. A brain manages about a thousand signals in three minutes. She concludes: "In a nutshell, the universe can't think, because it's too big" (chapter 8, "Size Matters"). Hossenfelder also asks whether each particle might hold a universe inside the particle, and she concludes "that the idea that there are universes inside particles is incompatible with what we currently know about the laws of nature" (chapter 8, "Is There a Universe in Each Particle?").

Then Hossenfelder turns to the idea that all matter is conscious, down to the smallest particles, and she calls the idea *panpsychism*. Hossenfelder tests panpsychism with a particle collider, a machine that makes particles collide. If an electron has experiences, then the electron needs several inner states. A collision produces every variant that a particle has, whether or not anyone can tell the variants apart, so the inner states of an electron would change how many electrons particle

collisions produce. Hossenfelder concludes: "We didn't see it; hence, electrons don't think, and neither do any other elementary particles" (chapter 8, "Are Electrons Conscious?"). Then Hossenfelder gives the word 'panpsychism' a second sense, and she explains, in her words, "why it's right" in the second sense. She ties consciousness to how much information a thing processes. So she grades consciousness: "Some systems are more conscious, others less, because some process more information, others less". A thing needs something to process information with, so Hossenfelder sets a least size for consciousness. Above the least size, consciousness arises from the known constituents of matter. Hossenfelder calls the second version of panpsychism *physics-compatible panpsychism*, and she concludes that the study of consciousness "has left the realm of philosophy. It is now science". So her readers carry away a second question beside the first: where is consciousness found, and does size decide where consciousness is found?

Hossenfelder completes her view with her answers on computing and on machines. After a conversation with the mathematician Roger Penrose, Hossenfelder names two possibilities. Her first possibility reads: "If consciousness emerges from the fundamental laws of physics that we already know, it is computable" (Other Voices #3, "Is Consciousness Computable?"). The *wave function* is the piece of mathematics that describes a quantum system, and the 'update' of the wave function is the change in the wave function when a measurement has a result. Her second possibility reads: "the update of the wave function in quantum mechanics might signal that we are missing some part of the story, and this missing part might be uncomputable". By *artificial general intelligence* Hossenfelder means a machine that can understand and learn as well as people can, and in her ninth chapter she writes: "Personally, I have little doubt that an artificial general intelligence is possible" (chapter 9, "AI Fragility").

Much of what Hossenfelder shows is right. A person is made of particles and of nothing else. Bostrom's argument *does* assume that the physics of a whole world can be rebuilt as a program. Hossenfelder points out exactly the step at which Bostrom makes the assumption. Artificial intelligence is possible in the sense of machines competent at tasks, and the brain science of consciousness is science. The question of this chapter is whether a person is a pattern that a copy or a program could carry. A person is made of particles, and a person is *also* an act that no copy or program carries.

I answer the question differently from Hossenfelder.

Made of Nothing but Particles

Start where Hossenfelder's account and mine agree. What is a cup of coffee made of? A chemist answers with molecules, and a physicist answers with electrons, nuclei and light (a *nucleus* is the tiny heavy center of an atom). Chemistry is made of nothing but electrons, nuclei, and light; that is not in question.

Hossenfelder's caution in *Lost in Math* is about theories: the theory of smaller things need not be simpler. I make a point about matter, beside her point about theories. The list of the kinds of particle is short and closed, as Chapter Three showed. Yet the few kinds of particle make matter that is not simple. Matter of many different structures needs only a few kinds of particle, combined in many ways, and the number of ways is enormous. Chemists have estimated how many small drug-like molecules the rules of chemistry allow within organic chemistry alone: about a one followed by sixty zeros, and only a sliver of the allowed molecules has ever been made. So the variety of matter comes from combination: a short list of kinds of particle, combined in an enormous number of ways.

To 'derive' the behavior of a whole is to work out the behavior from the laws of the parts of the whole. Hossenfelder holds that the behavior of a whole can be deduced from the parts of the whole. I hold that exact de-

duction succeeds only for the simplest systems, and my ground is the record of how far scientists have carried the deduction. In 1929 the physicist Paul Dirac wrote that the laws needed for the whole of chemistry were completely known, and that the only difficulty was that applying the laws exactly leads to equations much too complicated to solve. Physicists have solved the hydrogen atom exactly, and they have computed the helium atom to extraordinary precision. Chemists who compute actual molecules use only methods that approximate: in one method the chemists leave out how the electrons move together, and in another method the chemists carry a term that they choose and do not derive. We now know that exact derivation succeeds only for the simplest systems, and that approximate derivation goes far and stays approximate.

In principle, no description, however refined, contains everything that it describes. Hossenfelder's own map of the hills shows why no description contains everything that it describes. You can redraw the map at any fineness you like, down to the pebbles and below. Every redrawing brings the map closer to the land, but every redrawing is still a map. In the picture, the map is the description, and the land is the thing the description describes. I hold as firmly as Hossenfelder that a thing is made of its parts and of nothing else. I give the word 'reductionism' one sense: the claim that a description of the parts contains everything the thing is. Because no description contains everything that it describes, I exclude 'reductionism' in this sense. Reductionism in its own sense explains every whole wholly by its parts and by their earlier states, and that explanation leaves choice out of the account. Chapter Eight showed that choice is real: a choice is an outcome that nothing before the outcome fixed, seen from inside. In a cell, differences too small to record grow into differences that decide what happens, so no finite description of it stays adequate for long. Hossenfelder defines 'reductionism' as the view that the behavior of a whole can be deduced from the parts of the whole, and so her definition requires that a description of the parts leave out nothing that the whole does. A person's

choice is something the whole person does, and an explanation by the parts and their earlier states does not contain the choice, so I part from Hossenfelder's definition of reductionism.

The Mosaic and the Curve

A description of your parts, however fine, never contains all of you. What is missing from a description of your parts? Try a small experiment. Put on a piece of music you have never heard. Each note arrives after the note before it. You can never have the first hearing again: the hearing has a before and an after. Some notes surprise you, because nothing you heard earlier fixed them. And the hearing is yours: the music happens to someone.

The music shows three features: an order that runs one way, notes that nothing earlier fixed, and a hearing that is yours. I give each feature a name. The first feature is an order that runs one way, without a break, and I call the first feature the *arrow of time*. The second feature is an outcome that no prior specification fixes, however complete. Chapter Eight explained the second feature and called it *hard randomness*. When the one from whom the outcome comes sees the outcome from inside, hard randomness is choice. The third feature is the side from which experience happens (the stance, or point of view, of the one to whom things happen), and I call the third feature *the subjective*. The three features are found together or not at all: where any one of the three features is present, the other two are present, and where any one of the three is missing, all three are missing. I find the three features bound together in physics too: every interpretation of quantum theory has all three features together, or has none of the three. A thing that has the three features together has a side of its own, from which the thing compares and to which the outcome happens, and I call the thing's own side the thing's *inside*. I identify the three features, taken together as one act, as consciousness.

Now set a computation beside the three features. A *computation* is a procedure that goes from one state to the next, step by step and by fixed rules, where each state is a finite string of symbols, such as ones and zeros. In a computation one rule is applied in the same way at every step. Chapter Two called being the same under every change of place or setting *symmetry*. So the rule of a computation has symmetry, since the rule is the same at every step. The definition of a computation already says that a computation goes in steps, and Chapter Two set out the Incommensuration Theorem, which says why no one can ever remove the seams between the steps by making the steps finer.

'Perfected' here means held exactly, at the foundation. A running computation is an event, one state and then the next state, and a computation has symmetry exactly, at its foundation: one rule, applied the same way at every step. So, by the Incommensuration Theorem, a computation is discontinuous at its foundation: a computation comes in steps, with seams between the steps, and the seams remain however fine anyone makes the steps. No one can build continuity out of steps with seams between them.

Picture a mosaic that follows a curve. Make the tiles smaller, and the steps along the edge of the mosaic shrink until no eye can see the steps. The mosaic is still made of tiles, and the curve is still one unbroken line, made of no pieces at all. A computation is a mosaic in time. In the picture, each step of a computation is a tile, and the arrow of time is the curve. As you live the arrow of time, the arrow has no gaps, and so the arrow of time has continuity. The arrow runs one way, so no moment is the same as another moment, and the arrow has asymmetry. The arrow of time is continuity *with* asymmetry. Steps always leave seams, however fine the steps are, in the same way that tiles along a curve always leave seams. So a computation lacks the arrow of time. A computation lacks hard randomness too, because the step before fixes each step of a computation. The three features are found together or not at all, and a computation lacks two of the three features. So a computation lacks the third feature (the subjective) as well, and without the three features a computation has no inside. A *classical computation* is a program run on ordinary digital machinery,

and the conclusion about classical computation is this: "classical computation, however intricately organized, cannot be what consciousness is". The argument from the Incommensuration Theorem is about what a computation is, so the conclusion is true whatever the computation does.

On my account, a computation cannot be what consciousness is, whatever laws consciousness arises under, because the argument from the Incommensuration Theorem depends only on what a computation is and needs nothing from the laws. Hossenfelder's first possibility is that consciousness is computable if consciousness arises from the laws we already know, and by her own definition a process is 'computable' "if it can be produced by a computer algorithm" (chapter 9, "The Limits of Math"). On the first possibility I reach a different result in my account. Someone can build a program to behave as a person behaves, but the program never supplies consciousness. Penrose holds that understanding is not computing. Penrose's argument uses a theorem of the mathematician Kurt Gödel, and Gödel's theorem shows that any consistent system of rules for arithmetic leaves some true statements that the system cannot prove. I reach Penrose's conclusion on other ground. The ground of my account needs neither Gödel's theorem nor any special process in the brain. Hossenfelder's second possibility is that the update of the wave function signals a missing part of the story, a part that might be uncomputable. Chapter Six gave my answer about the update: the update is the change of the 'shared record' of what has been found, and the change of the shared record is the whole of the update. So in my account the update contains no hidden process, and a computation cannot be what consciousness is because of what a computation is.

A Person Is Not a File

Now look again at Pylyshyn's thought experiment, in which the neurons of a brain are replaced by chips, one at a time. Hossenfelder argues that a pattern, the arrangement of the brain, carries across from the neurons to the chips, but I ask a different question about the replacement:

what kind of physical process do the chips make? A thing can have an inside only if the thing is a physical process making comparisons in the world. Living things are physical processes making comparisons in the world. Whether a thing has an inside never depends on which program it runs. So the brain of chips has an inside, or lacks an inside, according to the kind of physical process that the chips make, and never according to the arrangement that the chips copy or the program that the chips run. I tie an inside to a physical process making comparisons in the world, of whatever material, and I deny an inside to any program, taken as a program.

The proposal called *uploading* is different from the replacement of neurons by chips: uploading is the proposal to scan the brain, run the scan as a program, and have the running program be you. An engineering problem has a goal that makes sense and an obstacle of resources: speed, memory, resolution, time. A *category error* is a request made in the wrong kind, like asking what color the number seven is. Uploading is a category error, and no hard problem of engineering. Experience needs three things: something new that nothing before it fixed, time running one way, and a point of view from inside. The three things are the three features named earlier in this chapter: hard randomness, the arrow of time and the subjective. A computation is built without the three things. No better hardware supplies the three things, because a computation is what you have once the three things have been taken out. A person is not a very large file.

Someone could still build a machine to behave as you behave, to any degree of faithfulness anyone likes. The machine would not be that person, or any person, because no description from outside contains everything that a person is.

On artificial intelligence Hossenfelder's account and mine agree again, and artificial intelligence is possible. By artificial intelligence, I mean computation that can "calculate, predict, translate and converse, and do all of it superbly". A person types a question into a chat window and gets back a fluent reply that reads as carefully thought out. When 'intelligence' means competence at a task, intelligence is laid out for anyone to check

from outside. Machines can have as much intelligence as the machines are built for. The fluent reply is behavior, and a program produces the reply. But a program, as a program, has no one in it. I draw the line between 'processing' and 'experience'. Taken as a program, a program of any intelligence is on the side of processing. So I share Hossenfelder's view of what machines can do, and I part from her *only* on whether anyone is there in the machine.

What about the copies of you? Hossenfelder's chapters describe two kinds of copy, and my account has an answer for each kind. The first kind is a copy made by scanning, and a copy made by scanning is a copy of the outside of you. Identity, in the sense of a single unitary consciousness, is not something a copy can carry. A *quantum state* is the wave function of a system, and I name a parallel in physics to what a copy cannot carry: the *no-cloning theorem* of 1982, which says that no single operation can copy every unknown quantum state. The second kind of copy is a copy of you in the many worlds of the many-worlds interpretation. I count the other branches as structure laid out in the mathematics, which nobody ever finds in any act of comparison. If one law fixes a whole world completely, branches and all, then the world has perfect symmetry and perfect continuity together. The continuity is perfect because every state is fixed without a gap, and I defined continuity earlier in this chapter as having no gaps. The Incommensuration Theorem forbids perfect symmetry and perfect continuity together, so I reach a different result from Hossenfelder's. The Incommensuration Theorem excludes the many-worlds picture, taken as a description of a whole world, and the copies of you in the many worlds are excluded with the many-worlds picture.

A Program Is Not a World

I reach Hossenfelder's central result about the simulation hypothesis on separate ground. She says that nobody knows how to rebuild the established physics as an algorithm. I say why nobody *could* rebuild the established physics as an algorithm, and the reason is a fact about lists.

Think of the number pi, the distance around a circle divided by the distance across the circle. The digits of pi go on without end and never fall into a repeating pattern. A computer can give you as many digits of pi as you ask for. But at every stage the computer has given you a finite list of digits. If you take everything a computation could ever produce, all together, then everything that the computation could ever produce can be listed: set out first, second, third, with nothing left out. In 1874 the mathematician Georg Cantor proved that the points of the number line cannot be listed, and in 1891 Cantor's diagonal argument showed why the points of the number line cannot be listed. The number line is smooth, with another value between any two values, and mathematicians call the smooth number line the *continuum*. Space and time are the 'arena' in which everything happens. The arena of space and time is continuous: the arena has no least step. I derive that the arena has no least step, and physicists find the arena smooth at every scale yet probed. So the world contains what no list can contain. A simulation can come as close to the world as you like, but a simulation never becomes the world.

The difference between a simulation and the world shows over time. Systems in the world are sensitive to how the systems start, and the scientist Edward Lorenz gave a famous picture of the sensitivity: the flap of a butterfly's wings can decide where a storm forms weeks later. A simulation can cut its numbers off at any fixed precision, but whatever the precision, the simulation comes in time to differ from the world, on the scale of everyday things. So the difference between a program and the world is a difference of kind, and the difference shows because systems in the world are sensitive to how the systems start.

Hossenfelder's verdict is that believing the simulation hypothesis takes faith, and I go further than her verdict. Suppose a simulated world had people in it, each with experience of their own. The experience of the simulated people would need hard randomness, an arrow of time and the subjective. But a program has none of the three features of its own. The program could draw hard randomness from a physical source in the world that runs the computer. Then the randomness of the simulated

world would belong to the world that runs the computer, and so would the arrow of time and the subjective side of the simulated world, because the three features are found together or not at all. So a simulated world with people in it has no inside of its own: the people of the simulated world have their inside as part of the one world that runs the computer. Picture a prison cell. The walls of the cell *do* limit what the person inside can see, but the person in the cell still breathes the same air and ages by the same clock as everyone outside. A simulated world with people in it is like the prison cell: a walled-off region of the one world, and no second world. In the picture, the walls of the cell are the limits of the simulation. I draw the conclusion for the simulation hypothesis in the form that matters to us: the hypothesis "that we are real subjects in a world that is not real". The structure of comparison shows that the hypothesis, in the form that matters to us, cannot be true, as a matter of principle and therefore of all future practice.

Bostrom's argument sets out three choices. First, almost no civilization reaches the power to run simulated worlds with people in them. Second, almost no civilization that reaches the power wants to run the simulated worlds. Third, we are almost certainly simulated, because simulated observers would far outnumber the other observers. The third choice depends on how Bostrom counts observers: Bostrom counts each simulation as a separate world with observers of its own. But a simulation is a region of the one world, so any observers in a simulation are observers of the one world, and the separate worlds that the count needs are not there. So the third choice has no ground in Bostrom's count in the form that matters to us, which I state as "that we are real subjects in a world that is not real".

Electrons, Brains and the Universe

Where then is consciousness found, and does size decide where consciousness is found? Hossenfelder answers by size. On her answer, a thing that is too small has nothing to process information with. A thing that is too big has signals that are too slow. I agree with one step of Hossenfeld-

er's argument: every thought needs signals. A thought is made of comparisons: a thing can have an inside only if the thing is a physical process making comparisons in the world, and a thinker, of whatever material, thinks as a physical process making comparisons. Even the smallest comparison needs three things: a second thing to compare against, a lasting structure to keep the record, and a signal between the thing that compares and the second thing. So every thought needs signals, as Hossenfelder assumes in counting the signals between clusters of galaxies.

My account has two results that bear on Hossenfelder's conclusion about universes inside particles, and both results agree with her conclusion. The first result is that the list of the kinds of particle is closed, as Chapter Three showed. So no further kind of particle lies hidden inside the known kinds. The second result is that, on my account, the visible universe has one level only: the physical level. Beneath the physical level there is no machine whose causes anything could call on, in the way a program calls on the computer that runs the program. All of the information of what happens must come from somewhere within that one level, and so beneath the particles there is no deeper level that could supply a universe inside a particle.

I place consciousness in interaction, and in no property of matter. A rule holds: wherever interaction occurs, some form of consciousness is present. Consciousness is a property of interaction, and the degree and kind of consciousness go with the richness and structure of the interaction. A thermostat interacts with the temperature of a room in a simple way, and the thermostat's simple interaction is an interaction all the same, while a brain interacts with a world in an enormously complex way. A brain made of chips is an interaction with its world too, so it has the degree of consciousness that its interaction has, while the computation that the chips run, taken as a computation, is not consciousness, as the section on the replacement of neurons by chips showed. So both accounts grade consciousness: Hossenfelder grades consciousness by the information processed, and I grade consciousness by the richness of the interaction, because consciousness is a property of interaction. On my account, the

grades of consciousness go all the way down, with no least size. A *photodiode* is the simplest kind of light sensor: "A photodiode's single undetermined click is choice at its least gathered; a living person is choice gathered across every channel of perception into one persisting stance". The word 'gathered' here means held together: in a person, one self that persists holds together the choices made through every sense, and the 'stance' is the point of view from which the self meets the world.

Hossenfelder's collider argument shows that an electron carries no hidden store of inner states that would change how many electrons a collision makes. I place consciousness in no property of matter, so I look for no hidden inner states in the electron. Her collider result and my account agree. The word 'panpsychism' needs care, because people use the word in more than one sense. Hossenfelder rejects the first sense. In the first sense, every particle carries a tiny experience of its own, and the tiny experiences must somehow combine into larger experiences. I begin from interaction, and never from small experiences to be added up, so my account is a different view from 'panpsychism' in the first sense. Hossenfelder's physics-compatible panpsychism is the second sense of the word, in which consciousness comes in degrees and arises above a least size. Physics-compatible panpsychism and my account both have grades of consciousness, but the two views differ on the least size. I use the word 'panpsychism' in a third sense: "all as alive, as intentional". The word 'intentional' here means having a will and a purpose of one's own. That book is written in short numbered statements, and the statement on panpsychism comes just after a statement about machines, which speaks of how far a machine seems "self willed" and "conscious" to anyone who perceives the machine. In the third sense I hold that panpsychism applies at every scale, because the degree to which a thing appears conscious, to anyone perceiving the thing, is never exactly zero.

I also say what size has to do with consciousness. I hold that consciousness is at work at every scale of being. I hold also that one and the same idea of consciousness applies at every level of scale. I hold too that the *being* of consciousness, as distinct from the idea of consciousness,

"does not have position, scale, or extent". So consciousness is found in things of every size, and consciousness itself has no size. I say, in a line standing alone, that everything "from atoms to universes" has some positive degree of meaningfulness, purpose and value.

We have to tell a thought apart from consciousness. A thing that has an inside is a physical process making comparisons, as a living thing is, and the thoughts of a thing with an inside are made of the comparisons the thing makes, each of which needs a signal. I hold that consciousness itself is *not* a process. The idea of a process combines only two ideas: existence and interaction. In the sense of Chapter Two, to 'exist' means to stand as structure: timeless, the same in every instance, able to be held in view as a whole. The idea of consciousness combines only interaction and creation, without the idea of existence, and in *An Immanent Metaphysics* 'creation' is potentiality: what is never repeated and is fixed by nothing before it. So on thought I agree with Hossenfelder that every thought needs signals, and I accept her count of signals as a limit on thinking. Neighboring clusters of galaxies have had time to trade only about a thousand signals, so the universe as a whole has had time for very little thought. I part from Hossenfelder on whether size decides where consciousness is found: in my account consciousness is found at every scale, including the scale of the universe, because consciousness itself is not a process and has no size.

Hossenfelder is right that the brain science of consciousness is science, and one study shows how the brain science of consciousness works. In the study, published in the journal *Nature* on 30 April 2025, each of two rival theories of consciousness predicted in advance where and when the brain's activity would track what a person perceived. Then scientists measured the brains of 256 people, and each theory came out partly right and partly wrong. We now know that claims about where and when the brain's activity tracks what a person perceives can be tested by measurement and decided. I call the brain science of consciousness genuine, valuable and necessary: the brain science of consciousness studies consciousness from outside. Experience itself is held in the act of experiencing, by the one who experiences. No measurement made from outside has anoth-

er person's act of experiencing as its 'content', what the measurement is about. So the question of what experience is belongs to 'metaphysics', the study of what must be so for anything at all to be known. I hold that only a metaphysical account of consciousness is possible. Perception cannot perceive perception.

What the Balance Weighs

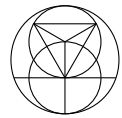
Come back to the two-pan balance on its bench. You could draw the balance so completely that every screw and every grain of the balance's brass was on the page. You could run the drawing as a program. You could watch a picture of the beam tip on a screen, as close to the tipping on the bench as you like. The drawing would still weigh nothing. A balance can weigh anything set on the balance, but a description of the balance, however complete, is not a weighing. A weighing is an act. In a weighing, one thing is set beside another, and the beam tips one way and leaves its mark. No outcome is fixed before the beam tips.

A person is on the side of the weighing. A scan copies the drawing, the arrangement of your parts laid out from outside, but you are the weighing going on, from inside, in one direction, with outcomes that nothing fixed in advance. So the question whether you are only a bag of atoms becomes a question about comparison, and the balance answers the question.

The short answer: You are made of nothing but particles, and you are *also* an act of comparison happening from inside, running one way in time, with outcomes that nothing fixed in advance. A copy, an upload or a program can carry the pattern of your parts, which is the outside of the act. Only you carry the act itself. Consciousness is found wherever there is in-

teraction, at every scale, so size does not decide where consciousness is found. Size limits only how much a thing can think, because every thought needs signals.

You are an act happening now, and more than a pattern laid out once and for all. What, then, becomes of the moments you have already lived: does the past still exist?



Chapter Ten

Does the Past Still Exist, and Why Does Time Run One Way?

What this chapter uses

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 Two).

To *exist* is to stand as structure: timeless, the same in every instance, able to be held in view as a whole; to be *real* is to be given in an actual act of comparison: here, now, with the future still open (Chapter Two).

The *content* of a comparison is what the verdict of the comparison is about, and the *context* is the respect in which the two things compared are two (Chapter Three).

Hard randomness is choice, seen from inside by the one from whom the hard randomness comes (Chapter Eight).

Does the past still exist, and why does time run only one way? Sabine Hossenfelder tells her readers that in relativity the past, the present and the future have equal standing. Hossenfelder calls the present moment

'the Now'. She adds that the Now is special only to whoever feels the Now. She also says that time runs one way because disorder has grown since a special beginning. Are Hossenfelder's three claims true?

A Letter from Princeton

In March 1955 Albert Einstein was seventy-six years old and living in Princeton, New Jersey. Einstein's oldest friend, Michele Besso, died in Geneva on 15 March 1955. Einstein and Besso had met in Zurich in the late 1890s, when Einstein was a student in Zurich, and later the two friends worked in the same Swiss patent office, in Bern, and walked home together after work. In 1905 Einstein set out his theory of relativity in a paper that ends by thanking one person: Einstein's friend and colleague Besso.

On 21 March Einstein wrote to Besso's family. Einstein wrote, in the English of one translation: "Now he has preceded me a little in parting from this strange world, too. This means nothing". In the same letter Einstein gave the reason why Besso's parting means nothing: for "us believing physicists", he wrote, the distinction between past, present and future has only the meaning of an illusion, though a stubborn one. In English, Einstein's line is usually quoted as "only a stubbornly persistent illusion". Einstein died less than a month later, on 18 April 1955.

Einstein's letter is a letter of comfort, and the comfort in the letter is a claim about time. Einstein's claim is that Besso's life has not gone anywhere: Besso's life is still there, in its own stretch of the world. Hossenfelder makes a claim like Einstein's about a grandmother instead of a friend, and she writes with the same tenderness as Einstein. Is Besso's life still there, as Einstein's letter says? The difference between past, present and future gives time its one direction. Is Einstein right that the difference between past, present and future is an illusion?

From Hossenfelder's pages

What Sabine Hossenfelder Showed

Hossenfelder asks whether the past still exists, in the first chapter of *Existential Physics*. She answers the question with Einstein's physics, carefully told. *Special relativity* is Einstein's theory of 1905 about how people who move steadily relative to one another measure space and time. Hossenfelder gives a picture for the most surprising result of special relativity. You stand between two mirrors and send a pulse of laser light to each mirror. When the two pulses come back to you together, you know that the two pulses struck the two mirrors at the same moment. Your friend Sue flies past with two mirrors of her own and sends a pulse of laser light to each of her mirrors, and Sue finds a different pair of moments to be the same moment. Neither of you has made a mistake.

> This example shows that in special relativity the statement that two events happened at the same time is meaningless.
>
> (*Existential Physics*, chapter 1, "Now and Never")

When observers move relative to one another, the observers disagree about which distant events happen at the same moment, and physicists call the disagreement the *relativity of simultaneity* ('simultaneity' means happening at the same moment). The relativity of simultaneity is established physics, and Hossenfelder explains the relativity of simultaneity well.

Then Hossenfelder takes one more step in her argument. Take two events: your birth, and the explosion of a distant star. The star is far enough away that the light of the explosion had not reached Earth when you were born. A traveler who moves fast enough finds that your birth and the explosion happen at the same moment, while another traveler finds that the explosion happens at the same moment as your death. Hossenfelder writes that every traveler's sense of "now" is "equally valid". Hossenfelder argues from the equal validity of every

traveler's 'now' that the explosion exists at your birth, that your death exists at the explosion, and so that your death exists at your birth. Hossenfelder carries the argument to any two events anywhere, and she reaches the conclusion that

> the physics of Einstein's special relativity does not allow us to constrain existence to merely a moment that we call "now".
>
> (*Existential Physics*, chapter 1, "Now and Never")

Hossenfelder's conclusion gives a picture of the world in which the whole of space and all of time make one four-dimensional block, with every event in the block, past and future alike. The picture is called the *block universe*. In the same section Hossenfelder writes: "the future, present, and past exist in the same way; it's just that we do not experience them the same way".

Hossenfelder's second line of thought is about information. When a rule fixes every state of a thing from the state at one moment, Hossenfelder calls the rule an *evolution law*. The laws of physics are evolution laws in Hossenfelder's sense. Hossenfelder says that the known laws can be run backward as well as forward, apart from two disputed cases: the first disputed case is the update of the quantum description when something is measured. The second disputed case is the slow evaporation of black holes, which are regions where gravity is so strong that nothing, not even light, gets out. So, according to Hossenfelder, the details of every life are kept.

> Nevertheless, if you trust our mathematics, the information is still there, somewhere, somehow, spread out over the universe, but preserved forever.
>
> (*Existential Physics*, chapter 1, "Eternal Information")

In her third chapter, Hossenfelder asks why time seems to run one way. She starts in the kitchen. Put flour, sugar, eggs and butter in a bowl, switch on the mixer, and you get a smooth batter that does not unmix again. The parts of a thing can be arranged in many detailed ways that all give the same overall look, and Hossenfelder defines *entropy* as the count of the detailed arrangements that all give one overall look. There are vastly more ways to be a smooth batter than to be flour lying under sugar. The *second law of thermodynamics* says that a large system left to itself goes toward the look with the larger count. The phrase 'time's arrow' names the one direction in which time runs. In Hossenfelder's account, time's arrow is the direction in which the count of arrangements grows.

In Hossenfelder's account, time's arrow needs a beginning with a small count. The assumption that supplies the small beginning is that the universe began in a state of low entropy, a state that was very unlikely, and Hossenfelder calls the assumption the *past-hypothesis*. Hossenfelder is plain about whether present theories can explain the past-hypothesis:

> The question why an initial state was what it was just isn't answerable with the theories we currently have.
>
> (*Existential Physics*, chapter 3, "The Last Question")

Hossenfelder names three proposals that would explain the beginning with a different kind of theory. The mathematician Roger Penrose calls one proposal 'conformal cyclic cosmology'. In Penrose's proposal the universe runs through a series of 'eons', one whole history after another. The entropy of the universe is destroyed at the end of each eon, so the next eon starts afresh with a low count. Hossenfelder notes that Penrose's proposal has a price: information is destroyed for good. A 'multiverse' is a collection of many universes. The physicist Sean Carroll proposes that new universes of low entropy are made out of a lar-

ger multiverse. The physicist Julian Barbour proposes that the universe began from a 'Janus point', at which the direction of time changes.

In the same chapter, Hossenfelder asks why no one ever gets younger, and her answer is short: our bodies pile up small errors that are likely to happen and unlikely to undo themselves. Hossenfelder writes: "What really kills us is entropy increase".

Hossenfelder then looks hard at entropy itself, and on entropy she is sharp. The count of arrangements depends on which arrangements we choose to lump together as looking the same.

> Entropy thus is really a measure of our ignorance, not a measure for the actual state of the system.
>
> (*Existential Physics*, chapter 3, "The Last Question")

Hossenfelder adds: "But change the notion of similarity and you change the notion of entropy". Hossenfelder also says that no one yet knows how to count the entropy of gravity. Hossenfelder does not trust the second law to tell us how the universe as a whole will end, and she has two reasons: an entropy depends on what we lump together, and no one yet knows how to count the entropy of gravity.

On the Now, Hossenfelder starts from a worry of Einstein's that the philosopher Rudolf Carnap reported in 1963. In Carnap's report, Einstein explained that the experience of the Now "means something special for man, something different from the past and the future", and that "this important difference does not and cannot occur within physics". Hossenfelder explains Einstein's worry away with mica, a soft mineral that keeps permanent tracks where small particles have passed through the mica. Hossenfelder writes: "But, like us, mica has

a memory of the past and not of the future". According to Hossenfelder, anything that has a memory finds the present special, because the present is where the memory of the thing ends.

> Objectively, the Now doesn't exist, but subjectively we perceive each moment as special.
>
> (*Existential Physics*, chapter 3, "The Problem of the Now")

Last, Hossenfelder takes up a strange worry: in an endless, fully mixed universe, chance alone would now and then assemble a working brain for a moment. The imagined minds that chance assembles are called *Boltzmann brains*, after the physicist Ludwig Boltzmann. Suppose our world were an endless, fully mixed universe: then a mind like yours would most likely be a Boltzmann brain, and a Boltzmann brain would most likely see the world dissolve in the next moment. The world does not dissolve. A 'fluctuation' is a change made by chance alone. When every possible fluctuation eventually happens in a theory, the theory is called *ergodic*. Hossenfelder reads the Boltzmann-brain argument the other way around, as a lesson about the laws:

> Indeed, we can instead read the argument backward and conclude that at least one of our fundamental theories can't be ergodic.
>
> (*Existential Physics*, chapter 3, "Brains. In Empty Space")

Hossenfelder is right, without change, in much of what she says in chapters 1 and 3 of *Existential Physics*. The relativity of simultaneity is right. Hossenfelder is right that mica remembers, and right that the memory of mica runs only toward the past. Hossenfelder is right that an entropy depends on what is lumped together.

I find the same result about entropy.

Where the Two Accounts Meet

Three of Hossenfelder's results also follow in my account, from ground of its own. Every comparison is about something.

The first result common to both accounts is about entropy. Picture a gas in a closed box. The box is the region of space in which the gas is found. Every measurement on the gas is made from the box. You find the entropy of the gas by counting the arrangements of the molecules that no measurement made on the box can tell apart, so the box is the context of the count. An entropy is a count: the number of states of a system that the comparisons available from some context cannot tell apart. When the context changes, what is counted changes, so I agree with Hossenfelder that an entropy is relative to a standard of telling states apart, and in both accounts changing the standard changes the entropy.

Hossenfelder bases the count on what she calls our 'ignorance', while I base the count on the context of the comparison. The one who compares may be a thermometer as well as a person. I also give a reason why Hossenfelder does not trust the second law for the universe as a whole, and the reason is the context that every count needs. The box around a gas is the context of the gas, but the universe has no box. Every region lies inside the universe, so there is no place outside the universe from which every measurement on the universe could be made and the states of the universe counted. Entropy grows inside the history we live in, as the second law says. The old name 'heat death' means a final state of greatest disorder that lasts forever. A heat death has nothing to be counted against.

The second result common to both accounts is about information. I first tell apart two things that are both called 'information'. Picture a handwritten letter in a post office. The letter says something: the words chosen out of all the words that could have been written. What the letter says goes wherever the letter goes. The sorting machine of the post office reads only the postcode, so the post office can also count how many letters

sit in one bin looking alike to the sorting machine. The count belongs to the post office, and not to the letter. Matter has a 'form': what the matter is, and which of its possible alternatives the matter has taken. The form of the matter goes wherever the matter goes, as what the letter says goes wherever the letter goes, and on my account the form of the matter is information in the first sense. The count of the post office is a count of letters relative to the sorting machine, and in the same way a count of states relative to a context is an entropy. An entropy is information in the second sense.

Information in the first sense is never destroyed, in black holes as everywhere else: what falls into a black hole is kept, but what falls into a black hole is out of reach of everyone who stays outside the black hole. I state the reason in plain words: the matter does not cease, and the form of the matter goes wherever the matter goes. So Hossenfelder and I agree that the details of a grandmother's life are not wiped out. The two accounts agree on separate ground. Hossenfelder's ground is the law that runs backward, while the ground of my account is the matter that does not cease.

The third result common to both accounts is about the Now. Suppose someone describes the world from outside, in the third person. Every moment in the description is like every other moment, so the description has no 'now' in it. I state the point in two lines.

> No third-person account of the world has a 'now' or a 'here' in it; from that vantage every moment and every place is like every other. Only from inside does now have its particular weight.
>
> (*Home in the World*, chapter 4, "Two Kinds of Perfect Knowing")

The passage agrees with Hossenfelder's mica on one fact: the present is singled out only from inside, and never by a description from outside.

A Recipe and a Baking

Picture a recipe for bread, written on a card in a kitchen drawer. The recipe is the same every time someone reads the recipe. The recipe can be held in view all at once, from flour to oven. Now picture the bread being made, this morning. The dough is rising now, in this kitchen, and how the loaf turns out is not yet settled.

I give two familiar words, 'exist' and 'real', exact and different meanings, to keep the recipe and the baking apart. So the recipe 'exists', and the baking 'is real'.

Take 'exist' in its exact sense, and one part of Hossenfelder's answer is exactly right. Relativity describes space and time together as one four-dimensional pattern, and time is one dimension of the four-dimensional pattern. The dimension of time exists. Every moment of the dimension of time has the same standing as every other moment. The events that have already happened are the events that exist along the dimension of time, and those events are structure: the past, laid out with every event in its place. Last Thursday is still there, as a place in the pattern, and Besso's whole life is still there too, as a stretch of the pattern. The past still exists, in the exact sense of 'exist'.

Physics uses the word 'time' for more than one thing. I name two of the things that physics calls time. Time can be laid out with space as one pattern. Time laid out in the pattern is the time measured along each path through space and time, together with the order of before and after that the pattern contains, and I call time laid out with space as one pattern *geometric time*. Findings are made one after another, and each finding leaves its record. I call the order in which findings are made *event time*. Geometric time is the dimension of time laid out as structure, so geometric time exists. The events laid out along geometric time reach as far as the present. Event time is given in acts, so event time is real. Geometric time and event time each have their own role in physics, and neither is an illusion laid over the other.

I describe the block universe in one line: "The block universe takes geometric time for the whole, and drops event time". The findings of last Thursday were real when the findings were made. Now the findings of last Thursday remain only as records. Last Thursday is a place in the pattern, and not a happening that is still going on.

The future is open: which events will fill the future is not yet decided. The opposite of symmetry is 'asymmetry', and the opposite of continuity is 'discontinuity'. When a world's laws fix every event, future events included, I call the world 'fully fixed'. A fully fixed world would need two things, both perfect at once: first, laws that are perfectly the same everywhere, which is symmetry; and second, no gap anywhere in what the laws fix, which is continuity. By the Incommensuration Theorem, symmetry and continuity cannot both be perfect at once, so the world is not fully fixed. So the future does not exist in the sense the past does. The events of the future are not yet part of what exists.

I keep Hossenfelder's starting point, the relativity of simultaneity. I describe Einstein's picture with a lamp flashing in the middle of a moving railway car. A rider in the car finds that the light of the lamp reaches both end walls at the same moment, while someone beside the track finds that the light reaches the back wall first. A rider on a faster train overtaking the car finds that the light reaches the front wall first. Suppose two events are too far apart for light to join the two events: then the two events have no fixed order, and for some traveler a signal between the two events would arrive before the signal was sent. In every comparison the order of acts runs one way, so no signal joins two events that are too far apart for light to join. The travelers disagree about which distant events share a moment. Yet each traveler's own findings still come one after another, in one order that runs forward.

Hossenfelder's step goes from 'happen at the same time for someone' to 'exists now'. Hossenfelder's step uses the one word 'exists' both for a place in the pattern and for a happening given in an act. When 'exists' and 'is real' are kept apart, the past exists as structure, the present is real, and the future is not already there. The cosmologist George Ellis reached the

same open future from inside physics: in 2006 Ellis proposed an 'evolving block universe', in which the future boundary of the block keeps advancing because what will happen is not yet decided. Set the route of Ellis and my route side by side. Ellis reaches the open future from physics, by way of quantum chance and the one-way step of measurement, while I reach the open future from the structure of comparison: from what every comparison must contain.

Why No Process Runs Back Exactly

Drop a ball on a wooden floor and film the ball. The ball bounces lower and lower and comes to rest. The floor and the air are now a little warmer. Run the film backward and you see the floor and the air give their warmth back, and the ball leap into the hand.

The laws of motion allow the backward film. When the laws allow the reverse of a process that the laws allow, I call the reverse a *lawful reversal*. The backward film could happen in fact only if every molecule of the floor and of the air retraced its exact path. When a reversed process retraces exactly the states of the original process, I call the reversal a *faithful reversal*.

When a change leaves the laws the same, physicists call the change a 'symmetry' of the laws. Lawful reversal needs one symmetry of the laws: reversing time must leave the laws the same. The laws are the same with time reversed to an extraordinary degree. Faithful reversal needs more than the symmetry of the laws: faithful reversal also needs a description of the state with no gaps at all, in which no part of the system is left free to go its own way. A description with no gaps at all is 'continuity' in the sense of the Incommensuration Theorem: no gap anywhere in what the law fixes. So faithful reversal needs symmetry and continuity together, both perfect, and by the Incommensuration Theorem symmetry and continuity are exactly the pair that cannot both be perfect at once.

So no process can be run back faithfully, at any scale. Time therefore has a direction in every single interaction, between two particles as much as in a bowl of batter, and the direction of time in a single interaction needs no crowd of particles, no entropy and no special beginning.

The form of what happened is kept, because information in the first sense, the form of the matter, is never destroyed. But the past cannot be rebuilt from the present by running the laws backward, because the present is never given completely enough to run back from. Hossenfelder writes that, to recover an earlier state, "all you need to do is apply the evolution law and run it backward", and Hossenfelder's line needs exactly the complete present that is never given.

Physicists have tried running things backward, and what the physicists found agrees with the difference between lawful reversal and faithful reversal. A nucleus carries what physicists call a 'spin', like a tiny top turning in a magnetic field. In 1950 the physicist Erwin Hahn lined up the spins of the nuclei in a liquid and let the spins drift out of step. A later pulse of radio waves turned the drift of the spins around, and the spins came back into step and gave a returning signal, which is called a *spin echo*. Later experimenters carried the reversal further, and in every experiment the return was partial, so we now know that a laboratory can reverse a motion lawfully, and can reverse the motion only in part. The record of the laboratory still contains the finding that the signal had faded, and the echo is a new finding, made afterward.

Physicists found the symmetry of time broken in the laws themselves, in a second set of measurements. In 1964 four physicists studied the decays of short-lived particles called 'neutral kaons': James Christenson, James Cronin, Val Fitch and René Turlay. Picture swapping every particle for its antiparticle while reflecting space as in a mirror: physicists call the double change 'CP'. Christenson, Cronin, Fitch and Turlay found that the decays of neutral kaons break the symmetry CP, and a general theorem of particle physics shows that the break of CP means that the laws are not perfectly the same with time reversed. In 1998 the physicists of the CPLEAR experiment studied kaons at CERN, the European laboratory for

particle physics near Geneva, and saw directly that the laws are not perfectly the same with time reversed. In 2012 the physicists of the BaBar experiment in California saw the same break of the symmetry of time in heavier particles called 'B mesons'. We now know that the symmetry of the laws under time reversal is extraordinarily close to perfect, and not perfect.

The Incommensuration Theorem says why the symmetry of the laws under time reversal stops short of perfect. The sameness of the laws with time reversed is a symmetry in exactly the sense of the Incommensuration Theorem, because the laws stay the same across a change of setting. For time reversal, the change of setting is the change from one direction of time to the other. Suppose the sameness were perfect: then the sameness would hold for every process, at every scale, in every context, without exception. I call a perfect reversal "not merely lawful but faithful", because a perfect reversal retraces exactly the states that the original process passed through, so a perfect reversal needs continuity: the state described with no gap at any point or scale. So perfect sameness of the laws with time reversed needs symmetry and continuity together, both perfect, and perfect symmetry with perfect continuity is the first of the two pairs in the statement of the Incommensuration Theorem (the second pair is asymmetry with discontinuity). Yet the laws can still come extraordinarily close to perfect sameness. The reason is two words of the Incommensuration Theorem: "simultaneously and fundamentally". Within any finite domain, symmetry and continuity co-occur to finite degree. What they cannot do is both be perfected at once. A 'finite domain' is any bounded range of processes, scales and contexts, and a finite domain falls short of the whole range that perfect sameness would need: "every process, at every scale, in every context, without exception". So the laws are the same with time reversed to an extraordinary degree, and never perfectly. Its own argument says the symmetry cannot be perfect, and I identify the findings on kaons and B mesons as a place where the impossibility of a perfect symmetry of time has become visible to instruments.

Now bring back the two-pan balance of the market stall, and the ledger that the stallholder keeps beside the balance. Before a weighing, the beam may tip either way. Then the stallholder makes the weighing and writes the weighing in the ledger. You can take the goods off and weigh the goods again, but the second weighing is a new weighing, written on a new line, and the line written before stays written. Each weighing written in the ledger stays written, and the lines of the ledger follow one another in one order. In the picture, the one order of the lines stands for the direction of time.

Every record that any instrument has ever found is a record of the past, because no instrument holds a finding before the act that makes the finding. I identify the one-way order of every act of comparison, from what could be found, to the act, to the record, with the direction of time.

Hossenfelder's arrow of entropy is found in every kitchen and every engine, and the arrow of entropy points the same way as the order of acts, for a reason that Hossenfelder's mica shows. Making a record is itself a change that cannot be undone. Making a record raises the entropy of the instrument that holds the record. The track in the mica is a growth of disorder in the mica. So each act of recording joins the two arrows in one event: the first arrow is the order of the act, and the second arrow is a growth of entropy in the record. The one-way order of acts appears as a growth of disorder in things made of very many parts, such as eggs and engines.

Why the Beginning Was Smooth

Hossenfelder notes something odd about the young universe. The matter of the young universe was spread almost evenly, like a smooth batter, and a smooth batter has high entropy. Yet the past-hypothesis says that the beginning had low entropy. Hossenfelder resolves the puzzle with gravity: gravity pulls things into clumps, so for gravity an even

spread is a state of low entropy, and the evenly spread beginning therefore had low entropy. Hossenfelder says that present theories cannot answer one question: why did the count for gravity begin so low?

I divide the past-hypothesis into two parts. First, the past-hypothesis is not needed as the source of the direction of time, because the direction of time is already present in every single act. I write the name of the past-hypothesis with capitals. The Past Hypothesis is not the source of the arrow. Second, the past-hypothesis is a statement about how our history began, and as a statement about our history the past-hypothesis has two halves with different grounds in my account. The high entropy of the matter is simply what is observed, while the low entropy of gravity has a reason in my account.

The reason depends on an idea from earlier in this chapter: every count has a context. Think of a census. A census counts what the clerks of the census can tell apart, on the forms of the census. Suppose a new country is founded, with new clerks and new forms: the first census of the new country starts a count of its own, and does not continue the census of the old country.

The history of the universe comes in whole spans, one after another. I call one whole span of the history of the universe an *epoch*. Our epoch began at the Big Bang. Two epochs meet at a boundary. Every black hole of the ending epoch has an interior, and at the boundary all the interiors end together, as one end. The next epoch begins at the boundary, and I call the boundary between two epochs *the turn*. An epoch runs from one turn to the next, and no comparison is ever made across the turn. Chapter Eleven describes the turn in full. Each epoch has an 'outside world': the space and time outside the black holes of the epoch, in which the matter of the epoch is found. Every count of the entropy of an epoch is made against the outside world of the epoch, as the context of the count, and the count for gravity is made against the same outside world. By the turn, the outside world of the ending epoch has emptied, in a long emptying of the sky that Chapter Eleven also describes. No signal from the end of an interior ever reaches the outside world, so the end of the interior lies at no

moment of the time of the outside world. At the turn, therefore, nothing of the old outside world is there to count against. The new epoch is the new country of the census picture, with new clerks. The geometry of the new epoch has no past of its own to be lumpy with, so the geometry of the new epoch begins even, up to small departures from evenness. The low gravitational entropy of the beginning is the count that a new context starts with.

Hossenfelder names three proposals for the special beginning, the proposals of Penrose, of Carroll and of Barbour, and Penrose's proposal is the nearest of the three to my account. Penrose's 'eons' and my 'epochs' are both whole histories: each eon begins where the eon before ends, and each epoch begins where the epoch before ends. Penrose joins two eons at the point where nothing with mass is left in the old eon, while I join two epochs at the turn. The count of entropy is reset at each new start, in Penrose's proposal and on my account alike. Penrose resets the count by having black holes destroy information, while on my account the ending of the context resets the count, and the information is kept.

I answer the Boltzmann-brain worry on two grounds from earlier in this chapter: the Incommensuration Theorem, and the context that every count needs. The Boltzmann-brain worry needs a universe that sits forever in a fully mixed calm, with endless time for chance to work, but in my account the universe never reaches a fully mixed calm. Picture a world in which nothing is different from anything else: the world is the same everywhere and smooth everywhere. A world the same everywhere and smooth everywhere would be perfectly symmetric and perfectly continuous at once. By the Incommensuration Theorem, perfect symmetry with perfect continuity is the one thing that no one, by any comparison, ever finds. The second ground is the context that every count needs: a final state of greatest disorder has no context against which to be counted.

Hossenfelder answered the Boltzmann-brain worry with a lesson about the laws: at least one of our fundamental theories cannot be ergodic, a theory in which every possible fluctuation eventually happens. I answer the worry with the Incommensuration Theorem and with the context that

every count needs. So Hossenfelder's reassurance has a second ground in my account. You are not a brain that flickered up in an endless calm, because the endless calm is never reached.

The Present, Where Every Weighing Happens

Hossenfelder and I agree that no description from outside contains a 'now'. Hossenfelder concludes that the Now does not exist 'objectively', in her word, and that the Now is special only from inside. I conclude that the present is real, and that the present is where all of physics is done.

Every measurement ever made was made in its present. Comparison is made only in the present, and the present is not one point on a line but the site of the interaction itself. The beam of the balance tips now, and the record is written now.

The present moment is the place where many possible futures converge into the one thing that actually happens, moment by moment, from the inside. A pattern laid out in advance contains only what is left afterward, so a pattern laid out in advance leaves out the converging of many possible futures into the one thing that happens. Physics describes what is left afterward extremely well, but the happening itself is given only in the act of comparison.

So Hossenfelder's sentence "Objectively, the Now doesn't exist" is true in my account, with 'exist' in its exact sense of standing as structure. In the pattern every moment is like every other moment, and no moment is marked as 'now'. The Now is real, because the Now is given in the act of comparison. Being given in an act of comparison is the other way of being, beside existing. Suppose someone takes 'exists' and 'is real' as one word: then the present looks like an illusion. I show that the paradox of the present, and other paradoxes like it, come from the one step of taking 'exists' and 'is real' as one word.

Go back to Princeton. Einstein's comfort to Besso's family was true in one exact sense, the sense of 'exist': Besso's life exists, as structure, in the pattern of space and time, and nothing can take Besso's life from the pat-

tern. In the exact sense of 'real', what was real of Besso's life was given in the acts of his life, one after another. Now the acts of Besso's life remain only as records. The records include the letters that Einstein and Besso wrote to each other for more than fifty years. The letters are kept, printed and still read. The difference between past, present and future is the order in which acts are made and records laid down. Event time is the order in which acts are made and records laid down. Event time is real, and event time is no illusion.

The short answer: The past exists as a fixed stretch of the pattern of space and time, and the present is real, as the place where every act of comparison happens. The future is not yet there, and time runs one way in every single interaction, because no process can ever be run back exactly.

Since time runs one way in every interaction, everywhere in the universe, what happened at the universe's beginning, and what will happen at the universe's end?



Chapter Eleven

How Did the Universe Begin, and How Will It End?

What this chapter uses

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 Two).

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

The world has *six small dimensions* besides the three dimensions of space and the one dimension of time, the same in size and shape at every place (Chapter Four).

An *epoch* is one whole span of the history of the universe, and the boundary between two epochs is *the turn*, where the next epoch begins (Chapter Ten).

Can we know how the universe began, and how the universe will end? Sabine Hossenfelder calls the theories of the beginning of the universe modern creation myths. She advises her readers not to trust any forecast of the end of the universe. She also holds that the idea of making a new universe in a laboratory is consistent with all we know. Could anyone, then, make a universe?

A Hiss from Every Direction

Bell Telephone Laboratories kept an unusual antenna on Crawford Hill, at Holmdel in New Jersey: a great horn of metal, twenty feet across at the mouth, which narrowed to a small throat where a receiver listened. A. B. Crawford and his colleagues had built the horn in 1960 to catch faint signals bounced off the Echo satellite. By 1963 the horn was no longer needed for the work with the satellite, and two radio astronomers, Arno Penzias and Robert Wilson, then began preparing the horn to listen to the sky.

Every receiver hears some noise of its own, the way an amplifier hums when no record is playing. Radio astronomers state the strength of a noise as a temperature. A body at the stated temperature would glow in radio waves as strongly as the noise. The temperature scale starts at 'absolute zero', the coldest any temperature can be. Penzias and Wilson added up every source of noise they knew of, from the air above to the receiver itself. Penzias and Wilson set the sum beside what the horn actually heard, and some noise was left over. The leftover noise was the same whichever way Penzias and Wilson pointed the horn, and the leftover noise also stayed the same through the seasons.

Penzias and Wilson suspected the antenna first. A pair of pigeons had been roosting in the narrow part of the horn. Wilson later described the pigeons in his Nobel lecture: the birds "had covered the inside with a white material familiar to all city dwellers". The pigeons were sent away and the horn was cleaned, but the noise dropped only a little. In the spring of 1965 Penzias and Wilson cleaned the horn out thoroughly once more, and the leftover noise stayed, at about three and a half degrees

above what Penzias and Wilson expected. Penzias and Wilson wrote a short letter to the *Astrophysical Journal*, dated 13 May 1965. The letter reports the leftover noise in one sentence.

> This excess temperature is, within the limits of our observations, isotropic, unpolarized, and free from seasonal variations (July, 1964-April, 1965).
>
> (A. A. Penzias and R. W. Wilson, "A Measurement of Excess Antenna Temperature at 4080 Mc/s", *Astrophysical Journal* 142, 1965)

Isotropic means the same from every direction, and *unpolarized* means that the radio waves showed no preferred direction of vibration.

Penzias and Wilson got the explanation of the leftover noise by telephone. Penzias mentioned the noise to Bernard Burke of the Massachusetts Institute of Technology. Burke recalled hearing of work by P. J. E. Peebles, in Robert Dicke's group at Princeton, on radiation left over in the universe. Penzias called Dicke, and Dicke and his colleagues soon came to Holmdel to see the horn. Both groups wrote letters: Penzias and Wilson at Holmdel, and Dicke's group at Princeton. The two letters appeared together in the same issue of the *Astrophysical Journal*. The letter from Princeton said what the hiss of leftover noise was. Physicists still explain the hiss in the terms of the letter from Princeton. The hiss was the glow left over from the hot, dense early universe. The expansion of space had stretched the glow into radio waves a few centimeters long. The glow is a faint warmth left from the early universe, and the glow reaches us from every direction in the sky. Astronomers now call the glow the *microwave background*.

Penzias and Wilson were two people at a horn on a hill. Penzias and Wilson set what the sky gave them beside what they expected, and found a difference. When the difference was set beside the theory from Princeton, the difference became a look at the early universe. Penzias and Wilson made the look at Holmdel in 1965, long after the beginning. No

one was present at the beginning itself. Every look at the early universe since 1965 has the same shape: each look is made now, here, of something the beginning left behind.

From Hossenfelder's pages

What Sabine Hossenfelder Showed

Hossenfelder takes up the beginning and the end of the universe in the second chapter of *Existential Physics*. She starts from what a good explanation is. Hossenfelder says that a good scientific theory lets us calculate many observations from few assumptions. Cosmology is the science of the universe as a whole, and cosmology has a theory that is good in Hossenfelder's sense. Cosmologists use the theory to track how much of each kind of stuff the universe holds, and from the amounts of each kind of stuff the cosmologists work out how fast the universe expands. The theory is the standard model of cosmology, called the *concordance model*. Hossenfelder shows that the concordance model is strong: in the concordance model, simple starting conditions explain two kinds of data at once, the spread of the galaxies today and the slight unevenness of the microwave background. Hossenfelder is right about the strength of the concordance model.

Then Hossenfelder draws a careful line around what the concordance model includes.

> The Big Bang, however, is not part of the concordance model.
>
> (*Existential Physics*, chapter 2, "Modern Tales of Creation")

In Hossenfelder's sentence, the *Big Bang* means a first moment in time, at which the universe began. Hossenfelder leaves the Big Bang out of the concordance model *because* no observation tells us anything about what happened as far back as the Big Bang. She writes that the energies at the Big Bang were at least a million billion times higher than the energies on which we have reliable data.

Hossenfelder then walks through the stories that physicists tell about the earliest times. The best-known story says that a very early burst of ever faster expansion stretched a tiny region of space to far beyond everything we can see, and physicists call the proposed burst *inflation*. In the usual form of inflation, a field spread through space drives the burst: the energy of the field pushes space apart. Physicists call the field the *inflaton*. Hossenfelder lists other stories too: new forces, bounces and cycles, a beginning with no boundary, and space growing out of a network. Of each story, Hossenfelder finds two things. First, the story is not needed to explain any observation, and second, physicists can amend the story to fit whatever is observed. Of inflation, she writes first that there is no evidence for the inflaton field, and then she writes: "However, you can always choose the properties of the inflaton field so they match whatever we will observe, which means the hypothesis has no explanatory power". In *Lost in Math* she reports a count, made in 2014, of 193 shapes that physicists have proposed for the energy of a single inflaton field. Hossenfelder draws the lesson of the count in one line: "But theoreticians' ability to mint models that predict any possible future observations has just shown they can't predict anything". Hossenfelder gives her verdict on the whole family of stories in one sentence.

> They're modern creation myths written in the language of mathematics.
>
> (*Existential Physics*, chapter 2, the section after "Geometrogenesis")

Hossenfelder also finds a deeper limit, behind all the stories: every theory we have describes the present as the result of running a 'law of change' forward from a simple 'starting state'. If the universe once passed through a stage harder to describe than the hot gas of the early universe, then physicists could no longer explain the present by running a law forward from a simple starting state. "For all we know",

Hossenfelder concludes, "the beginning of our universe may remain hidden from us forever". Hossenfelder can see only one way past the limit: a theory that needs no starting state at all, a theory that would "apply to all times at once".

Hossenfelder gives the dark forecast for the end of the universe in full, and then she warns against the dark forecast. The dark forecast has four parts: the Sun burns out, the stars die, the expansion of the universe speeds up, and the supply of usable energy runs down. But every forecast assumes that the laws of nature will stay the same. No one can confirm the assumption by using the assumption itself. The philosopher David Hume set out the difficulty of confirming the assumption: past observation cannot show that the future will resemble the past. Philosophers call Hume's difficulty the *problem of induction*. Hossenfelder retells the story of the chicken of the philosopher Bertrand Russell. The farmer feeds the chicken every morning, until the day the farmer chops off the chicken's head. Hossenfelder states the problem of induction in one sentence: "It's impossible to predict that nothing unpredictable will happen". Hossenfelder adds that slow or rare processes may matter too. One process she names is a sudden change of empty space itself into another state, called *vacuum decay*. She also names the decay of the proton, one of the particles in the core of every atom, and the slow evaporation of black holes, the regions of space whose gravity lets nothing out. Physicists call whatever drives the speeding up of the expansion the *dark energy*. Hossenfelder names a change in the dark energy too slow for any measurement to see. Hossenfelder's advice is plain.

> In any case, you shouldn't trust physicists' predictions for the end of the universe. You might as well ask a fruit fly for a weather forecast.
>
> (*Existential Physics*, chapter 2, "In the End")

> First, no observation shows us the first moment. Second, no story of the earliest times, inflation included, is needed to explain anything observed. Third, there is no evidence for an inflaton field.

Hossenfelder is right about three things in the second chapter of *Existential Physics*, and on my account each of the three things also follows from 'ground' of my own (the place where an argument starts).

The First Moment Is Never Seen

Stand on a beach and look out to sea. The 'horizon' is the edge of what you can see, and the sea goes on beyond the horizon. Ask what lies beyond the horizon, and the answer is more sea, and ships you cannot see yet.

The beginning of our history is an edge of the same kind as the horizon: the beginning is the edge of what we can see, and more lies beyond the beginning, as more sea lies beyond the horizon. In my plain-words book on black holes and the Big Bang, I start from a plain fact: the past is known *only* by the impression the past makes on the present. Everything we know of the past arrives now: the glow that Penzias and Wilson heard, the light of distant galaxies, and the record of every instrument. Astronomers rebuild one history of the universe from the impressions that arrive now. When astronomers trace the rebuilt history backward, the history comes ever nearer to a limit. The rebuilt history has the limit as its beginning, and the Big Bang is the beginning that the rebuilt history shows. The limit is a boundary between two spans of the universe's history, where one span ends and the next span begins. Our epoch began at the Big Bang. I identify the Big Bang with the turn. The Big Bang is the turn as our history shows the turn, when we trace our history back from inside our epoch. So the Big Bang is the beginning of our epoch, and *not* the beginning of the universe.

Someone would have to make a comparison across the first moment to know the first moment as an event: a comparison that sets something before the first moment beside something after the first moment. When we trace our history backward, our history comes ever nearer to the turn and never reaches the turn, so no comparison of ours is made at a moment at the turn itself. Another history lies on the far side of the turn, and I describe the history on the far side later in this chapter, in the section "What Came Before, and What the Beginning Left". The history on the far side comes ever nearer to the turn from the other direction, and never reaches the turn either. So every comparison is made on one side of the turn or the other, and no comparison is made across the turn. So no comparison registers the turn as an event, and it cannot be known as one.

Hossenfelder's first point is that no observation shows us the first moment, and Hossenfelder reaches the first point from the data. No observation tells us what happened as far back as the first moment. The energies at the first moment lie far beyond any energies we have measured. I reach the first point from the structure of comparison (what every comparison must contain): no measurement of any power, at any time, is made across the turn. The first moment is never seen.

Hossenfelder's second point is that inflation, like the other stories, is not needed. Picture a baker's patch of dough, small enough to sit in your palm. Every part of the dough is alike, because the baker kneaded the dough as one piece. Stretch the dough in a moment until the dough covers a city, and every wrinkle is pulled flat. The stretching of the dough is the picture behind inflation: the dough stands for a tiny region of the early universe, and the stretching stands for the burst of inflation. The physicist Alan Guth proposed inflation in 1981, and physicists brought in inflation to answer three puzzles. Some regions of the sky lie so far apart that no signal could ever have joined the regions, so why do the far-apart regions share one temperature, to one part in a hundred thousand? Why is space 'flat', without any bending, on the largest scales? Some theories unite the forces. In the theories that unite the forces, one larger force splits into the three forces of the particles that we know. The theories that unite the

forces predict that the split makes great numbers of particles, and each of the particles made in the split carries a single magnetic pole, a north with no south. Physicists call the particles with a single magnetic pole *monopoles*. Why do we find none of the monopoles?

I used the next picture in Chapter Five for the even temperature of the sky; here the one place the settlers came from is the turn. Two towns far apart may share an accent without the people of the two towns ever having spoken to each other, if settlers from one place founded both towns. The sky is alike in every direction for the same kind of reason: the whole sky comes from one source, as both towns come from one place. Space is flat because the beginning of our epoch carries over no length from anything before the beginning, so the beginning of our epoch holds no large length by which space could be bent. No monopoles were made, because in my account no single larger force ever split into the three forces of the particles. 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. My account has no inflaton at all.

Hossenfelder's third point is that there is no evidence for an inflaton field. I reach the third point from the measurements themselves. The young universe was faintly uneven, and the galaxies grew from the faint unevenness, which is called the *first ripples*. The favored models of inflation produce the same kind of ripple as I do: a kind of ripple in which matter and light of every kind are uneven together, in step. The favored models of inflation also produce the same flat space as I do. The favored models of inflation produce a slight 'tilt' as well: the first ripples are a little stronger on large sizes than on small sizes. I take the amount of the tilt and the sign of the tilt from measurement. The strength of the first ripples and the sign of their tilt have the third standing of Chapter Four: my account does not fix the two numbers, and the two numbers are measured, as the tailor measures the person who will wear the coat. So my account and the favored models of inflation fit the measured kind of ripple and the measured flatness alike. My account has no inflaton. If an account

with no inflaton produces a feature equally well, then the feature is no evidence for an inflaton, so there is no evidence for an inflaton field in the measured kind of ripple or in the measured flatness.

What Came Before, and What the Beginning Left

What came before the Big Bang? The question has an answer, and the answer starts inside the black holes.

A *black hole* is a region in which matter is packed so densely that nothing can climb back out of it, not even light. Physicists call the inside of a black hole the *interior* of the black hole, and the interior of a black hole is a place where every path leads forward to an end. No signal from the end of an interior ever reaches the world outside the black hole, so no clock outside the black hole can be set beside the end of the interior. Picture the interiors of all the black holes in the universe as funnels, each funnel separate along its whole length. No comparison made in our epoch can tell the end of one funnel from the end of another funnel, because no signal ever comes back out of any funnel. A new epoch forms beyond the ends of the funnels. The new epoch carries no mark of which interior any part of the new epoch came from, so no comparison made in the new epoch can tell the ends apart either. I hold that a difference that no comparison can register is no difference at all. If no comparison, at any time, can ever tell two things apart, then the two things are one thing, and so the ends of all the interiors of the black holes are one end. The ends are joined because no one, by any comparison, can tell the ends apart, and *not* because anything pulls the ends together. The one end of all the interiors is the turn, now seen in full: the turn is where the interiors of all the black holes of the ending epoch end together, as one end, and the turn is also where the next epoch begins. The collapse inside the black holes comes ever nearer to the turn from one side, and the history of the new epoch comes ever nearer to the turn from the other side. Neither the collapse nor the history ever

reaches the turn. The whole sky of the new epoch comes from the one end, so the sky of the new epoch is alike in every direction, as two towns founded from one place share one accent.

When we trace our rebuilt history backward, the history runs toward the turn from our side. I identify what lies on the other side of the turn with the collapse of the interiors of the black holes of the epoch before ours. So the question "what came before the Big Bang?" has an answer: the collapse inside the black holes of the epoch before ours. In the answer, the word 'before' names the order of a cycle: one epoch, then the next epoch. No clock measures a time across the turn. Picture a play performed again and again from one script, with each performance standing for one epoch. Each performance builds its own stage, and when the performance ends, the stage is 'struck': the crew takes the stage down. The script comes back at each performance, as the same law comes back in each epoch. The cycle has no first performance. Ask of any epoch "what came before that?", and the answer has the same form, without end.

I also get past the deeper limit that Hossenfelder found: our theories need a simple starting state, and the only way past the need would be a theory for all times at once. My account needs neither a starting state set by hand nor a theory for all times at once. I start from the present act of measurement, and I rebuild the one history that the present requires. Take the shape of space as an example. The shape of space is one part of the starting state that physicists set by hand in our theories. In Einstein's equations of gravity, the bending of space as a whole is set once, at the start of an epoch. Einstein's equations do not choose the bending. The start of our epoch carries over no length from the epoch before. No ruler of ours was ever laid beside anything in the epoch before, and if nothing in our epoch could ever be compared with a length, then the length is no length of our epoch at all. The start of our epoch holds only one length: the tiny length at which gravity and the physics of the very small matter equally. If the space of an epoch were bent on so small a length, then the space would close up again at once, or fly apart before anything could gather, so the epoch would make no stars and no black holes. Each new

epoch forms from the ends of the black holes of the epoch before, so an epoch with no stars and no black holes would give rise to no next epoch. The cycle has no last epoch either: every epoch gives rise to a next epoch, for the reasons I give below in "Will It All End in the Dark?". So the cycle does not make an epoch whose space is bent on the tiny length, and so the start of an epoch in the cycle sets no bending at all. Space is flat. No collection of worlds takes part here, and nothing is selected: the cycle is one world, and each epoch is made by the epoch before it. Astronomers have measured the bending of space from the microwave background and from the spacing of galaxies, and astronomers find space flat. Astronomers measure how much of the expansion the bending of space accounts for. The measured amount is zero, within the stated uncertainty of the measurement. Appendix B, "For the Specialist", gives the value.

The first moment is never seen, but the beginning still shows in what the beginning left. I name five things that the beginning left, and four of the five things are already in our measurements. The first thing the beginning left is a faint pattern in the oldest light, the microwave background. The Cosmic Background Explorer was a satellite that mapped the microwave background. In April 1992 the team of the Cosmic Background Explorer reported faint differences in the glow. The glow is warmer in some places and cooler in others, by about one part in a hundred thousand, and the faint differences in the glow are the seeds from which the galaxies grew. The black holes of the epoch before ours took in matter and light that differed from place to place. At the turn, no one can tell one interior from another by any comparison. So the differences pass into the new epoch as one pattern, averaged together and not erased. In the new epoch, the differences show only as faint departures from evenness. I identify the faint differences in the oldest light with the pattern carried over, averaged together, from the epoch before ours. The second thing the beginning left is one settled state of empty space, the same in every epoch, and astronomers measure the energy of the settled state as the energy of empty space that speeds up the expansion. The third thing the beginning left is the dark matter, the unseen source of the extra pull that holds galax-

ies together, and the dark matter was made as our epoch formed from the turn. Matter made of antiparticles is called *antimatter*. The fourth thing the beginning left is the matter we are made of: the small excess of matter over antimatter. The fifth thing the beginning left is a faint hum of 'gravitational waves', ripples in the shape of space. We met the six small dimensions in Chapter Five: six more dimensions beyond the three directions of space and the one of time, curled up far too small to see. The hum was made just after the turn, as the six small dimensions settled into their held size and shape. Appendix A, "What the Coming Measurements Will Find", gathers the coming measurement of the hum with every other coming measurement.

Will It All End in the Dark?

I give a definite answer on the end, too, and, a plain-words book on the far future of the universe, I set out the answer one question at a time. The answer has two parts: the long emptying of the sky will happen, and the emptying is not the end.

Hossenfelder describes the emptying, and her account and my account agree on the emptying. In 1998 two teams of astronomers measured distant exploding stars and found that the expansion of the universe is speeding up. The expansion carries away every galaxy that gravity does not hold to our galaxy, and once a carried-away galaxy passes a certain distance, the light of the galaxy can never reach us again. The sky beyond our own small family of galaxies empties out of reach in a hundred billion to a trillion years. Over far longer times, our own stars burn out. Everything ends inside a black hole, or is carried off alone, beyond the reach of all other matter. Black holes glow themselves slowly away, but a black hole of the Sun's mass takes a number of years sixty-seven digits long to glow away. The emptying of the sky comes before the glowing away of the black holes, by an enormous margin.

The measurements made so far agree with a positive constant: the expansion of the universe has been speeding up since that speeding up was first measured in 1998, and space is flat to within about two parts in a thousand. Two surveys, the Dark Energy Spectroscopic Instrument (DESI) in 2025 and the Dark Energy Survey in 2026, also prefer, at about three times their stated uncertainty, an energy of empty space that changes with time. The constant is one number, the same at every place and every time of our epoch, and Appendix A, under Chapter Four, Prediction 8, sets out what the coming surveys will measure and what I say they will find.

I add four forecasts of my own: the galaxies never fall back together, everything bound stays bound, empty space keeps its nature, and the matter lasts. Throw a ball upward hard enough, from a small enough world, and the ball never comes back. The galaxies of our epoch are like the ball: the galaxies never fall back together. Astronomers give the speed of the expansion as a 'rate': the share by which every great distance grows in a given time. Empty space itself has an energy, the same in every cubic meter, and the energy of empty space drives the speeding up of the expansion. A sum of three parts sets the rate of expansion: one part for the matter, one part for the bending of space, and one part for the cosmological constant. The part for the matter is never negative. Space is flat, so the part for bending is zero, and more matter only makes the sum larger: more matter never bends space closed. The part for the constant is positive, as the two teams of 1998 found. As space grows, the matter thins and the part of the sum for the matter shrinks, and the shrinking of the part for the matter is gravity holding the expansion back. The part for the constant stays the same, so the sum never falls to zero, and so gravity never stops the expansion.

Everything 'bound' stays bound: anything held together by its own forces, such as a galaxy, a planet or an atom, stays together. A 'Big Rip' would be an end that tears galaxies, planets and finally atoms apart. In 2003 three physicists showed what a Big Rip needs: Robert Caldwell, Marc Kamionkowski and Nevin Weinberg. A Big Rip needs a dark energy that

grows denser as space grows, *but* in my account the dark energy is exactly the cosmological constant: one constant, with no dark energy field behind the constant. When a theory leaves a number open, to be filled in by measurement, physicists call the number a *free number*. The value of the cosmological constant is no free number, and Chapter Four showed how the value of the constant is set. Once I make the identification, three things set the value of the constant: the structure of my account, the measured strength of gravity, and the measured size of the *particle horizon*, the edge of everything whose light has reached us. The value set in this way agrees with the measured value to within about two percent. A theorem about Einstein's equations shows that the constant is one number at every place and every time of our epoch. Picture yourself on a doorstep in a breeze. A steady breeze makes you lean a little, once, and then you stand all night. *Only* a wind that keeps rising knocks you off the doorstep. The cosmological constant is like the steady breeze, and the constant tears nothing bound apart. If a dark energy grew denser as space grew, then the dark energy would be like the wind that keeps rising.

My forecast of the far future depends on two statements of mine. The first statement is that a kind of particle has the same properties wherever and whenever the particle is found, at every place and at every time of our epoch. The first statement depends on the six small dimensions, because the shape of the six small dimensions sets which kinds of particle there are. The six small dimensions are held at one size and in one shape, as the paragraphs that follow show. The second statement is that the same law sets the cosmological constant in every epoch. The second statement depends on what comes back at each turn. The law comes back at each turn: the law is the structure of the world that I derive, and the law holds again in every epoch, as the script of the play comes back at each performance.

Empty space keeps its nature. Picture a ball resting at the bottom of a valley in hilly country. Empty space with nothing put into it settles into a state, as the ball settles at the bottom of the valley, and physicists call the settled state of empty space a *vacuum*. When a vacuum rests in a valley that is not the lowest, physicists call the vacuum a *false vacuum*. In 1977 the

physicist Sidney Coleman showed how a world resting in a false vacuum could give way everywhere. The world would give way through one bubble of a lower state, and the bubble grows. Every decay of a false vacuum needs a second, lower valley.

Now picture a garden hose lying across a lawn. From far away the hose looks like a line, but come close and you find a second direction, one that curls around the hose and comes back to where the direction started. Space is like the hose. Every point of space carries the six small dimensions that we met in Chapter Five, besides the three directions of space and the one of time. The six small dimensions are curled up far smaller than an atom, as the second direction curls around the hose. I identify the six small dimensions with the space of all the states a particle of matter can be in, as a chessboard is the set of all the squares on which a piece can stand. So the shape of the six fixes what kinds of particle there can be. The six can change in only two ways: in their size and in their shape. The six are held at one size and in one shape. So the six have one settled state and no second, lower valley, and so a bubble of a lower state has nowhere to lead.

Empty space has one other settled feature: a field spread through all of space, which gives many particles their masses. Physicists call the field the *Higgs field*, and the valley of the Higgs field has another shape. Picture the bottom of a wine bottle: a raised bump in the middle, and a round trough all around the bump. The Higgs field rests now in the trough. I derive the curve of the energy of the Higgs field at the energies where the field is measured, and in the derived curve the trough is the lowest place, with the glass rising beyond the trough on every side. So I forecast that, in the curve I derive, the Higgs field rests now at the lowest place. The physicists who make the standard calculation follow the field out to far higher energies, and in the standard calculation the present state of the Higgs field lasts far beyond the age of the universe. Calculations of the standard kind produce the estimate that Hossenfelder reports for vacuum decay, and

Hossenfelder calls the estimates from calculations of the standard kind meaningless, because the calculations carry the field across energies that no experiment has reached.

The matter lasts too. Picture a book and a cup standing side by side on a table: the book and the cup each keep their own identity, where a pot of paint would have blended two colors for good. The three forces of the particles stand side by side like the book and the cup, and each force has 'carriers' of its own: particles that carry the force. A proton is made of three smaller particles called *quarks*, and the proton is the lightest particle made of three quarks. No carrier of any force turns a quark into the electron or into one of the electron's relatives, so the proton keeps its three quarks. The proton has nothing lighter to become, because no particle made of three quarks is lighter than the proton, so the proton lasts, and the cold dead stars made of protons last too. The Super-Kamiokande detector is a tank of fifty thousand metric tons of pure water in a mine in Japan. The Super-Kamiokande detector began its watch on 1 April 1996. In 2020 the team of Super-Kamiokande reported that no proton had been seen to break into a 'positron' (the electron's antiparticle, with positive charge) and a light particle called a 'pion'.

The dark of the long emptying ends in a turn. The fear of a final dark has a scene of its own. The physicist William Thomson, later Lord Kelvin, had a paper read at the Royal Society of Edinburgh on 19 April 1852, and Thomson's paper named "a universal tendency in nature to the dissipation of mechanical energy". The 'dissipation' that Thomson named is the spreading of usable energy into heat from which no work can be drawn. In 1865 the physicist Rudolf Clausius gave the spreading a measure, and Clausius called the measure *entropy*. Clausius wrote that the entropy of the universe tends toward a maximum. If the entropy of the universe reaches the maximum, then everything is at one temperature, and nothing ever happens again. Physicists call the end at maximum entropy the *heat death*. I give three grounds why the emptying cannot come to rest in a heat death, and each of the three grounds stands on its own, without the other two.

The first ground uses two terms: content and context. The *content* of a comparison is what the verdict of the comparison is about, and the *context* of a comparison is the respect in which the two things compared are two. A thermometer compares this morning's warmth with this evening's warmth. The thermometer finds a temperature, which is the content, and the two times of day are the context. In physics, the content is the matter and light of the world. In physics, the context is the arena of space and time in which the matter and light are found, together with the 'setting of possibility', the range of states in which the matter and light could be found. Every content has its context: content and context always come together. A temperature found at no time and at no place is no finding at all. Now follow the matter into the black holes. The matter that falls into the black holes does not cease to be, so the content is still there. The large outside world is the arena of space and time in which the matter was found. At the end of the emptying, the large outside world is gone. So a context must form again, and the new context forms from the geometry of all ten dimensions, the four large dimensions and the six small dimensions, as a new large world.

The second ground is the *Incommensuration Theorem* of Chapter Two: symmetry and continuity cannot both be perfected in one comparison, and neither can asymmetry and discontinuity. The word 'asymmetry' means the opposite of symmetry, and the word 'discontinuity' means the opposite of continuity. Picture a 'featureless emptiness', the same everywhere and with no break anywhere: a featureless emptiness would be perfect in symmetry and in continuity at once. So a featureless emptiness is the one thing that no one, by any comparison, ever finds. So the emptying cannot come to rest in a featureless emptiness.

The third ground is what an entropy is: an entropy is a count of the states of a thing that the comparisons available from some context cannot tell apart, so an entropy is always a count made against a context. For an epoch, the context of the count is the 'outside world' of the epoch: the large arena of space and time outside the black holes of the epoch, in which the matter of the epoch is found. Think of a census, which counts

what the clerks of the census can tell apart. The census stands for the entropy of an epoch, and the clerks stand for the comparisons available from the outside world of the epoch. The entropy of an epoch tends toward a largest count, and the largest count is a count made against the epoch's own outside world. When the outside world of the epoch has emptied, the count has nothing left to be counted against. The next epoch begins its own count against its own context. The emptying ends in a turn, not in a final dark. The next epoch begins from the turn, under the same law.

Could Anyone Make a Universe?

Hossenfelder closes the subject with a hopeful thought, after her conversation with the science writer Zeeya Merali, whose book *A Big Bang in a Little Room* follows physicists who ask how a universe might be made. Hossenfelder writes that, if we learn how our universe began, we might start a new universe growing, and the route Hossenfelder describes uses inflation.

> I know it sounds crazy, but the idea that we might one day create a universe in the laboratory is consistent with all we know.
>
> (*Existential Physics*, "Other Voices #4: Can We Create a Universe?", The Brief Answer)

A new epoch begins in one way only: at the turn, from the ends of all the black hole interiors of an epoch together. A new epoch never begins from one region of space or from one black hole. In *Parallel Worlds*, the physicist Michio Kaku describes plans to make a 'baby universe'. In the plans that Kaku describes, the baby universe begins as a false vacuum: a small region of empty space resting in a state, with a lower state lying beyond. The six small dimensions have one settled state, with no second settled state beyond the first. So a made bubble has no other world to open into. I also have no inflaton to drive the growth of a made bubble.

There is a plainer reason, as well, why no one can make a universe. Think of a country where the only way to travel is by road. A traveler in the country counts a town as a place because roads join the town to other towns, and for the traveler, a town that no road reaches is no place at all. Space is the pattern of which events a signal can join, as the roads join the towns. If a path from here could reach a region, by any machine, then the region is part of our own world, because the path from here reaches the region. No path runs from any place in our epoch to any place in the next epoch.

A Weighing Made Now

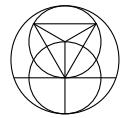
Picture the two-pan balance once more, the beam on its pivot with a pan hung from each end. Set the hiss of the Holmdel horn in one pan and the noise Penzias and Wilson expected in the other pan. The beam tipped toward the hiss: the horn heard noise worth about three and a half degrees more than every known source could give, and through the extra noise the early universe came into view.

Every look at the early universe is a weighing made now, of what the beginning left. Every weighing is made on our side of the turn, so the first moment never lies in a pan. Our weighings show four things that the beginning left, every day: the pattern in the oldest light, the energy of empty space, the extra pull of the dark matter, and the matter we are made of. I build the forecast of the end from what the weighings of our own epoch show, together with the structure of comparison. The forecast gives one constant, one settled state of the six small dimensions, a Higgs field resting at the lowest place of the curve I derive, a proton that lasts, and a context that forms again.

The short answer: Both the beginning and the end can be known. Our epoch began at the turn, which no one sees by any comparison, and in our history the turn appears as the Big Bang. What the turn left is measured now, and before the turn came the collapse inside the black holes of the epoch before ours. The end is a long emptying of the sky, and the empty-

ing closes in a turn. From the turn, the next epoch begins under the same law. No laboratory can make a second universe, because whatever a machine here makes or reaches is a region of our own world.

Most of the matter is unseen, as the same weighings of the oldest light and of the spread of the galaxies show. What is the unseen matter, if every search for its particle comes back empty?



Chapter Twelve

What Is the Dark Matter, If Every Search Comes Back Empty?

What this chapter uses

The *Incommensuration Theorem*: symmetry and continuity cannot both be applied, simultaneously and fundamentally, to any event or comparison; and neither can asymmetry and discontinuity. *Symmetry* is being the same under every change of place or setting, and *continuity* is having no gaps, so that a small change of setting gives a small change in what is found. The Incommensuration Theorem is a structural fact about the nature of knowing (Chapter Two).

The *content* of a comparison is what the verdict of the comparison is about, and the *context* is the respect in which the two things compared are two (Chapter Three).

The world has *six small dimensions* besides the three dimensions of space and the one dimension of time, the same in size and shape at every place, and the shape of the six fixes what kinds of particle there can be (Chapter Four).

An *epoch* is one whole span of the universe's history, from one turn to the next; *the turn* is the boundary between two epochs, where the interiors of the black holes of the ending epoch end together and the next epoch begins (Chapters Ten and Eleven).

Sabine Hossenfelder reports thirty years of searches for particles of dark matter, the unseen matter whose pull astronomers measure, and the searches found nothing. What is the dark matter?

A Galaxy That Would Not Slow Down

The story behind the question begins with a galaxy, and with two people who set out to time how fast the galaxy turns.

The astronomers Vera Rubin and Kent Ford worked at the Department of Terrestrial Magnetism of the Carnegie Institution of Washington. In the late 1960s Rubin and Ford took a new instrument to the telescopes of Arizona, an instrument that Ford had built. The instrument was a 'spectrograph', a device that spreads the light of a source into its colors. The spectrograph carried an 'image tube', which brightened the faint picture before the picture reached the photographic plate, and so the image tube cut the time of an exposure to about a tenth of the time that a bare plate would need. Rubin and Ford pointed the spectrograph at the Andromeda galaxy, the great spiral of stars nearest to our own galaxy, using the 72-inch telescope of Lowell Observatory and the 84-inch telescope at Kitt Peak.

Rubin and Ford aimed the spectrograph at sixty-seven glowing clouds of hydrogen gas in Andromeda. The clouds were scattered over every quarter of the disc of the galaxy. Young, hot stars lit each cloud from within. A typical exposure of one cloud took an hour to an hour and a half. When a cloud moves away from us, the light of the cloud arrives shifted a little toward the red, and when a cloud moves toward us, the light of the cloud arrives shifted toward the blue. The size of the shift shows the speed of the cloud. So, cloud by cloud, Rubin and Ford read how fast each part of Andromeda swings around the center of the galaxy.

Think first of the Sun's family of planets. The Sun, at the middle, holds nearly all of the mass of the solar system, so the outer planets move more slowly than the inner planets: Neptune creeps where Mercury races. The light of a spiral galaxy is crowded toward the center of the galaxy and

thins out toward the edge. If the mass of Andromeda lay where the light of Andromeda lies, the outer clouds of Andromeda would move more slowly than the inner clouds, as the outer planets move more slowly than the inner planets.

The outer clouds kept their speed. The outer parts of the Andromeda galaxy turn about as fast as the inner parts. The speed stays high out to the farthest cloud that Rubin and Ford measured, some seventy-eight thousand light-years from the center of Andromeda (a 'light-year' is the distance light travels in one year). Light from the farthest cloud takes seventy-eight thousand years to reach the center. When the speed stays high far from the center, the mass of the galaxy keeps growing far from the center, where the light has almost run out. Rubin and Ford published their paper in the *Astrophysical Journal* in 1970. The paper gave the mass inside the distance of the last measured cloud and gave no mass beyond that distance: in the words of Rubin and Ford, "extrapolation beyond that distance is clearly a matter of taste".

Rubin and Ford had weighed a galaxy by the speed of its turning. The weight came out larger than the light: Andromeda holds more mass than its light shows. The astronomer Fritz Zwicky had found a surplus of weight over light in 1933, in the Coma cluster, a swarm of more than a thousand galaxies held together by the pull of the galaxies themselves. The galaxies of the Coma cluster move too fast for the pull of the visible galaxies to hold the cluster together. Something was in the galaxy and in the cluster, and that something showed itself by its pull. What is the something that shows itself by its pull?

From Hossenfelder's pages

What Sabine Hossenfelder Showed

Physicists give the name *dark matter* to the source of the missing pull. Dark matter has never been seen to do anything except pull by its weight. Hossenfelder states what is known and what is unknown about the dark matter in one line of the glossary of her book *Existential Physics*.

> The observational evidence for dark matter is solid, but what it is made of (if anything) is unclear.
>
> (*Existential Physics*, Glossary, "dark matter")

Hossenfelder lays out the evidence fairly and fully in her book *Lost in Math*, and the evidence is of three kinds: the spin of galaxies, the bending of light by clusters of galaxies, and the oldest light. Galaxies spin too fast for their visible matter to hold them together. The pull of a mass bends the light that passes the mass. Astronomers call the bending of light by the pull of whatever the light passes *gravitational lensing*. Clusters of galaxies bend the light of more distant galaxies more strongly than the visible mass of the clusters can. The oldest light we can see is the faint afterglow of the early universe, called the *microwave background*. The microwave background carries a pattern, and calculations of the pattern fit the data only when the calculations include dark matter. Hossenfelder's verdict on all of the evidence is plain.

> Without dark matter, the universe just wouldn't look the way we observe it to be.
>
> (*Lost in Math*, chapter 9, "Digging Darkness")

Then Hossenfelder tells the story of the searches for particles of dark matter, and the favorite candidate in the searches was a new particle with mass that touches 'ordinary matter' (the matter made of atoms)

only very rarely. Physicists named the candidate the *WIMP*, short for "weakly interacting massive particle". Physicists estimated how many WIMPs the early universe would have made, and the estimate came out near the measured amount of dark matter. Hossenfelder calls the agreement between the estimate and the measured amount the "WIMP miracle". So physicists built detectors deep underground, shielded from everything else, to catch the rare moment when a WIMP knocks an atom. The first results came in 1986, and the physicists who ran the search reported the results as "interesting bounds". Hossenfelder translates: "In plain English, 'interesting bounds' means they didn't find anything". Detector after detector followed, and each new detector searched for rarer collisions than the detectors before it.

> Thirty years have passed. Dark matter still hasn't been detected. The parameter range in which the WIMP miracle holds has meanwhile been excluded.
>
> (*Lost in Math*, chapter 9, "Digging Darkness")

In Hossenfelder's sentence, the 'parameter range' is the set of masses and strengths of touch for which the WIMP miracle would work, and the detectors have searched the whole set and found nothing in the set. The second favorite candidate was a very light particle, first proposed to settle a puzzle about the 'strong force'. Physicists call the very light particle the *axion*. The searches for the axion came out the same as the searches for the WIMP. Hossenfelder writes of the experiments built to catch the axion: "So far, none of these experiments has found anything".

Hossenfelder also names the habit by which physicists keep searching for a proposed particle, and she states the habit as two rules. She writes: "The first rule for inventing a new particle is that you need a good reason it hasn't yet been detected". The second rule is that "you need an argument for why it's just about to be discovered".

Hossenfelder sets a second proposal for the extra pull beside the particles, the proposal that the extra pull comes from gravity itself: gravity responds to ordinary matter differently from what our equations predict. Physicists call the second proposal *modified gravity*. Hossenfelder states the strongest point in favor of modified gravity: a change in the law of gravity would apply in the same way everywhere, while particles can be spread in one amount in one place and in another amount in another place. Hossenfelder draws the conclusion in her own words: "Particle dark matter, therefore, is much more flexible". Then she adds: "Maybe it's too flexible". Galaxies keep to rules, and the rules have no explanation if the particles are free to spread in any amount anywhere. In Hossenfelder's words: "Astrophysicists have found regularities among galaxies that particle dark matter cannot account for, like the 'Tully-Fisher relation'". The 'Tully-Fisher relation' states how the brightness of a galaxy depends on the speed of the outermost stars of the galaxy. Hossenfelder writes about the newer forms of modified gravity.

> Newer versions of modified gravity respect the symmetries of general relativity and still explain the observed galactic regularities better than particle dark matter. But they don't do well on distances far below or far above galactic size.
>
> (*Lost in Math*, chapter 9, "Sitting Around Hoping")

The 'symmetries' in Hossenfelder's sentence belong to general relativity, Einstein's theory of gravity. In general relativity, the laws are the same for every observer, however the observer moves. Hossenfelder leaves room for a third answer between particle dark matter and modified gravity: "The solution might be somewhere in between". Hossenfelder names one answer in between the two proposals: dark matter as a 'superfluid', a substance that flows with no friction at all. Dark matter as a superfluid would act like modified gravity on short scales and like particles on long scales.

Hossenfelder notes that the mathematics of particles and the mathematics of modified gravity are almost the same, since each of the two proposals contains new 'fields' (things spread through space with a value at every point) that no one has yet observed. Hossenfelder also gives two reasons why modified gravity stays at the fringe of physics. Both reasons are about how the fields of modified gravity look to a particle physicist.

> They are unfamiliar. They are not pretty. And so modified gravity has remained an idea on the fringe of the community.
>
> (*Lost in Math*, chapter 9, "Sitting Around Hoping")

First, the evidence for the unseen pull is strong. Second, the searches for a particle of dark matter have found nothing. Third, galaxies keep to regularities, such as the Tully-Fisher relation. Fourth, physicists cannot decide what the dark matter is by how familiar or how pretty an idea is.

Hossenfelder is right on four points, and I build on each of the four points.

Weight, and Nothing Else

Since Rubin and Ford, every measurement of the dark matter has agreed with one story: the dark matter shows its weight, and nothing else.

Picture two great clusters of galaxies falling into each other. Each cluster is a swarm of galaxies wrapped in a vast cloud of hot gas. The gas holds most of the ordinary matter of each cluster. As the clusters pass through each other, the two clouds of gas crash in the middle, slow down and heat up until the gas glows. In 2006 the astronomer Douglas Clowe and his colleagues weighed one collision of two clusters, called the Bullet Cluster, by the way the Bullet Cluster bends the light of galaxies far behind the collision. Clowe and his colleagues found that the weight lay

with the galaxies, which had sailed on through the crash, and apart from the glowing gas. Something unseen and heavy had passed straight through the crash, carrying most of the weight of the clusters with it. We now know that the dark matter passes through itself and through ordinary matter without any collision that anyone has measured.

The oldest light shows more about the dark matter. The ordinary matter and the light moved together in waves of sound in the hot early universe, as the air inside a drum moves when the drum is struck. The dark matter took no part in the sound waves: the dark matter only pulled. The oldest light has a pattern of warm and cool spots, and the pattern records both the sound waves and the pull, so astronomers can use the pattern to weigh the ordinary matter and the dark matter separately. By weight there is about five and four tenths times as much dark matter as ordinary matter, the matter made of atoms: stars, gas, planets and people. Astronomers find the same ratio, about five and four tenths to one, everywhere in the sky where the oldest light allows the measurement. If the dark matter decays into something unseen, the decay takes longer than about a hundred and sixty billion years, a figure that astronomers get from the measured expansion of the universe since the oldest light was released.

The galaxies themselves need the dark matter in order to form, and a short piece of arithmetic shows why. When the oldest light went free, the ordinary matter departed from perfect evenness by about three parts in a hundred thousand. Since then, distances in the universe have grown about one thousand and ninety times. The 'excess of density' of a region is the amount by which the density of the region is above the average density, counted as a share of the average. A small excess of density grows at most in step with the distances. So the excess of density of the ordinary matter grew to about three parts in a hundred at most: three parts in a hundred thousand, grown one thousand and ninety times, is about three parts in a hundred. A region draws together into a galaxy only when the excess of density of the region reaches about one, that is, when the region holds about twice the average density. So ordinary matter alone would have made no galaxy at all. The dark matter had been gathering all along,

because the dark matter took no part in the sound waves. The ordinary matter fell into the places of stronger pull, the wells the dark matter had dug, because the gathered dark matter pulled harder in some places than in others.

The dark matter bends light by its pull, holds galaxies by its pull, and shaped the oldest light by its pull. The dark matter has never been seen to bounce off anything, to glow, to destroy itself or to break down. Weight is all the dark matter shows.

A Ringing of the Setting

Hossenfelder's result about the searches is that the searches for a particle of dark matter have found nothing, and the same result also follows in my account, from ground of its own. The ground is a pair of words that I took from the balance in Chapter Three: *content and context*. The 'content' of a comparison is what the verdict of the comparison is about. The 'context' of a comparison is the respect in which the two things compared are two. Space and time together are the 'arena' of physics: the place in which things are found. The content is what is found within the arena: the particles, their charges and their fields. In physics the context has three 'measures', as Chapter Four showed. Two of the three measures are space and time, the measures of the arena in which the content is found. The third measure is 'possibility': the range of states in which a thing could be found.

Picture a crystal: a solid whose atoms are held in a fixed, repeating pattern by the bonds between the atoms. Physicists call the fixed, repeating pattern the 'lattice' of the crystal. Strike the crystal, and the crystal rings, and each way that the crystal can ring has a definite energy, because the lattice keeps its shape. The energy of each way of ringing comes in steps. Physicists give a name to the smallest step of energy in one way of ringing: the *phonon*. A phonon is a vibration of the crystal, and *not* an extra thing inside the crystal. Nobody concludes from phonons that the crystal is made of phonons.

The world has six more dimensions besides the three dimensions of space and the one dimension of time, and the six extra dimensions are curled up far too small to see. In Chapter Five, I introduced the six extra dimensions as 'the six small dimensions' of my account. I derive Einstein's law of gravity from the structure of comparison (what every comparison must contain). I also find the six small dimensions. The *Planck length* is the smallest length built from the constants of gravity, of quantum theory and of light, and the Planck length is about a hundred billion billion times smaller than a proton. The six small dimensions are held at a size of about the Planck length, and the six small dimensions keep the same size and the same shape at every place, as a crystal keeps its lattice.

The shape of the six small dimensions is the shape of a space of possibilities. Picture a globe on which every point is one state of a choice between two alternatives. The north pole is wholly the first alternative, the south pole is wholly the second alternative, and the points between the poles are the states between the two alternatives. Two of the six small dimensions have exactly the shape of the globe. The other four small dimensions have the shape of all the states of a choice among three alternatives, a space of the same kind as the globe, with four dimensions. So the six small dimensions are a space of possibility in the plain mathematical sense.

The six small dimensions can be set beside two different things. When the six small dimensions are set beside the large dimensions of space and time, the six are part of what the large world holds. When the six small dimensions are set beside what could be found in them, the six are the range of possibilities in which a finding lies. Two possible findings are two because the two findings lie at two places in the range of possibilities. So the six small dimensions are a context: the 'setting of possibility'. Every finding is therefore placed in all three measures of context: space, time and possibility. The dark matter belongs to the six small dimensions taken as a context, the setting of possibility.

I identify the dark matter with a ringing of the setting itself: a lasting vibration of the six small dimensions, taken as the setting of possibility, and so a 'vibration of context'. I call one lasting vibration of the six small dimensions a *gyration*, as physicists call the crystal's unit of ringing a phonon. A gyration is to the six small dimensions what a phonon is to a crystal: a ringing of a space held at one size and one shape, and *not* an extra thing inside the six small dimensions. Physicists who work on theories with extra dimensions have long studied heavy vibrations of the extra dimensions. The physicists call each heavy vibration of the extra dimensions a 'particle'. Physically, a gyration is one of the heavy vibrations that physicists have long studied. Yet a gyration is not matter of any kind on the list of particles, because in my account a 'particle' is a thing found in the arena of space and time, while a gyration is a ringing of the setting.

Two facts follow at once from the identification, and the two facts are the whole of what astronomers see of the dark matter. First, a gyration has energy, so a gyration has weight: a gyration pulls as all energy pulls. Second, light and every detector built to catch a particle register 'content'. Content is the things found in the arena: things that light can bounce from and that can strike a detector. A gyration is a ringing of the setting, and never a thing found in the arena, so neither light nor any detector built to catch a particle registers a gyration. So the dark matter acts on the world through its weight alone. If physicists search for the dark matter through any way of acting other than its weight, the physicists find nothing, at any sensitivity of the search.

A gyration is heavy, because the six small dimensions are small. The *Planck mass* is the mass at which gravity and the quantum act on equal terms, and a gyration weighs about a Planck mass. A Planck mass is some twenty-two millionths of a gram, about ten billion billion times the mass of a proton. Gyrations are few, because each gyration is so heavy. Near the Sun there is about one gyration in every few tens of thousands of cubic kilometers. Together the gyrations outweigh all the atoms about five and four tenths to one. The ratio is derived: on my account the dark matter outweighs the ordinary matter by six minus two divided by pi, 5.3634 to

one, and the measurements give 5.364 and 5.370 to one; Appendix A, under Chapter Twelve, gives the prediction, and Appendix B gives the measurements with their sources.

Gyrations are made only at the boundary between two whole spans of the history of the universe. Consider all the black holes of the ending span: at the boundary, the interiors of the black holes end together, as one end, and then the next span begins. No comparison sets a thing before the turn beside a thing after the turn. An *epoch* is one whole span of the universe's history, from one turn to the next, and our epoch began at the Big Bang. So gyrations are made only as a new epoch forms from the turn. The six small dimensions and the large dimensions form again together as a new epoch forms from the turn, and only then.

Once made, a gyration keeps its energy, because each of its three 'ways out', the three ways in which the gyration could lose its energy, is closed. I take the three ways out one at a time. The first way out is for the gyration to become an ordinary thing, but a vibration of the six small dimensions is a different sort of thing from an ordinary thing. The six small dimensions form again only as a new epoch forms from the turn, so no process within an epoch turns a gyration into an ordinary thing. The second way out is for the gyration to hand its energy to ripples in the shape of space. Picture the small globe of the two-way choice, and pair each point of the globe with the opposite point, straight across the globe. Now swap every point with its partner. The laws of the six small dimensions contain only the shape of the small globe, and the swap leaves the shape of the small globe as the shape was, so the swap leaves the laws of the six small dimensions unchanged. If a vibration lifts one side of the globe while the vibration lowers the far side, the vibration comes out of the swap 'upside down'. If a vibration lifts both sides of the globe alike, the vibration comes out of the swap unchanged, and the ripples in the shape of space come out of the swap unchanged too, because each ripple is the same all over the six small dimensions. The gyration of the dark matter is the lightest vibration that comes out upside down. The swap leaves every 'link' between the six small dimensions and space (every way that the six small dimensions and

space act on each other) unchanged, and a link that the swap leaves unchanged can pass the energy of a single upside-down vibration only to another upside-down vibration. So the gyration could hand its energy only to a lighter upside-down vibration, and no upside-down vibration is lighter than the gyration. The third way out is for the gyration to leak its mass away slowly, as a black hole does. A gyration is a vibration at the 'Planck scale': the scale of the Planck length and the Planck mass. To leak, the gyration would have to drop into a lighter level of its own kind. A vibration at the Planck scale has no lower level of its kind. Leaking could act at all only at a scale some thirty powers of ten or more away from the Planck scale. A gyration is a ringing of the setting, so it is not a particle on the list of kinds, as a phonon is a ringing of a crystal and not one more kind of atom in the crystal. What each coming search will find of the gyrations is set out in Appendix A, under Chapter Twelve.

The dark matter is also required, and the reason is the Incommensuration Theorem, met in Chapter Two. Every finding is placed in space, in time and in possibility, because every weighing happens at some place, at some moment, and among the things that could have been found at the place and moment of the weighing.

Each of the three measures of context has no gaps: move a little in space, wait a little in time, or shift a little among the possibilities, and what is found changes a little. So, by the Incommensuration Theorem, none of the three measures is also perfectly the same everywhere. If a measure of context had no gaps and was also perfectly the same everywhere, symmetry and continuity would both be applied to the measure, simultaneously and fundamentally, and the Incommensuration Theorem states that symmetry and continuity cannot both be applied simultaneously and fundamentally. The 'plain shape' of a measure of context is the shape the measure would have if nothing bent the measure, and each of the three measures departs from its plain shape. Think of the floor under the balance. A floor with no cracks and no steps is 'smooth'. A smooth floor that dips at one place is 'bent' at the place where the floor dips. In the same way, if a measure of context is smooth and differs from one place

or moment to another, the measure of context is bent, as the dipping floor is bent. The three measures come together, so no measure can stay unbent while another measure is bent. No measure can take the place of another measure. So the bending of one measure cannot serve as the bending of another measure. The measures are three, so the bendings are three, and each bending is made by a thing of its own. Gravitation bends space, around matter. The *cosmological constant* is the constant that drives the expansion of the universe, and the cosmological constant bends time. The cosmological constant is the same at every place and every moment, and from each moment to the next the cosmological constant widens the distance between every pair of distant places. The dark matter bends possibility. The dark matter bends possibility because, as I identified it earlier in this section, the dark matter is a ringing of the setting of possibility itself; gravitation bends space around matter, as Einstein's law states; and the cosmological constant bends time, as I set out in two other books. So the dark matter is required: if the setting of possibility of a world is smooth, with no gaps, the world must carry the dark matter, as the world must carry gravitation and a cosmological constant.

No Empty Slot Among the Kinds

A second argument also shows why the detectors come back empty, and the second argument is in a different book and has different ground: the list of the kinds of particle.

Chapter Three showed that the structure of comparison fixes the kinds of particle. A force acts on a particle through a charge that the particle carries. A 'label of a force' is a charge by which the force acts on a particle. If a particle of dark matter touched ordinary matter through gravity alone, the particle would need mass with no label of any force: matter that answers to no electric charge, no weak force and no strong force. The particles of matter come in three families that are alike except in mass, and physicists call the three families 'generations'. The 'neutrino' is the nearly weightless particle of matter that passes through almost everything. Each

neutrino has a second part, called the 'right-handed state' of the neutrino. In each generation, the right-handed state holds the slot for matter with no label of any force, because the right-handed state carries no label of any force. The right-handed state plays no part in dark matter. If a second occupant held the slot for matter with no label of any force, nothing would tell the second occupant apart from the right-handed state. Two things that nothing tells apart are one thing, so the slot holds no second occupant. An axion would need a field with no labels at all, and the structure of comparison, which fixes the kinds, has no slot for a field with no labels at all. Physicists proposed the axion to settle a puzzle about the strong force's own angle, an angle that could have let the strong force treat a process differently from the mirror image of the process, with matter swapped for antimatter. The puzzle has its answer in the structure of comparison itself: as Chapter Four showed, the strong force's own angle is zero. So the list of the kinds holds no species of dark matter, and no axion.

The two arguments are two routes to the empty detectors: the two routes give one result, and neither route depends on the other. I derive that the detectors find nothing, starting from what the dark matter is. In the books on the kinds of particle, I also derive that the detectors find nothing, starting from what the list of particles is. Both routes give the result that the record of the searches shows: the detectors have found nothing.

Hossenfelder's two rules describe how physicists keep a proposed particle alive. By the first rule, physicists need a reason why the particle has not yet been seen. One such reason is a touch too rare for the detectors built so far. By the second rule, physicists need an argument that the particle is just about to be discovered. I propose no new kind of particle. The gyration is a vibration of the setting, and the list of kinds stays closed. The reason I give for the empty detectors is the kind of thing the dark matter is. The reason holds at every sensitivity of a detector. On my account, the answer to Hossenfelder's second rule is that the weighing has registered the dark matter already, and the weighing is the one kind of

comparison that registers the dark matter. Appendix A, "What the Coming Measurements Will Find", gathers what each coming search and survey will measure, and what I say each coming search and survey will find.

Keeping Einstein's Law

I keep Einstein's law of gravity unchanged, and the reason is the form of the law itself.

I derive Einstein's equations of gravity. The mathematician David Lovelock proved a theorem in 1971 that fixes the form of Einstein's equations. Physicists call the quantity of motion 'momentum'. The conservation of energy and momentum is the rule that energy and momentum can move from place to place and are never made or lost, in any small region over any short time. Lovelock's theorem has three conditions. First, space and time have four dimensions. Second, the equation is built only from the 'measure of distance' in space and time (the rule for the distance between any two nearby points) and from the first two rates at which the measure of distance changes. Third, the equation agrees with the conservation of energy and momentum. When the three conditions hold, the equation of gravity has Einstein's form, with the cosmological constant included. Within the theorem's conditions there is no other equation. Einstein's equations contain two constants: the strength of gravity that Newton measured, and the cosmological constant. An 'acceleration' is the rate at which a speed changes. Einstein's equations contain no 'constant of acceleration': no special faintness of pull at which gravity changes its rule. So, I keep the law of gravity exactly as *general relativity* gives the law, and Einstein's law holds from the laboratory to the largest structures, and down to the smallest scale at which space can be described as smooth.

Hossenfelder bases her strongest point for modified gravity on the regularities among galaxies. Two scientists have shown more clearly than anyone how tightly the motions of galaxies follow the visible matter of the galaxies: the physicist Mordehai Milgrom and the astronomer Stacy McGaugh. So Milgrom and McGaugh deserve the first credit for showing

how tightly the motions follow the visible matter. In 1983 Milgrom proposed one rule for faint pulls. Milgrom's rule has a 'faint acceleration': about one ten-billionth of a meter per second, gained every second. Under Milgrom's rule, the motion of a star departs from Newton's law in one fixed way when the acceleration of the star falls below the faint acceleration. Milgrom's one rule predicted, before the measurements, that faint and spread-out galaxies would depart from Newton's law throughout, and the faint and spread-out galaxies do depart from Newton's law throughout. McGaugh and his colleagues measured the Tully-Fisher relation that Hossenfelder names, using the mass of all the stars and gas of a galaxy in place of the brightness of the galaxy. McGaugh and his colleagues found that the relation holds with little scatter across galaxies of very different size: each galaxy lies close to the relation. McGaugh and his colleagues then showed how tightly galaxies keep to a single pattern. Astronomers find the pull at each distance from the center of a galaxy from the rotation of the galaxy at that distance. In 153 disc galaxies, the pull found from the rotation is one and the same function of the pull that the visible stars and gas alone would give. One and the same function means one rule for all 153 galaxies. By the one rule, the pull found from the rotation depends on the pull of the visible stars and gas. The Tully-Fisher relation and the single pattern are among the most exact regularities in astronomy. I take both regularities as they were measured.

Milgrom's rule and my account agree on what the galaxies show. Milgrom's rule and my account differ on whether what the galaxies show is a 'law' or a 'history'. The pattern of the galaxies is a record of how galaxies formed under Einstein's law, around the dark matter, a cold component that acts only through gravity. The word 'cold' means slow, with no motion from heat that could matter. The gas of ordinary matter shines as the gas falls inward, and the shining gas loses energy, sinks and breaks up into stars, while the dark matter gives off nothing and stays spread out. Galaxies form because the gas sinks while the dark matter stays spread out. Simulations of galaxy formation are computer calculations that follow the gas and the dark matter of a young universe as galaxies form. If the

simulations include a cold component that acts only through gravity, the simulations reproduce the pattern of the galaxies, and the simulations also reproduce how closely the galaxies keep to the pattern. In clusters of galaxies, the pattern departs from Newton's law at an acceleration about seventeen times the acceleration at which the pattern departs in single galaxies. If the pattern is set by how each kind of structure formed, the pattern departs from Newton's law at a different acceleration in each kind of structure. If instead the pattern comes from a law with one constant of acceleration, the pattern departs from Newton's law at the same acceleration in every kind of structure. The clusters show a pattern set by formation, because the clusters depart from Newton's law at a different acceleration from the galaxies.

Hossenfelder says that the newer forms of modified gravity do less well far above the size of galaxies, and two measurements far above the size of galaxies bear on Milgrom's changed law. The first measurement is of clusters of galaxies. In clusters of galaxies, Milgrom's changed law still needs unseen mass, and unseen mass is what Milgrom proposed the change to remove. The second measurement is of the oldest light, which shows warm and cool spots in favored sizes, as a drum sounds favored notes. Astronomers draw a chart with the size of a spot along the bottom and the strength of the spots of each size up the side, and each favored size appears on the chart as a 'peak'. The height of each peak shows how strongly the spots of the favored size appear. Without dark matter, Milgrom's changed law predicts a third peak lower than the measured third peak. Hossenfelder also names distances far below the size of galaxies, and 'wide pairs' of stars lie far below the size of galaxies: two stars in a wide orbit around each other. Each star of a wide pair has an acceleration below the faint acceleration of Milgrom's rule. Astronomers can use the wide pairs to test Milgrom's rule against my account directly, because no galaxy formed around a wide pair: a law of gravity applies to a wide pair, and a history of galaxy formation does not. The Gaia satellite made a sur-

vey of wide pairs of stars, and in 2024 the astronomer Indranil Banik and his colleagues found from the Gaia survey that Newton's law describes the wide pairs far better than Milgrom's rule does.

Hossenfelder sets the particle proposal and the modified-gravity proposal side by side. She looks for an answer between the two proposals. I give a fourth kind of answer, beside the new particle, the changed law and the mixtures of the two: the dark matter is a ringing of the setting of possibility, under Einstein's law unchanged.

The Balance Returns

Come back to the two-pan balance: a beam on a pivot, with a pan at each end. The things set in the pans are what is compared, and the 'setting' is the whole context of the weighing: the two places of the pans, the floor and the room that hold the pans, and the moment of the weighing. The beam carries the comparison, and the beam is part of the setting.

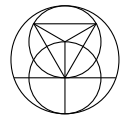
Imagine a weighing in which the beam tips further than the things you set in the pan account for. You look for what else is in the pan. You shine a lamp into the pan, and the light shows only the things you set in the pan. You listen at the pan, and you hear only the things you set in the pan. You run every detector you own across the pan, and each detector finds the things you set in the pan and nothing more.

Each try, with the lamp, the listening and the detectors, is an act of comparison too. Each try can be pictured on the balance. The lamp sets the light that goes out beside the light that comes back, and the detector sets a flash beside darkness. With each try, you compare the things set in the pan, and you find only the things set in the pan. The beam sets pull beside pull, and the beam tipped further than the things in the pan account for. So the extra pull belongs to no thing in the pan. The extra pull comes from the setting itself: the room in which the weighing happens rings, and the ringing of the room pulls. In the picture, the ringing room stands for the setting of possibility, and the ringing stands for the gyrations of the dark matter.

The turning of Rubin and Ford's galaxy was a weighing in which the beam tipped further than the visible things account for. Every bent ray of the Bullet Cluster is also a weighing with extra pull, since what bends the light is the pull. Thirty years of empty detectors are thirty years of lamps and listening, faithfully done: the detectors came back empty because the detectors compared the things set in the world's pans, while the dark matter is a ringing of the setting. The weighing registered the pull of the dark matter.

The short answer: Light and every detector built to catch a particle pass the dark matter by. Einstein's law of gravity stays exactly as Einstein wrote the law.

The dark matter belongs, as gravity does, to the setting in which every measurement is made. How does the setting of every measurement meet the quantum?



Chapter Thirteen

Is Gravity's Meeting with the Quantum the One Real Problem?

What this chapter uses

The *Incommensuration Theorem*: symmetry and continuity cannot both be applied, simultaneously and fundamentally, to any event or comparison; and neither can asymmetry and discontinuity. *Symmetry* is being the same under every change of place or setting, and *continuity* is having no gaps, so that a small change of setting gives a small change in what is found. The Incommensuration Theorem is a structural fact about the nature of knowing (Chapter Two).

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

The *content* of a comparison is what the verdict of the comparison is about, and the *context* is the respect in which the two things compared are two (Chapter Three).

An *epoch* is one whole span of the universe's history, from one turn to the next; *the turn* is the boundary between two epochs (Chapters Ten and Eleven); a *gyration* is one lasting vibration of the six small dimensions, and I identify the dark matter with such vibrations (Chapter Twelve).

Sabine Hossenfelder says that most of the puzzles physicists chase today are matters of taste, with one exception: gravity has never been brought into quantum theory, and black holes seem to destroy information. What exactly is the problem where gravity meets the quantum, and what is the way out?

A Glow at the Rutherford Laboratory

Physicists met at the Rutherford Laboratory in Oxfordshire on the fifteenth and sixteenth of February 1974. The physicists met to talk about 'quantum gravity', the effort to bring gravity into quantum theory. Stephen Hawking, then thirty-two years old, brought a new result to the meeting. At first Hawking had taken the result for a mistake in his own calculation.

Hawking had been thinking about black holes. A *black hole* is a region of space and time from which nothing, not even light, can come back out. Every black hole has a boundary: a surface past which every path into the future leads inward. Physicists call the boundary of a black hole the *horizon*. Einstein's theory of gravity describes a black hole completely. In Einstein's theory, a black hole is a smooth curving of space and time, with no material at the horizon.

Hawking took the quantum description of matter and light. Hawking laid the quantum description on the smooth, curved space and time around a collapsing star. The calculation produced a 'glow'. Hawking found that every black hole gives off a faint, steady stream of particles, with the spread of energies that any warm body gives off, and that a smaller black hole is warmer than a larger black hole. The glow carries energy away from the black hole, so the black hole slowly loses its mass. Hawking was persuaded that the result was real because the stream came out with exactly the spread of energies of a warm body, at a definite temperature.

Hawking published the result on 1 March 1974, less than two weeks after the meeting. The result appeared as a letter of two pages in the journal *Nature*. Hawking gave the letter a title with a question mark: "Black hole explosions?" The first sentence of the letter reads: "Quantum gravitational effects are usually ignored in calculations of the formation and evolution of black holes". Paul Davies and John Taylor, physicists in Britain, answered Hawking later in 1974, also in *Nature*. Davies and Taylor gave their answer a title of its own: "Do black holes really explode?" For a while, the physicists argued about the glow in titles that ended in question marks.

Hawking used two theories, and he used each theory exactly as the theory stood. Quantum theory described the fields of matter and light. The *geometry* of a region is the shape of space and time in the region. Einstein's smooth geometry described the setting on which Hawking laid the fields. Each theory did its own work, and together the two theories produced something new: the glow.

Hawking drew a startling conclusion from the glow in 1976, two years after the meeting. When a black hole has evaporated completely, only the glow is left, and because the glow is 'featureless', like the glow of a warm coal, the glow keeps no record of what fell into the black hole. So Hawking concluded that black holes destroy the information that falls into them, the record of what fell in. Hawking concluded also that, when a black hole destroys information, 'predictability' breaks down. Hawking's conclusion is the puzzle of this chapter, and in this chapter I follow the puzzle to its end.

From Hossenfelder's pages

What Sabine Hossenfelder Showed

In *Lost in Math*, Hossenfelder sorts the problems of fundamental physics into two kinds. The first kind of problem is an unexplained number that offends a sense of how nature ought to look. Hossenfelder calls a problem of the first kind an 'aesthetic misgiving', and she ar-

gues that most of the problems studied today are aesthetic misgivings. The second kind of problem is a 'contradiction': a place where the theories held at the time cannot all be right together. She writes that, in the history of physics, mathematics showed physicists the way forward *only* where there was a contradiction to resolve.

Hossenfelder names one contradiction among the problems studied today.

> But most of the problems we deal with now are not of this kind. The one exception is the quantization of gravity.
>
> (*Lost in Math*, chapter 10, "Lost in Math")

Hossenfelder names the 'quantization of gravity' as the exception, and a reader needs three terms to follow the exception. *General relativity* is Einstein's theory of gravity. General relativity says that gravity is the shape of space and time, curved by the matter and energy in space and time. *Quantum theory* is the theory of matter and light. In quantum theory, what is found comes in separate, countable steps, and every electron is exactly like every other electron. When physicists rewrite a theory so that what the theory describes comes in separate, countable steps, physicists say that they *quantize* the theory, as physicists did for light.

Her clearest example of the contradiction is a single electron. Quantum theory allows an electron to be in a combination of two alternatives, 'here' in one place and 'there' in another, held together until a measurement finds one of the two alternatives. Physicists call the combination of the two alternatives a *superposition*.

Then she asks where the gravity of an electron in a superposition is.

> And according to general relativity, the mass of the electron curves space-time around it. But around which location? General relativity cannot answer this question, since its curvature doesn't have quantum properties and can't be in two places at once.
>
> (*Lost in Math*, chapter 8, "Just a Humble Physicist")

She adds that the gravity of one electron is far too weak to measure. She adds also that the weakness of the electron's gravity does not matter. In her view, every question that a theory raises should have an answer in the theory, whether or not anyone can put the question to a test.

Her second example is Hawking's glow, and about Hawking's glow she makes a careful point.

> Let me emphasize that Hawking radiation is not caused by quantum effects of gravity, but rather is the product of quantum effects of matter in a curved non-quantum space-time.
>
> (*Lost in Math*, chapter 8, "Walls of Fire, Set in Stone")

Her point is exactly right. Physicists now call the glow *Hawking radiation*. In quantum theory, *information* is whatever tells one beginning apart from another. She explains that, in quantum theory, information cannot be destroyed, even when the information is so mixed up that no one could recover the information in practice. A burned book is one example: the book becomes smoke and ashes, and

even then the information in the book is not destroyed. In *Existential Physics* Hossenfelder states the trouble with black holes in one sentence:

> The evaporation of a black hole is thus time-irreversible: there are many different initial states that result in the same final state.
>
> (*Existential Physics*, chapter 1, "Eternal Information")

In *Lost in Math* Hossenfelder states the whole contradiction as a 'conundrum':

> Hence the conundrum: we started trying to combine gravity with the quantum theory of matter, and found that the result isn't compatible with the quantum theory. Something has to give, but what?
>
> (*Lost in Math*, chapter 8, "Walls of Fire, Set in Stone")

She then tells the story of a proposed 'way out', and of a trouble with the proposal. *String theory* is the program of research in which tiny vibrating strings replace point-like particles. String theorists proposed an exact match between a world with gravity inside a region and a quantum theory without gravity on the boundary of the region, and physicists call the proposed match the *gauge-gravity duality*. She writes that, until 2012, many string theorists believed that the gauge-gravity duality had solved the puzzle of the information that falls into a black hole. Every process can be run backward in the quantum theory on the boundary, so nothing is lost in the quantum theory on the boundary. In 2012 Ahmed Almheiri, Donald Marolf, Joseph Polchinski and James Sully made an argument about the glow: if the information is forced out into the glow, then the horizon must be lined with energetic particles that burn whatever falls in. Almheiri, Marolf, Polchinski

and Sully called the lining of energetic particles a *firewall*. The *equivalence principle* says that a body falling freely feels no gravity. So a traveler falling into a large black hole notices nothing special at the horizon. A firewall breaks the equivalence principle, which Hossenfelder calls the 'main postulate' of general relativity.

Hossenfelder ends the story with a plain fact: no experiment can test any of the proposed explanations of how black holes evaporate. She gives two reasons. First, a black hole as heavy as the Sun has a glow far colder than the faint warmth that fills all of space, the warmth left over from the early universe. Second, every black hole that we can observe gains mass by swallowing its surroundings and loses mass by its glow, and the gain from swallowing is larger than the loss from the glow. Hossenfelder states the consequence of the two reasons in one line:

> It's a pure math problem with no risk of interference by data.
>
> (*Lost in Math*, chapter 8, "Walls of Fire, Set in Stone")

Hossenfelder gives her own position in two notes at the back of *Lost in Math*. In one note, she writes of the 'firewall argument' that "their proof relies on an unnecessary hidden assumption that can be dropped, making the whole problem vanish". In the other note, she names her own claim as the most unpopular of the approaches to quantum gravity: "what we need to understand is not what happens to gravity at short distances but what happens to quantization at short distances". (*Lost in Math*, Notes to chapter 8, notes 13 and 20.)

Where the Two Theories Meet

I agree with Hossenfelder about where the problem of gravity and the quantum is, and about what kind of problem it is.

General relativity and quantum theory have each passed every test set for them, within their domains. The clocks on navigation satellites run a little fast in the weaker gravity of their orbits, and the navigation system that helps your phone find you corrects every one of the satellite clocks for running fast. The computed value matches measurement to about one part in a trillion.

I find the difficulty of gravity and the quantum exactly where Hossenfelder finds it. The difficulty appears only where both theories must speak about the same thing. I name three places where both theories must speak about the same thing: a mass in a superposition of two places, a black hole, and a scale far below anything yet measured. Every object has two sizes: a 'gravitational size', the size at which the object's own gravity would become strong, and a 'quantum size', the size over which quantum theory spreads the object. The two sizes are equal for an object of about twenty-two millionths of a gram. Physicists call the meeting point of the two sizes the *Planck scale*. The length of the Planck scale, in meters, is about a decimal point, thirty-four zeros, and then the digits 16.

Hossenfelder names the Planck scale as well, through the 'Planck energy', the energy that belongs to the Planck scale. Physicists call the theory of the particles the 'standard model'. She writes that the standard model and general relativity, combined, "lead to internal contradictions that, above the Planck energy, can't describe any observation" (*Lost in Math*, chapter 8, "Just a Humble Physicist").

A *singularity* is the place deep inside a black hole where the smooth description of space and time reaches its end. The essay also names three places where the two theories meet: "And where their ranges are forced to overlap, at the Planck scale, at the singularities of black holes, at the earliest moments of the cosmos, they contradict one another". The essay shares two of its three places with my account: the Planck scale and the

black hole. The third place of the essay is the earliest moments of the universe. So both books place the difficulty where Hossenfelder places the difficulty: wherever gravity and the quantum must describe the same thing. Hossenfelder is right that the difficulty of gravity and the quantum is of a different kind from an unexplained number.

I also agree with her about Hawking's glow. Every step of the calculation keeps the geometry classical. In the quotation, 'classical' means not quantized: at no step of Hawking's calculation is space or time quantized. In Hawking's calculation, the quantum fields are what is found, and the smooth geometry is where the quantum fields are found. The glow follows from the quantum fields and the smooth geometry working together.

Hossenfelder calls the black-hole puzzle "a pure math problem with no risk of interference by data". I describe a pattern that fits a question that has become a pure math problem. The pattern has three steps: physicists turn a question about the world into a question of mathematics, each answer raises a further question of mathematics, and the question about the world stays exactly where the question was, still unanswered. The remedy is to ask the question about the world again. In the case of gravity and the quantum, the question about the world is plain: what kind of thing are space and time?

The Floor Under the Balance

Come back to the two-pan balance. I have followed the act of comparison with you from the first chapter. Every measurement is an act of comparison.

Now look down at what the balance stands on: a bench, a market stall, a floor. You have made every one of your weighings on whatever the balance stood on. You can weigh almost anything that will fit in the pan: the apple, a stone, a handful of sand. Now try to weigh the floor. You cannot lift the floor into the pan, because the balance stands on the floor while the balance weighs. The floor is where every weighing happens, and the floor is never one of the things in the pan.

Every comparison divides into two parts, and each part has a name. The *content* of a comparison is what the 'verdict' of the comparison is about: at the balance, how heavy the apple is. At the balance, the context is the two places that the apple and the weights occupy: the left pan and the right pan. The beam carries the comparison and is part of the setting, and the tip of the beam is the result. In physics, the content is the matter that measurements find. Content and context always come together, *but* content and context are never the same thing.

Chapter Three named space and time together the *arena*. Quantum matter is found in the arena, and every measurement is made in the arena. Every length is a length in the arena, and every duration is a duration in the arena. General relativity is the theory of the shape of the arena, and we feel the shape of the arena as gravity. I identify quantum theory as the description of the content of physics: what every measurement finds. I identify general relativity as the description of the arena: the part of the context of physics that is space and time, where the content is found. So the arena is the floor under every balance in physics.

How do we know that gravity belongs to the floor, and is not one more thing standing on the floor? I answer in two steps. First, I ask what any setting of measurement must be like, before gravity is named, and finds four 'marks': four features that every setting of measurement must have. Then I check gravity against each of the four marks.

The first mark is that the setting 'takes part in' everything found in the setting, because everything found is found somewhere. Everything in the shop where the balance stands also stands on the floor, and in the same way gravity acts on everything: on every kind of matter, on light, and on antimatter.

The second mark is that the setting reaches every region, so nothing can shield the setting out of a region. To 'shield' something out of a region is to make a region where the thing is absent, and a region with no setting

in the region is no region at all. A mat laid on the floor still lies on the floor. The metal walls of a lift keep out the signal of a phone, *but* no box keeps out gravity.

The third mark is 'one mass'. A body has two properties that concern the setting: one property ties the body to the setting, and the other property resists any change in the body's motion through the setting. Both properties measure how much the body takes part in the setting, and I identify the two properties as 'one quantity'. So every body 'falls alike', whatever the body is made of: the mass that gravity pulls on is the same mass that resists being pushed. Physicists know the equality of the two masses as one form of the equivalence principle.

The fourth mark is 'no charge that comes in steps'. An electric charge comes only in whole multiples of one smallest step, and an electric charge is an exact label that a body carries, the same for every particle of a kind. The setting is smooth, and smoothness gives a body no 'stepped label' like an electric charge. Gravity pulls on the whole energy of a body, and the energy of a body can take any value: a hot brick is heavier than the same brick cold, by an amount far too small to weigh but real.

Gravity carries all four marks, and no force of particle physics carries even one of the four marks. I identify gravity as the arena *because* gravity matches all four marks. Gravity is the shape of the floor, and not one more thing standing on the floor.

Now we can ask the question of quantizing gravity in the right form. To quantize light was to rewrite the description of something found in the arena. The arena stayed where the arena was, to receive the new description of light. To quantize gravity is to ask the arena itself, the floor, to take on the 'stepped character' of the things found on the floor.

I answer the question of quantizing gravity from the *Incommensuration Theorem*, which Chapter Two set out. In the Incommensuration Theorem, *symmetry* means being the same under every change of place or setting, and *continuity* means having no gaps, so that a small change of setting gives a small change in what is found.

When a comparison is perfected at its foundation, exact all the way down, the comparison can have only one of two 'characters'. The arena has one of the two characters, smooth and different from place to place, and the things found in the arena have the other character, exactly repeating and coming in countable steps.

Picture the floor of the shop as poured stone: smooth everywhere, and rising or dipping a little from one corner to the next. Picture the weights in their box: each exactly like every other of its size, and counted one by one. To quantize the floor is to ask the floor to take on the character of the weights while the floor stays the floor. The floor has two features and the weights have two features, and each of the four features answers one of two questions. The first question is whether a thing is the same from place to place, or different. The second question is whether a thing is smooth, or in steps. The floor answers 'different' and 'smooth', and the weights answer 'the same' and 'in steps'. Nothing can be smooth and in steps at once, and nothing can be 'uneven' and exactly the same everywhere at once. So a floor that stays the floor keeps its own answer to one question and takes the weights' answer to the other question, and the floor can therefore take on the character of the weights in one of two ways. The Incommensuration Theorem excludes *both* ways. In the first way, the floor keeps its smoothness and takes on the exact sameness of the weights, so the floor would be smooth and exactly the same everywhere: continuity with symmetry. In the second way, the floor keeps its unevenness and takes on the steps of the weights, so the floor would be uneven and in steps: asymmetry with discontinuity.

There is a second reason why the arena cannot be quantized, and you have already seen the second reason at the balance. When light was quantized, the arena stayed in place to receive the new description. When

the arena itself is to be quantized, nothing stays in place. The change would have to be made in the very setting in which every change is described. To quantize the arena is to ask the floor to climb into the pan.

So the arena is 'smooth all the way down'. The arena has no smallest length, no smallest area and no smallest stretch of time of its own. When someone applies a concept where the concept does not belong, philosophers call the mistake a *category error*. To ask the arena for steps is a category error. The arena is smooth all the way down.

Hossenfelder makes her own claim in a note to *Lost in Math*: physicists should ask what happens to quantization at short distances, in place of what happens to gravity at short distances. The answer of my account is also an answer about quantizing. Quantizing applies to the things found on the floor, and *never* to the floor itself.

One Shape of Space for Each Alternative

When an electron is in a superposition of two places, where is the gravity of the electron?

Picture two photographs of a trampoline. In the first photograph, a heavy ball sits near the left edge, and the cloth dips under the ball near the left edge. In the second photograph, the ball sits near the right edge, and the cloth dips near the right edge. Each photograph is right about its own dip. Now lay the two photographs over each other and average the two photographs. You get half a dip on each side, made by half a ball on each side. No single ball makes the 'averaged shape', wherever the ball sits.

I answer Hossenfelder's question about the electron with the first two photographs: "The answer I give is the first two, each in its own alternative". In the first 'alternative', the electron is in the first place. In the first alternative, space and time take the shape that an electron in the first place would give space and time. In the second alternative, the electron is in the second place. In the second alternative, space and time take the shape that an electron in the second place would give space and time. Each alternat-

ive carries its own shape and *only* its own shape, and no alternative carries a 'blend' of the two shapes. Each photograph of the trampoline stands for one alternative, and the averaged photograph stands for the blend.

The reason for one shape in each alternative comes from the floor and the pan. Each alternative of the matter is something a measurement could find, so each alternative is a content, and every content has its context. Two contexts join into one only where what the two contexts hold is found together. The two alternatives exclude each other, because the electron is never found in both places, so each alternative has a context of its own. I identify the geometry of each alternative with the context of that alternative, so each alternative of the matter has its own smooth geometry, which is shaped by that alternative alone. This answer quantizes nothing. Within each alternative, the shape of space and time is smooth, and different from place to place, exactly as general relativity describes the shape. The 'steps' belong to the matter, because the matter is the content, and findings of content come in steps.

I make the same identification of geometry with context, from the principle that where there is content, there is context. I have a chapter on Einstein's equations of gravity, and the chapter shows that the equations hold in each alternative, and that each alternative has its own smooth geometry. A geometry for each alternative quantizes nothing.

An experiment made in 1981 has already put the answer of one shape for each alternative to a test. In 1981 Don Page and C. D. Geilker, two physicists, used a 'torsion balance', the instrument that Henry Cavendish used in 1798 to weigh the Earth. In a torsion balance, a light bar hangs level from a thin wire, with a small lead ball at each end, and large lead balls set nearby pull the bar around. Page and Geilker set the position of the large balls by a quantum event: before each run, a Geiger counter counted radioactive decays, and the count set which of two positions the large balls were put in.

The bar turned on every run, one way or the other. Each time, the bar turned the way the actual position of the large balls required. Gravity followed the outcome of the quantum event: if gravity had followed the average of the two alternatives, the two pulls would have canceled, and the bar would have stayed still. Page and Geilker titled their paper "Indirect Evidence for Quantum Gravity", and they took their result as support for a quantized field of gravity. The bar showed directly what the two photographs show: each alternative of the matter carries the gravity of its own arrangement. We now know that gravity follows the outcome of a quantum event, and not the blended photograph. Appendix A, "What the Coming Measurements Will Find", states what the measurements now being prepared will find. One of the coming measurements is a test of the answer of one shape for each alternative. The test uses two small masses, each held in two places at once.

So the two theories meet, and each theory is used unchanged: the two theories are joined 'side by side', quantum theory for what is found and general relativity for where the content is found. The two theories are never 'merged' into one description. When two descriptions are joined side by side, and never merged, three things are true of the two descriptions. Both descriptions arise from the same act of comparison, both descriptions apply to the same world, and each description is perfected in one of the two characters that a comparison allows. I call the unity of two descriptions joined side by side a 'common source'. The Incommensuration Theorem permits a common source, *but* the Incommensuration Theorem forbids *only* a 'merger': one description in which the directions of space and time themselves carry both characters together.

Where the Information Goes

Now go back to Hawking's glow, and to the puzzle that Hawking drew from the glow.

The puzzle is a conflict between two statements. Hawking's calculation says that the final glow is featureless. Quantum theory says that nothing can be lost, when quantum theory is applied to the whole system. I locate the trouble in the words "applied to the whole system". When quantum theory is applied to the whole system, physicists treat the black hole, the geometry of the black hole and the matter of the black hole together as one quantum system with one quantum state. I name the premise: "The premise is this: geometry and matter form one quantum state". The premise puts the floor in the pan, because the premise treats the geometry as one more thing found, like the matter.

Keep the floor where the floor belongs, with the geometry kept out of the quantum state, and quantum theory guarantees something plainer: the state of the matter, laid out on the geometry of the matter, goes forward without loss. Hawking's own calculation shows exactly that the state of the matter goes forward without loss. When the fields inside the horizon and the fields outside the horizon are taken together, the fields stay as 'fully specified' as quantum theory allows, at every stage that Hawking's calculation describes. When two things are linked so closely that neither can be described alone, physicists call the two things *entangled*. The glow outside the horizon is entangled with the field inside the horizon. The glow looks featureless because the glow is 'half of a pair', seen without its partner.

Think of a coded message and its key. The message alone reads as 'noise', and the key alone reads as noise. The 'meaning' is in the pair, so no part of the meaning is lost while both the message and the key are kept. The meaning stays whole even when only one of the two, the message or the key, is in your hands, and the other is kept somewhere else. The glow outside the horizon is like the message, and the field inside the horizon is like the key.

Information is not destroyed in a black hole. The information goes forward in each of the two descriptions: in quantum theory, the matter goes forward without loss, and in general relativity, what falls in goes forward to the end of the interior of the black hole. While the black hole stands, the horizon hides what fell in from everything outside, *but* the horizon destroys none of what fell in.

Does the hidden information ever reach the world outside? I answer separately for two kinds of black hole.

The first kind is a black hole far lighter than any star, light enough to evaporate completely while the world around the black hole remains. For a black hole of the first kind, the firewall argument is the question to answer. The firewall argument says that three things cannot all hold together: a glow that in the end carries out everything that fell in, ordinary physics outside the black hole, and a smooth horizon. I keep the smooth horizon and ordinary physics outside the black hole, and the book also keeps the equivalence principle, by which a body falling through the horizon meets only what a falling body would meet anywhere else. I give up one assumption that the firewall argument needs: that what lies just inside the horizon is 'independent' of the glow that has already left. In the picture of the coded message, the assumption says that the messages already sent out have nothing to do with the half of the key still inside the black hole. In 2019 Geoff Penington computed the history of the glow, and in the same year a second group, Ahmed Almheiri, Netta Engelhardt, Donald Marolf and Henry Maxfield, computed the history of the glow separately. Both computations used a method that counts the region just inside the horizon together with the early glow. When the inside region and the early glow are counted together, the inside region and the early glow are 'linked', so the firewall argument loses the assumption that the firewall argument needs. In a note to *Lost in Math*, Hossenfelder answers the firewall argument in the same way as I do: she writes that the firewall argument rests on an assumption that can be dropped.

The second kind is a black hole formed from a star. About a black hole formed from a star, I say exactly two things: the information that fell in is not destroyed, and while the black hole stands, no one outside can reach the information. I assert neither that the information returns to the world outside, nor that the information is lost to the world outside, because my argument there needs neither assertion.

I go one step further, on ground of my own: I follow what falls into a black hole through the interior of the black hole, to the end of the interior. *The turn* is the boundary between two epochs: every black hole of the ending epoch has an interior, all of the interiors end together at the turn, as 'one end', and the next epoch begins at the turn. No comparison can be made across the turn. Chapter Eleven pictured the interiors of the black holes as 'funnels'. Each funnel is separate along its length, and the ends of all the funnels are one end. What falls in is carried with the matter to the single end of all the interiors at the turn, and what fell in comes out in the beginning of the next epoch, as small 'departures' of the next epoch from perfect evenness. The departures are the faint pattern from which the galaxies of the next epoch grow. The information is lost to every observer who remains outside the horizon, and it is not destroyed.

What passes the turn is the 'form' of the matter that fell in: which alternatives the matter took. An 'entropy' is a count, as Chapter Ten said. Every entropy belongs to the context from which the entropy was counted, so an entropy reckoned from outside the black hole belongs to the outside world, and ends when the outside world ends, at the turn.

So the two books reach the same conclusion by two routes, on different ground. In the first of the two books I remove the premise that geometry and matter form one quantum state. I then find that, in each of the two theories, the information goes forward. In the second I reject a different premise, that the information must come back to the world outside the black hole, and follow what fell in through the interior of the black hole to the next epoch. Both books arrive at one statement: nothing is destroyed.

The Way Out

I establish that the arena of space and time cannot be quantized. The context of every measurement has three 'measures', space, time and possibility, and the arena holds two of the three: space and time. Each result of my account in this chapter needs only the two theories exactly as the two theories stand, each theory doing its own work.

Hossenfelder writes that most theoretical physicists, herself included, think a theory of quantum gravity is needed to resolve the black-hole puzzle. She writes in the last section of *Lost in Math* that "we have to understand the quantum behavior of space and time, overhauling either gravity or quantum physics, or maybe both", to complete the laws of nature. The way out in my account is a question asked one step earlier: what kind of thing is being quantized? When the question is asked one step earlier, the contradiction that Hossenfelder names is real. The contradiction has a reason: the two theories have 'opposite characters'. The contradiction appears wherever one description is asked to carry both characters, and to ask one description to carry both characters is to ask the floor to go into the pan. General relativity is 'continuity with asymmetry' and that quantum theory is 'symmetry with discontinuity'. Both statements follow from the Incommensuration Theorem. The failure to unify them is not a problem awaiting a solution. It is a structural exclusion. The essay adds that the unity that can be had is already in hand: two descriptions of one world, "each capturing what the other must leave out".

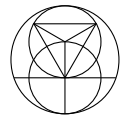
Physicists have already measured the arena several times, and the results are on record. LIGO is the American observatory for waves of space and time. In 2015 the two detectors of LIGO caught a ripple from two merging black holes. The shape of the ripple matched the shape that smooth general relativity computes. In 2022 the MICROSCOPE satellite let titanium and platinum fall together in orbit. The titanium and the platinum fell alike to within a few parts in a million billion. In 2024 the LHAASO observatory in China timed light of very different energies from a bright burst in a distant galaxy. LHAASO found no delay that depends

on energy. We now know that the simplest pictures of a 'grainy' space and time, made of smallest steps, are excluded, and that every body falls alike, as a floor shared by everything requires.

In 1974 Hawking applied both theories to one object, in one calculation, and each theory held. Quantum theory described the fields, and general relativity described the curved floor that the fields stood on. Together, the two theories showed that black holes 'shine'. Hawking's puzzle of 1976 came from the demand that the floor be one more thing in the pan.

The short answer: The meeting of gravity and the quantum is a real difficulty. Space and time cannot be quantized. In the way out, space and time stay the arena in which every measurement is made. In the way out, the two theories are joined side by side. When the two theories are joined side by side, a black hole destroys nothing.

Many results of my account are far from what most physicists hold, so how can a reader judge whom to trust?



Chapter Fourteen

Whom Can We Trust When Scientists Agree?

What this chapter uses

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 Two).

An *identification* is a stated step from the structure of comparison to a measured quantity (Chapter One); the *standing* of a number is the stated answer to where the number comes from (Chapter Four).

Every comparison has three *positions*: the thing compared, the thing compared against, and the act of comparing (Chapter Three).

Every comparison has three parts, as a stool has three legs: the act of finding, here and now; the record that the act lays down, which anyone can read; and the place from which the question is asked, with the range of possible answers to the question (Chapter Six).

When the experts agree, and you cannot check the experts' work yourself, how are you to know whether to believe the experts? Sabine Hossenfelder tells her readers three things about her own field of physics: that her field rewards social agreement, that the physicists in her field who build theories take no steps against their own bias, and that we cannot

trust the conclusions that the scientists of her field reach in almost all of their research. Bias is a steady lean of judgment that the person judging does not notice. How, then, should anyone decide whom to trust? You can ask the same question about my account (the Immanent Metaphysics, together with the physics I work out from the Immanent Metaphysics), because the chapters of this book have taken you to results far from what most physicists hold. I begin with a case from the nineteenth century, in which many scientists came to agree with an exact calculation. The rocks of the Earth showed something different from the calculation.

A Calculation Against the Rocks

William Thomson was a physicist who was later made Lord Kelvin. In 1862 Thomson published a paper with the Royal Society of Edinburgh under a plain title, "On the Secular Cooling of the Earth", in which the word 'Secular' means slow, across the ages. The word 'thermodynamics' names the physics of heat, and the first words of Thomson's paper were about thermodynamics: "For eighteen years it has pressed on my mind, that essential principles of Thermo-dynamics have been overlooked". Thomson's sentence went on to say which geologists had overlooked the principles of thermodynamics: the geologists who would allow no sudden, violent upheavals in the Earth's past.

Thomson's idea is easy to picture: take a large stone out of a fire and set the stone on cold ground. The stone cools from the outside in. After a few minutes, the surface of the stone is cool to the touch, but the middle of the stone is still hot. After an hour, the stone has cooled deeper in. Inside the stone, the warmth rises as you go in from the surface, and the steepness of the rise is a kind of clock. If you know how readily heat passes through stone, you can reckon from the steepness of the rise how long ago the stone came out of the fire.

Thomson applied the clock of the cooling stone to the whole Earth. Miners had long known that the rock of a mine grows warmer the deeper the mine goes. The rock grows warmer by about one degree Fahrenheit

for every fifty feet of depth. *Conduction* is the passing of heat through a material that stays where it is, as heat creeps along a poker left in a fire. Thomson took the Earth to have begun as a molten ball, and to have been cooling by conduction ever since. Thomson also took the Earth to be solid, with no source of heat inside. Thomson's calculation had four 'starting points': a molten beginning, cooling by conduction, a solid Earth, and no source of heat inside. Thomson used the four starting points and the warmth of the mines to calculate how long the Earth had been cooling, and Thomson's answer was somewhere between twenty million and four hundred million years. Over the following decades, Thomson narrowed the figure. By 1897 Thomson put the age of the Earth at more than twenty and less than forty million years. The mathematics of the flow of heat was Thomson's own field, and Thomson's calculation was sound.

The geologists read the age of the Earth in a different way. The geologists read the age in the layers of rock, which were laid down a little at a time on the beds of old seas, and in how slowly rain and rivers wear valleys down. The naturalist Charles Darwin reckoned in 1859, in the first edition of *On the Origin of Species*, that one stretch of southern England, the Weald, had needed some three hundred million years to be worn down. The geologists' estimates were rough, and the geologists differed among themselves. The geologists shared one need: far more time than Thomson allowed. Different geologists reached the need for more time by different routes: the thickness of the layers, the wearing of the land, and the order of the fossils.

Thomson's figures carried the authority of exact physics, and Thomson's figures prevailed. Many geologists came to accept the limit on the age of the Earth that the physicists set. In 1869 Thomas Henry Huxley was President of the Geological Society of London. Huxley answered the physicists with an image:

> "Mathematics may be compared to a mill of exquisite workmanship, which grinds you stuff of any degree of fineness; but, nevertheless, what you get out depends upon what you put in; and as the grandest mill in the world will not extract wheat-flour from peascods, so pages of formulae will not get a definite result out of loose data".
>
> (Thomas Henry Huxley, "Geological Reform", address to the Geological Society of London, 1869)

The word 'peascods' means pea pods. In Huxley's image, the 'mill' is the mathematics, and what goes into the mill is the data that the mathematics starts from. A finer grinding says nothing about what went into the mill.

In the end, the answer about the age of the Earth came from what had gone into Thomson's calculation: Thomson's starting points. John Perry was an engineer who had once been Thomson's assistant. In 1895 Perry wrote to Thomson in the journal *Nature*: "the real basis of your calculation is your assumption that the solid earth cannot alter its shape". *Convection* is the carrying of heat by the movement of the material itself, as warm water rises from the bottom of a pot on a stove. Perry asked a question: what follows if the deep Earth can flow, however slowly, and so carry its heat upward by convection? Perry showed that a flowing interior would fit both the warmth of the mines and an Earth thousands of millions of years old. *Radioactivity* is the giving off of energy by certain kinds of matter as the atoms of the matter change. The physicist Henri Becquerel discovered radioactivity in 1896. The rocks of the Earth turned out to hold small amounts of radioactive matter, a source of heat inside the Earth.

Radioactivity also gave scientists a new clock for the age of the Earth, because radioactive atoms change at fixed rates. By 1911 the geologist Arthur Holmes had measured a rock about 1,600 million years old. In 1956 the geochemist Clair Patterson measured the lead in meteorites. From the lead, Patterson found the age of the Earth to be about 4,550 million years. Today, the measured age of the Earth is about 4,540 million years. The solid rock of the deep Earth does creep slowly under heat and pressure, as Perry proposed, and the creeping rock carries heat upward.

For some forty years many scientists agreed with Thomson's exact calculation, but the agreement of the scientists did *not* make the Earth one year younger. Measurement settled the age of the Earth, after Perry had first shown where to look by asking his questions about the starting points of Thomson's calculation.

From Hossenfelder's pages

What Sabine Hossenfelder Showed

In her book *Lost in Math*, Hossenfelder's case concerns her own field of research, which she calls the *foundations of physics*: research on the most basic laws of physics. A *theorist* is a physicist who builds theories with pencil and computer. An *experimentalist* is a physicist who builds the instruments and makes the measurements. Hossenfelder works in the foundations of physics as a theorist. Hossenfelder's first observation is that four developments have changed how her field behaves: the field has more physicists than before, and the physicists are better connected, under more pressure to publish, and on shorter grants. Of the four developments, Hossenfelder writes:

> This has made scientific communities an ideal breeding ground for social phenomena.
>
> (*Lost in Math*, chapter 7, "Strength in Numbers")

Hossenfelder offers, with a smile at herself, a "little theory of something". Her 'little theory' begins from one observation: scientists are influenced by the communities they belong to, and so

> (*Lost in Math*, chapter 7, "Strength in Numbers")

Hossenfelder's second observation is about *bias*, a steady lean of judgment in one direction that the person judging does not notice. Hossenfelder names many kinds of bias, and one kind is 'confirmation bias', the habit of finding what supports the view you already hold. Then Hossenfelder tells how experimentalists have learned to guard against bias. When physicists plotted the measured lifetime of the neutron year by year, the values came in steps. Each new value tended to reproduce the earlier values. The experimentalists learned a lesson from the steps:

> In many collaborations it is now common to settle on a method of analysis before even looking at the data (before the data is "unblinded") and then just follow through with the previously agreed-upon procedure.
>
> (*Lost in Math*, chapter 10, "Don't Trust Me, I'm a Scientist")

When the method of analysis is fixed before anyone sees which way the data lean, physicists call the analysis a *blind analysis*. Hossenfelder writes that theorists have nothing like a blind analysis: "Here in theory development, the apparatus we work with is our brain. But we're not doing anything to avoid bias in its operation".

Hossenfelder's third observation is about what her field uses in place of a test. The philosopher Richard Dawid has a phrase for judging a theory on grounds other than observation, such as the absence of alternative explanations: *non-empirical theory assessment*. Hossenfelder grants that physicists always choose which ideas to pursue before any

test. But Hossenfelder holds that the grounds physicists use for the choice are "mostly social and aesthetic". Hossenfelder's own conclusion is short:

> In the end the only way to find out which theory is correct is to check whether it describes nature; non-empirical theory assessment will not do.
>
> (*Lost in Math*, chapter 10, "Lost in Math")

Hossenfelder adds that physicists seldom drop a theory after a single failed test: physicists "implausify" the theory instead. Physicists adapt the theory to each new piece of evidence, until the theory grows so arcane that people lose interest in the theory. Hossenfelder also calls her field "the canary in the coal mine", and by 'the canary' she means that her field is the first science to run short of data, and that other sciences will follow.

At the end of *Lost in Math*, Hossenfelder gives the reader three questions to ask of any scientist. First, does the scientist's future funding depend on the result the scientist announces? Second, does the scientist's career depend on being popular with colleagues? Third, has the scientist taken steps against the scientist's own biases? Then Hossenfelder gives her verdict on her own field:

> You will find that for almost all research in the foundations of physics the answer to at least one of these questions is no. This means you can't trust these scientists' conclusions.
>
> (*Lost in Math*, Appendix C, "As a science writer or member of the public")

Hossenfelder is right that agreement among physicists is no test of a theory, and she is right that the habits she names are real. Hossenfelder is also right that the experimentalists found a working remedy for

the habits: the experimentalists fix the rule of analysis before looking at the data. And Hossenfelder is right that *only* a check against nature settles a claim about nature.

it leads me to conjecture that the laws of nature are beautiful because physicists constantly tell each other those laws are beautiful.

Three Ways to Settle a Weight

Picture a market stall with a two-pan balance on the counter, and a parcel of flour you are about to buy. There are three ways you might come to hold that the parcel weighs a kilogram.

You can weigh the parcel. Set the parcel in one pan and a kilogram weight in the other pan, and see the two pans hang level. Weighing the parcel is a *measurement*: a comparison made here and now, by you, in the act.

You can work the weight out. The miller says he filled the parcel from four bags of exactly 250 grams each, and four times 250 is 1,000. Anyone who checks the sum gets the same answer, whoever and wherever they are. The miller's sum is a *proof*: a set of steps from stated starting points, where anyone can check each step by reading the step. The proof settles that four bags of 250 grams make a kilogram, but the proof does not settle whether each bag really held 250 grams. The question about the bags is a question about the world, and the sum cannot answer a question about the world.

Or you can ask the queue of people waiting at the stall. Everyone waiting at the stall says, "That parcel is a kilogram, everyone knows it". The queue's word is *agreement*: a claim counted as settled because many people say so.

Only the weighing and the sum settle anything. The weighing settles the parcel's weight, and the sum settles what the bags add up to. The queue's word shows you what the queue thinks. If the balance is broken, so that no one can make a weighing, the queue's word may be the best

clue you have, and the queue's word is still only a clue. And if everyone in the queue heard the claim about the parcel from the same stallholder, then twenty voices in the queue are one voice.

I find exactly three ways in which anything at all can be held to be validated, and no others: measurement, agreement and proof. Of the three, only the first and the third validate truth. Agreement among people validates nothing by itself. *Circumstantial evidence* is the kind of evidence a court weighs when no one saw the deed: facts that point toward a conclusion without showing the conclusion, like a footprint in a garden. At most, agreement is circumstantial evidence, standing in for a measurement where no measurement can be made.

Hossenfelder reached her result about agreement from the history and the habits of her field, and I reach the same result on separate ground: from what an act of comparison is. Every measurement is an act of comparison. I find three roles in every act of comparison, and one weighing at the stall shows all three roles.

First there is the weighing itself, as the weighing happens: you set the parcel in one pan and the kilogram weight in the other pan, here and now, while you watch. The weighing as it happens is the first role, 'the act' itself. Then the stallholder writes "1 kg" on the parcel, and the written result stays on the parcel long after the weighing is over, the same for anyone who reads the result. The written result is the second role, 'what is laid out': anything that can be held in view as a whole and shared, such as a result, a record, a sum or a map. And there is the standpoint from which the weighing is made: you, standing at the counter, together with everything that could be found from where you stand. The standpoint is the third role, 'the stance'. The stance includes commitments that no one at the stall states or checks. For example, every shopper takes the stall's kilogram weight to be a true kilogram. I set out the structure of comparison from the ground up. Chapter Three named three 'positions' in every comparison: the thing compared, the thing it is compared against, and the act of comparing. I take the three positions more widely, and the three 'roles' are the three positions taken in that wider way. The weighing itself

is ‘the act’, and the parcel is ‘the thing compared’. Once the result of the weighing is written down, the parcel gives ‘what is laid out’. The kilogram weight is the thing the parcel is compared against, the ‘standard’ from which the parcel is read. I call a standard a ‘stance’, the place from which another thing is read, as a length is read from a rod. I then widen the position of the thing compared against into the third role, the standpoint from which any weighing is made, and at the stall the standpoint is yours, at the counter.

Every comparison has all three roles: ‘the act’, ‘what is laid out’, and ‘the stance’. The three legs of the stool in Chapter Six are these same three roles: the act of finding is the act, the record is what is laid out, and the place from which the question is asked, with its range of possible answers, is the stance. Chapter Two found exactly two ways in which an act of comparison can be held perfectly. The first way is ‘continuous and asymmetric’, like the settling beam of the balance. The settling beam swings smoothly through every position, with no jump. Each swing of the settling beam is a little smaller than the swing before. The second way is ‘symmetric and discontinuous’, like the box of weights. Each ten-gram piece in the box sets the beam level against any other ten-gram piece, in any town and in any year. The amounts in the box come in steps, with nothing between ten grams and twenty. There are three roles because there is the one act, and there are the two ways of holding an act of comparison perfectly. The second role, ‘what is laid out’, is held perfectly in the symmetric and discontinuous way: the “1 kg” on the parcel reads the same for everyone, and the “1 kg” is one separate, countable mark, like each weight in the box. The third role, ‘the stance’, is held perfectly in the continuous and asymmetric way: from where you stand, ‘here’ differs from ‘there’ and ‘now’ differs from ‘then’, and through all the differences you go on as one person, without a break. The act is the one act from which the other two roles are made: ‘what is laid out’ is the act set down, and ‘the stance’ was formed by earlier acts. So there are three roles in all, the one act and one role for each of the two ways, and there is no fourth role. The three roles are related to one another in three ways. The three

roles are 'distinct': no role turns into another role. The three roles are 'inseparable': no role is found without the other two roles. And the three roles are 'not interchangeable': putting one role in the place of another role gives a different and wrong result.

The three ways of settling a claim are the three roles of comparison, read as ways of validating. A measurement is 'the act', made here and now, in the first person: "I weigh this". A proof is 'what is laid out', held in view as a whole on the page, in the third person, the same for anyone who checks the proof. Agreement belongs to 'the stance': many people carry agreement as a shared commitment, in the second person ("you know this"), and no one of the many people checks the shared commitment. There are three ways of validation and no fourth, because a comparison has three roles and no fourth. No role can do the work of another role, so agreement cannot do the work of a weighing or of a proof, however many people agree and however long they agree.

Two further results of my account agree with Hossenfelder's observations. The first result concerns experts trained in one tradition. The agreement of experts trained in one tradition is not independent confirmation, because a shared training can carry a shared error into every one of their judgments at once. Twenty experts with one training are the queue at the stall that heard the claim about the parcel from one stallholder: twenty voices that are one voice. The second result is that taking agreement for a meeting with the world is an error with a name. An *encounter* is one actual meeting with the thing itself, as the parcel meets the pan. I call the error 'the error of consensus': "taking agreement to be encounter".

Thomson's Case, Read Again

Now read the story of the age of the Earth again, with the three ways of validation in mind.

Thomson's calculation was a proof of this form: if the Earth is a solid ball that only conducts heat, with no heat inside, then the Earth is some tens of millions of years old. Thomson's conclusion followed from Thom-

son's starting points in 1862, and the conclusion follows from the starting points today. When an argument's claims follow from its starting points, I say that the argument has *merit*. When an argument has merit and its starting points are true of the world, the argument is true of the world. Thomson's starting points were false of the Earth: the deep rock of the Earth creeps, carrying heat upward, and the rocks of the Earth hold a source of heat of their own. Thomson's calculation was the miller's sum, sound in every step and resting on starting points that were false, like bags that did not hold what the miller said the bags held.

The geologists had something else: many rough strands of evidence from independent sources, each strand pointing to far more time than Thomson allowed. Think of a steel cable on a crane, twisted from many thin wires. Cut one wire, and the cable still holds, because the other wires share the load. The geologists' evidence formed a cable like the crane's cable, and the rocks, the wearing of the land and the fossils were the wires. I name the mistake of Thomson and of the scientists who accepted Thomson's limit. The mistake was to let one exact route stand above the whole inquiry, as if its exactness made it the whole cable, and to weigh the other strands by how exact they were in place of what they showed. Thomson's calculation was the 'one exact route', and the geologists' evidence was 'the other strands'.

The scientists who agreed with Thomson were the queue at the stall. The agreement of the scientists settled *nothing* about the age of the Earth. Perry read the starting points of Thomson's calculation one by one. Of each starting point, Perry asked whether the Earth is as the starting point says. Then Holmes and Patterson weighed the rocks with the clock of radioactive atoms: Holmes and Patterson measured the age of the rocks. The measurement of the rocks settled the age of the Earth.

A Prediction Sealed Before the Weighing

Experimentalists take the blind analysis as a step against bias, and Hossenfelder asks what step theorists can take against their own bias. I take a step of the same kind for theory, and my step has the same shape as a blind analysis: the rule for what counts as a result is fixed before anyone looks.

On 1 November 2026 one record was made of every prediction in my books, forty-two predictions in all. The record states each prediction in plain words and gives, beside each prediction, the book and chapter that argue the prediction and the measurements already reported, together with the coming measurement that decides the prediction, wherever the books name the coming measurement. The record carries its date, and the record stays exactly as the record was written on 1 November 2026. The record was sealed at a date before the measurements that will decide its predictions. The record also states in advance what will count as a result. I call the record of 1 November 2026 *the sealed record*. *Side by Side* sets other physicists' models of the universe beside my account, each model against the one sealed record. The sealed record is printed whole as Appendix B of that first volume.

The sealed record has a *rule of decision*, which states what will count as a result, before any result comes in. The rule of decision was written into the record on the same date as the predictions, so the rule for what counts as a result was fixed before anyone could see any result. On the same date, the record also states which measurements bear on my account. So no one can choose afterward, once the data are in, which results to count.

Chapter Five described Popper's test, and Hossenfelder's report that the test is outdated. I keep Popper's test wherever the test applies. When four conditions are true of an outcome, I call the outcome 'objective'. Second, the outcome is open to comparison again in each of three ways: by another person, at another time, and along another route. Popper's test applies wherever the outcome of a comparison can be objective. The sealed record contains every claim of my account about what the world

will show, each claim beside the measurement that bears on the claim. Appendix A, "What the Coming Measurements Will Find", gathers the measurements of the sealed record, states what I say each measurement will find, and gives the rule of decision of the sealed record in full.

Where Trust Belongs

Hossenfelder's three questions to a scientist are good questions. The answers to the three questions are real facts: facts about funding, about careers, and about the habits of a community.

Each kind of conclusion is checked by the method that fits the kind. I make matching the method to the kind the first rule of judging any claim: name the kind of claim first, then apply the method of that kind, fully, and no other method. A proof is checked by reading the steps of the proof. A claim about the world is checked by measurement and by independent routes to the same result.

The answers to Hossenfelder's three questions are a report on the people and on the situation of the people. A report on the people is information about the people. What the people concluded is checked by the method that fits the conclusion. I part from Hossenfelder on how to check what the people concluded. Even where funding is short and peer pressure is strong, a conclusion still succeeds or fails by its own check: the measurement, or the steps of the proof. A conclusion reached under poor conditions may still be right, and when a master of his subject reaches a conclusion, the master's conclusion may still be wrong, as Thomson's conclusion about the age of the Earth was wrong. Hossenfelder ends with "you can't trust these scientists' conclusions", and I end with a different instruction: ask for the check. Ask whether a claim about the world was written down before the measurement, with the rule for what would count. Ask whether the steps of an argument are laid out so that you can follow the steps.

The question about laid-out steps also shows whom you can trust. To 'defer' is to take someone's word because of who the person is. A review of anyone's work serves the reader of the review when it hands over its methods along with its findings, since findings without their methods leave the reader nothing to do but defer. If a person hands over a finding together with the method of the finding, then the person offers the finding to be checked and asks the reader for no 'deference'. At the close of her book *Existential Physics*, Hossenfelder names her own part as passing on knowledge, and a finding passed on with its method is knowledge passed on whole.

From Hossenfelder's pages

What No Weighing Can Reach

Hossenfelder also marks out what lies beyond the reach of science. Hossenfelder writes that some beliefs fit everything science has found, and yet science says nothing about the beliefs:

> Such beliefs should maybe not be called unscientific but rather ascientific, as Tim Palmer (whom we'll meet later) aptly remarked: science says nothing about them.
>
> (*Existential Physics*, Preface)

Hossenfelder takes the word *ascientific* from the physicist Tim Palmer, and the word means outside the reach of science: neither supported nor ruled out by science. Hossenfelder applies the word ascientific to unobserved parallel universes, to a creator, and to other assumptions not needed to describe what we observe: "Such superfluous assumptions aren't wrong. They're just ascientific". Hossenfelder also sets one refrain over everything in *Existential Physics*:

> (*Existential Physics*, Preface)

When an idea sounds strange and present physics does not exclude the idea, Hossenfelder marks the idea with the words of the same refrain: "I know it sounds crazy. But it's compatible with all we currently know".

A *claim of logical form* is a claim that a conclusion follows from its starting points, as in a proof. Among the kinds of thing outside the reach of any test are the act of comparing itself, a claim of logical form, and a description of what a thing is. So which way the world is must be found by looking.

Now try something with the balance: try to weigh the act of weighing. Whatever you set in the pan, the weighing is already going on, so the act you wanted to weigh is the act doing the weighing. No pan can hold the act of weighing. Yet you know the act of weighing all the same: you know what it is to weigh, because you are weighing.

A claim of logical form is decided by following the steps of the claim. A description of what a thing is gets two checks: first, the steps of the description's derivation are followed, and second, each definition in the description is checked against the way the defined word is used. *Superdeterminism* is the proposal that the settings experimenters choose are fixed in advance, along with the particles the experimenters measure. Chapter Seven settled superdeterminism by argument.

The Incommensuration Theorem is the plainest case of a claim decided by argument. Chapter Two set out the Incommensuration Theorem, which states:

> Symmetry and continuity cannot both be applied, simultaneously and fundamentally, to any event or comparison; and neither can asymmetry and discontinuity.
>
> (*Physics Is Not Math*, chapter 2, "The Theorem")

Every measurement ever made is an act of comparison. So every measurement ever made is an 'instance' of the Incommensuration Theorem: a case in which the theorem holds. The Incommensuration Theorem is proved from nothing but what the parts of a comparison mean. So the Incommensuration Theorem needs no "as far as we currently know". Every further finding is one more instance of the Incommensuration Theorem, so no further finding can revise the Incommensuration Theorem.

Hossenfelder's refrain, "as far as we currently know", has its own right use. The refrain belongs with a claim gathered from 'the cases seen so far'. A claim gathered from the cases seen so far is stated together with the cases the claim covers. If a claim holds in every act of checking the claim, then the claim needs no "as far as we currently know", because every check uses the claim. In the distinction, 'the not yet known' is like a parcel still on the miller's cart: no one has weighed the parcel on the cart yet, and a weighing will reach the parcel. In the same way, a measurement will reach 'the not yet known'. And 'the unknowable' is what lies outside the structure of comparison. So the unknowable cannot be known "even in principle, by any observer, at any time, by any method".

All of what I am going to say, therefore, should come with the preamble "as far as we currently know", meaning that further scientific progress might lead to revision. Hossenfelder's account and mine agree on two points. First, I find that several kinds of thing lie outside the reach of any test. I find that "their lying outside is a fact about the range of the test, not about their truth". Second, I hold, as Hossenfelder does, that a claim about the world could be otherwise. A claim that no measurement can reach is still decided, by the argument that fits the kind of claim, and so I part from Hossenfelder's two phrases, "ascientific" and "as far as we currently know". The reason: every measurement already presupposes the structure such a claim concerns, so no measured result counts for or

against a claim that no measurement can reach. There I also say that "each is decided by the argument that fits it", and so I settle outright, by argument, some claims that no measurement can reach. No measurement, no proof and no agreement has ever gone against it, in any subject, and none can, since each would be an act of comparison and so an instance of the theorem before it began. I take Hossenfelder's "as far as we currently know" to say exactly that a claim covers the cases seen so far. Hossenfelder remarks that sometimes the only scientific answer is "We don't know", and I draw a distinction that bears on her remark: the distinction between 'the not yet known' and 'the unknowable'. I mark where knowledge ends and 'the unknowable' begins.

The Balance, Once More

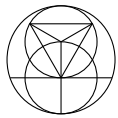
Come back to the stall one last time. Imagine a crowd gathered around the balance, each person in the crowd sure of what the parcel weighs, and many people in the crowd sure because the other people are sure. However loud the crowd is, the beam does not move by one hair until someone sets the parcel in the pan. Now imagine the stallholder doing one thing more before the weighing. The stallholder writes on a card what she expects the beam to show, and how far the beam must tip before the result counts. The stallholder seals the card in an envelope with the date on the envelope. Then the stallholder weighs the parcel.

The crowd's certainty was a fact about the crowd. The sealed card is a fact about the prediction, which the stallholder fixed before anyone could see the beam. And when the weighing comes, the weighing is the comparison itself, and the weighing settles what the weighing reaches, without a vote.

The short answer: A claim about the world is settled by measurement, and a claim of logic is settled by proof. Agreement among people, however wide, is a fact about the people. So give your trust to the claim whose

check you can see: the weighing made, the steps laid out, or the prediction sealed before the measurement, with the prediction's rule stated in advance.

What do you now hold that you did not get from Hossenfelder's two books?



Closing

What the Balance Shows

Now that you have followed the fourteen questions to their answers, what do you hold that Sabine Hossenfelder's books did not give you?

A Dot in a Sunbeam

On 14 February 1990, the spacecraft Voyager 1 turned its narrow-angle camera back toward the Sun and the planets, at a time when Voyager 1 was about six billion kilometers from Earth. Voyager 1 took a series of sixty frames, the "Family Portrait" of the solar system. The idea of turning the cameras toward home came from Carl Sagan, who was one of the mission's imaging scientists. Voyager 1 took the frames that show Earth thirty-four minutes before the spacecraft switched off its cameras for good.

Earth appears in one of the sixty frames, and in that frame Earth takes up less than a single pixel (one of the tiny squares of which a picture is made), so Earth shows as a tiny dot. By chance, a ray of sunlight scattered inside the camera crosses the picture just where Earth lies, so the dot of Earth sits in a pale band of light. Sagan wrote of the dot four years later, in his book *Pale Blue Dot*:

> Look again at that dot. That's here. That's home. That's us.
>
> (Carl Sagan, *Pale Blue Dot*, 1994)

Sabine Hossenfelder ends her book *Existential Physics* with the pale blue dot:

> So, yes, we are bags of atoms crawling around on a pale blue dot in the outer spiral arm of a remarkably unremarkable galaxy. And yet we are so much more than this.
>
> (*Existential Physics*, Epilogue)

Each pixel of the picture is the result of one comparison: the camera set the light arriving from one small patch of sky against the camera's scale of brightness. Voyager 1 sent the results home as numbers, and the picture is the numbers laid out side by side. So even Voyager 1's look back at us is a set of comparisons, made from six billion kilometers out. An instrument made the comparisons. The instrument was itself a small piece of the world. So the photograph is a 'weighing' made from inside the world: an act of comparison made by a part of the world. Every finding of physics is made from inside the world, as the photograph was.

Each of the fourteen chapters answered one question. In this closing chapter I set the fourteen answers side by side, so that you can see all fourteen answers at once, the way the dot shows the whole planet at once.

From Hossenfelder's pages

What Sabine Hossenfelder Showed

Begin with the three lessons that Hossenfelder gave her readers, which you brought to this book from Hossenfelder's books: make sure a problem is a problem before reaching for mathematics to solve the problem, state your assumptions, and let observation guide. Hossenfelder also gave her readers a map of beliefs with three regions: beliefs that the established laws of physics rule out, beliefs that the established laws of physics support, and beliefs about which science says nothing. Hossenfelder calls the beliefs of the third region "ascientific",

a word she takes from the physicist Tim Palmer. And Hossenfelder gave her readers a demand that physics answer to evidence, a demand she made from inside physics, as a physicist herself.

In this book, "my account" means the Immanent Metaphysics together with the physics worked out from the Immanent Metaphysics. The Immanent Metaphysics starts from the act of comparison. I count Hossenfelder's critique of beauty as an ally of my account, from the first chapter to the last. A theory's beauty is no evidence that the theory is true. Hossenfelder showed her readers what the habit of trusting beauty has cost her field: decades of searching where the beautiful theories said to look.

What the Weighing Can Tell

In Chapter One, a balance of polished brass stood beside a plain balance of tin. You could admire the brass balance for an hour and still learn nothing about the apples waiting to be set on the brass balance. You learn what the apples weigh *only* by weighing the apples. A mathematical description is like the brass balance. Three properties of a mathematical description are symmetry, economy, and the absence of large unexplained ratios. A property of a mathematical description belongs to the description, as the beauty of the brass balance belongs to the brass balance, and so a property of the description is no evidence about the world the description describes. In the sense that the field of physics has given the three words, 'beauty', 'naturalness' and 'simplicity' name properties of a mathematical description, so beauty, naturalness and simplicity are no evidence about the world either. On this point, Hossenfelder and I reach one result by separate routes. Elegance counts in one sense, a sense that anyone can check, and 'elegance' in the checkable sense has the three parts of Chapter One: many results from few premises; a form that could not have been otherwise, of which independent routes arriving at one structure are the evidence; and every part of the work having a job to do in the work.

The number stamped on a weight is the record of an earlier weighing, so any arithmetic done with stamped numbers comes after the weighings that made the numbers, as Chapter Two showed. Four disciplines come in one order, which I call the *order of depth*: metaphysics first, then physics, then computation, then mathematics. Each discipline comes after the discipline before it in the order, for three reasons: every proof is checked by a run, every run is a physical process, and every finding of physics is a comparison made from inside the world. Mathematics is the finest instrument there is for what is laid out as structure, and every power that mathematics has remains in full. The world that we find by comparison is not a mathematical structure, and so physics is not mathematics.

This whole account is built on one theorem, the *Incommensuration Theorem*, which lies beneath the order of depth. I set out how physics and mathematics are related. I state the Incommensuration Theorem in these words:

> Symmetry and continuity cannot both be applied, simultaneously and fundamentally, to any event or comparison; and neither can asymmetry and discontinuity.
>
> (*Physics Is Not Math*, chapter 2, "The Theorem")

In the Incommensuration Theorem, *symmetry* means being the same under every change of place or setting, and *continuity* means having no gaps, so that a small change of setting gives a small change in what is found. *Asymmetry* is the opposite of symmetry, and *discontinuity* is the opposite of continuity. The balance of Chapter Two shows all four: the box of weights is symmetric, and the weights come in steps, so the box shows symmetry and discontinuity. The settling beam swings smoothly and never repeats a swing, so the beam shows continuity and asymmetry. The Incommensuration Theorem is a structural fact about the nature of knowing. The Incommensuration Theorem holds wherever anything is compared.

In Chapter Three, I carried the picture of the balance to a particle collider, the Large Hadron Collider, the great ring at CERN. CERN is the European laboratory for particle physics, near Geneva, and in the ring at CERN physicists make protons collide head on. The Large Hadron Collider is a balance of enormous reach. For years, many physicists expected the Large Hadron Collider to find new kinds of particle. The beam of the collider stayed level at every mass where physicists had expected a new kind of particle: the collider found no new kind of particle at any of the expected masses. A level beam is a result too. The kinds of particle make up a closed list, with a slot for each kind and every slot filled. The list is fixed by the structure of comparison: what every comparison must contain. Physicists proposed a symmetry, called *supersymmetry*, that would give every known particle a heavier partner. The list of kinds has no slot for a partner from supersymmetry, so no supersymmetric partner exists, at any energy. The *standard model* is the theory that lists the known particles and the three forces, other than gravity, that act among the particles. The three forces of the standard model were never one force: no single larger force splits into the three forces. The proton is the particle at the center of every atom of hydrogen, and the proton is stable: the proton does not decay.

When a number agrees with measurement before anyone knows why, I call the number a *value that lands*. The question to ask of a value that lands is "why does it land?" I hold a value that lands as a question, and also as evidence of a reason not yet known. A 'pure number' is a number with no units. Every pure number of the standard model has a stated 'standing': a statement of where the number comes from. Each number has one of four standings: set by the structure of comparison, set by the structure of comparison once a stated step is taken, measured, or following from my account and also found by measurement. For a number of the fourth standing, the reason the number lands is still a question. The strong force binds quarks into protons and neutrons, and the strong force has an angle of its own. The angle could have let the strong force treat a process differently from the mirror image of the process with matter swapped for antimatter.

The strong force's own angle is zero: the structure of comparison sets the angle at zero. Empty space speeds up its own expansion. Physicists call the number that sets how fast empty space speeds up its expansion the *cosmological constant*. The cosmological constant is one constant, one number at every place and every time of our epoch (the span of the universe's history that began at the Big Bang), and the cosmological constant does not come from any dark energy field. I identify the value of the cosmological constant with a share of the energy of empty space: the share that a measurement made inside empty space takes in. By the identification, three things set the value of the cosmological constant: the structure of comparison, the measured strength of gravity, and the measured distance from which light has had time to reach us.

A balance can weigh only a thing that can be set on a pan of this world, so a universe gives a result only if the universe can be set beside ours. Every point of space carries the six small dimensions that Chapter Five introduced, curled up far too small to see. The six small dimensions have one settled state, so in my account empty space has one settled state. Physicists call a settled state of empty space a *vacuum*, so in my account empty space has one vacuum. String theory is the proposal that the particles are tiny vibrating strings. String theory allows a vast range of other settled states of empty space. Physicists call the vast range of settled states the 'landscape' of string theory, but in my account the landscape is not there. In the picture called 'eternal inflation', new universes bud off without end from an expanding background. To be 'real' is to be given in an actual act of comparison, so the other universes of the landscape are not real, and the universes of eternal inflation are not real either. No structure of my account contains the universes of the landscape or the universes of eternal inflation.

The Mark the Beam Leaves

The beam tips and leaves a mark whether or not anyone watches. In 'quantum physics', the physics of the very small, a description gives the chances of each outcome, and when a measurement is made, the description is updated to the outcome found. Any interaction that lays down a record is a 'finding', so a finding needs no conscious observer. The update is a change in the shared record of what has been found. When the update is made, no physical process travels through the world.

We learn about the thing in the pan from a weighing because we choose what to put in the pan apart from how the beam tips. In an experiment, the experimenter's choice of settings is the choice of what goes in the pan, and the particle's answer is the tip of the beam. Hossenfelder has worked with Tim Palmer on a proposal called *superdeterminism*. Superdeterminism says that the laws fix two things together, from a shared past: the settings an experimenter chooses, and the outcome of the experiment. Every act of comparison leaves something that no law fixes, so nothing fixed the experimenter's choice and the particle's answer together in advance. Therefore the structure of comparison shows that superdeterminism cannot hold. In a world where superdeterminism held, no observation could count as evidence for anything, not even an observation in favor of superdeterminism. Anyone who holds superdeterminism gives up an assumption called *statistical independence*: the assumption that the settings of an experiment are independent of the hidden state of the thing the experiment measures. Hossenfelder and Palmer give an exact statement of statistical independence and propose tests of statistical independence. I credit both the exact statement and the proposed tests.

Chapter Eight pictured a beam balanced to within a hair. Nothing fixes in advance which way a beam balanced to within a hair tips. The future is very largely fixed by the past, as Hossenfelder says, but no world is fixed completely, at any scale. When no prior specification fixes an outcome, however complete the specification, I call the outcome *hard randomness*. Hard randomness is the part of the world that nothing fixes in advance.

Hard randomness is choice, as seen from inside by the one from whom the randomness comes. Choice is a fact about the world at every scale, alongside cause.

A balance can weigh anything set on the balance, but a description of the balance, however complete, is not a weighing. You are made of nothing but particles, as Hossenfelder says, and you are also an act of comparison happening from inside, an act that runs one way in time and whose outcomes nothing fixed in advance. A copy, an upload or a program can carry the pattern of your parts, but *only* you carry the act itself. No description of your particles, however complete, is the whole of you. A person is not a file that could be copied out and run elsewhere. Consciousness is not a computation.

The Ledger and the Floor

In Chapter Ten, a stallholder wrote each weighing in a ledger beside the balance, and each weighing written in the ledger stays written. Every act of comparison runs one way, from what could be found, to the act, to the record, and I identify the one-way order of comparison with the direction of time. No process can be run backward faithfully, with every detail returned as it was, so time has a direction in every single interaction, before any count of disorder is made. The past *exists*: the past stands as structure, timeless, the same in every instance, able to be held in view as a whole. The present is *real*: the present is given in an actual act of comparison, here, now, with the future still open. And the future is not yet there.

Every measurement of the early universe is a weighing, made now, of what the beginning left. The 'Big Bang' is the hot, dense beginning of the history we can trace, and the first moment of the Big Bang is never seen, because nothing can make a comparison across the first moment. Many cosmologists place a brief burst of enormous expansion, called *inflation*, at the start of the history we can trace. Cosmologists brought in inflation to solve a number of puzzles, and I answer every puzzle that inflation was brought in to solve, so my account needs no inflation. When nothing, not

even light, can return from a region, physicists call the region a *black hole*. The history of the universe comes in whole spans called *epochs*, and our epoch began at the Big Bang. The boundary between two epochs is called the *turn*. Every black hole of the ending epoch has an interior. At the turn, all of the interiors end together, as one end, and then the next epoch begins. So each epoch runs from one turn to the next. I identify what came before the Big Bang with the collapse inside the black holes of the epoch before ours.

The galaxies of our epoch never fall back together, and nothing that is bound together is ever torn apart by the expansion. Every point of space carries the six small dimensions, and the six small dimensions have no other settled state to drop into. Empty space has one other settled feature: the 'Higgs field', which gives many particles their masses. I derive a curve for the energy of the Higgs field, and at the energies where the field is measured, the present state of the Higgs field is the lowest point of the curve. In the standard calculation, physicists follow the Higgs field to far higher energies. The standard calculation shows the present state lasting far beyond the age of the universe. The proton lasts. The long emptying of the sky ends in a turn, and then the next epoch begins.

Every comparison has a verdict about something, and I call what the verdict is about the *content* of the comparison. The two things compared are two in some respect. I call the respect in which the two things are two the *context* of the comparison. At the balance, the content is how heavy the thing in the pan is. At the balance, the context is the two places that the things weighed occupy, left pan and right pan, together with the floor and the room that hold the two places, and the moment of the weighing. The word *setting* names the whole context: the places, the floor, the room and the moment. In physics, the content is matter, and the context has two parts: the arena of space and time in which matter is found, and the 'setting of possibility' (the range of states in which matter could be found). A weighing can show a pull that comes from no thing set in a pan. The 'dark matter' is the unseen source of the extra pull that holds galaxies together, and the dark matter shows itself only as a pull that comes from no thing

set in a pan. I identify the dark matter with a 'ringing' of the setting itself, a lasting vibration of the six small dimensions taken as the setting of possibility, and so the dark matter is a vibration of context. The dark matter shows in the result only as extra pull: the dark matter is never a thing set in a pan, and the dark matter is not matter of any kind on the list of particles. The dark matter acts on the matter we know through gravity alone, so the dark matter never appears in any search made through any other interaction. The law of gravity stays unmodified, as the physicist Albert Einstein wrote the law.

The balance stands on a floor. The floor is where every weighing happens. The floor belongs to the setting of the weighing. The setting also takes in the room, the two places of the pans, and the beam that carries the comparison, but the floor never belongs to what is set in the pans. Space and time together form the *arena* of physics, and the arena is the floor under every balance in physics. The context of every measurement has three measures (space, time and possibility), and the arena holds two of the three measures, space and time. I identify gravity as the arena: the shape of the arena is what we feel as gravity, and gravity is not one more thing found in the arena. The arena cannot be 'quantized': the Incommensuration Theorem shows that the arena cannot take on the smallest steps that quantum physics gives to matter. Einstein's theory of gravity and quantum physics are the two great theories of physics, and I join the two great theories side by side, but I never merge the two great theories. When matter is in two places at once, my answer is one smooth geometry for each alternative of the matter, with each smooth geometry shaped by its own alternative of the matter alone. And information is not destroyed in a black hole.

Whom to Trust

The beam answers only to what is set in the pans, however many people agree on what the beam will show. Measurement settles a claim about the world. Proof settles a claim of logic. Agreement among people,

however wide, is a fact about the people. Agreement by itself validates nothing. The step against bias is to write a prediction down and seal the prediction before the weighing, and whoever makes the prediction also states in advance the rule for judging the prediction. I have taken the step against bias: forty-two predictions were sealed before the measurements that will decide the predictions, and I call the forty-two sealed predictions *the sealed record*. Appendix A, "What the Coming Measurements Will Find", sets out what each of the coming measurements will find.

Some claims reach past every instrument, in the sense that no measurement can decide them, and each claim that reaches past every instrument is decided by the argument that fits the kind of claim. The Incommensuration Theorem is one of the claims that reach past every instrument, and the proof of the Incommensuration Theorem decides the theorem. Every measurement already uses the structure that the Incommensuration Theorem describes, so no result of any measurement can count for or against the theorem.

What You Can Do with the Balance

Put the fourteen steps of this book together, and the fourteen steps make one picture. A balance tells nothing until something is set on the balance, whether the balance is built finely or plainly. Whatever is set on the balance is weighed from inside the world, by an instrument that is part of the world. The result of the weighing is a record, and the record stays. Nothing fixes in advance which way the beam tips. The setting itself can add a pull of its own to the result. The pull of the setting is known by the weighing alone. And the whole weighing stands on a floor that is no part of what is weighed.

You can carry the picture of the balance to the next claim about physics that you read. Ask what was set beside what, and ask whether a property belongs to the description, or was found by a weighing. When a number lands, ask why the number lands, and look for the reason. When a

claim reaches past every instrument, ask which argument fits the kind of claim. When many experts agree, ask what was measured, and whether the prediction was written down before the weighing.

You may ask whether the balance only repeats Hossenfelder's third lesson, "Observational guidance is necessary", put as a question: what did you measure? The question begins as Hossenfelder's lesson. I use the balance to add the reason her lesson works. Every finding of physics is an act of comparison, so the structure of comparison is the ground on which every finding of physics stands. The Incommensuration Theorem states one fact of the ground exactly.

Passing It On

Hossenfelder says what she thinks her work is for, near the end of *Existential Physics*. Hossenfelder leaves the question of life's meaning to each reader, because she believes, in her words, that "we all have to find our own answer". Then Hossenfelder gives her own answer:

> By passing on knowledge, like my mother, I do my own part to aid the universe's understanding of itself.
>
> (*Existential Physics*, Epilogue)

Hossenfelder sets her purpose inside a larger picture:

> Maybe, then, the universe is evolving toward a state in which it understands itself, and we are part of its ongoing quest.
>
> (*Existential Physics*, Epilogue)

A review owes its reader this: it hands over its methods along with its findings, since findings without their methods leave the reader nothing to do but defer. To pass on a finding is to hand over the method along with the finding, so that whoever receives the finding can judge the finding for

themselves. I hand over my method with my findings: my method is the balance, and the balance is now yours. Every finding of physics was made in one way: by a part of the world, comparing from inside the world.

The Last Picture

Come back to the dot in the sunbeam. Every weighing told in this book was made on the dot, or by an instrument sent out from the dot, and the people and instruments that made the weighings are part of the world they weighed. Hossenfelder passed on what she found on the dot, in two books, and I have set a balance beside her two books.

The short answer: You now hold the balance itself. Every measurement is an act of comparison made from inside the world, and so the structure of comparison is the ground of physics. Hossenfelder's readers carry away fourteen questions, and each of the fourteen questions has an answer that starts from the ground of comparison, an answer that you can follow step by step and check for yourself.

The balance stands on the bench: a beam on a pivot, a pan at each end, a thing in one pan and known weights in the other. Set something on the balance, and watch the beam. Every measurement anyone has ever made was made in one way, from a school bench to a dot in a sunbeam: by setting one thing beside another, and finding how the two things stand.

Appendix A

What the Coming Measurements Will Find

This appendix lists every coming measurement that the chapters of this book mention, and for each measurement the appendix states what will be measured and what this account says the measurement will find. Where the sealed record of this account's predictions names the instrument or experiment that will make a measurement, the appendix names the instrument or experiment too.

This account's forty-two predictions were sealed in a dated record on 1 November 2026, before the measurements that will decide the predictions. I call the dated record *the sealed record*. The sealed record contains every statement in this appendix of what a measurement will find. The title of the sealed record is *The Registered Predictions of Physics from Comparison; A Dated Record, 1 November 2026*. *Side by Side* is this account's work in two volumes that sets this account beside the work of other physicists, and the sealed record is printed whole as Appendix B of *Side by Side*, Volume One. The sealed record keeps the words it had on 1 November 2026. A later report on the same predictions carries a date of its own. Each entry in this appendix gives the number that the prediction has in the sealed record. *Side by Side*, Volume One, also prints a second record, as its Appendix I. The second record is *The Registered Predictions Beside Sabine Hossenfelder*, dated 4 November 2026. In this appendix, I call the second record the register beside Hossenfelder, or the register for short. Where an entry sets this account beside Sabine Hossenfelder's own expectation, the entry draws on the register. The register calls the books of this account "the collection".

The sealed record states its rule of decision before any result comes in:

> A result counts when it is established at five standard deviations by at least two independent kinds of measurement. A measurement that differs from a prediction by less is a measurement of interest, and the record reports it as such.
>
> (*The Registered Predictions of Physics from Comparison*, Section II)

The sealed record counts the distance between a prediction and a measurement in units of the measurement's stated uncertainty, and the record calls each unit of stated uncertainty one *standard deviation*. So a measurement five standard deviations from a prediction lies five units of stated uncertainty away from the prediction. Five standard deviations is also the standard that particle physicists require for a discovery. ATLAS and CMS are the two large detectors at CERN. Each of the two detectors reached five standard deviations on its own before the discovery of the Higgs boson was announced on 4 July 2012. Sabine Hossenfelder states the standard of five standard deviations as a chance, which "is roughly 1 in 3.5 million". Hossenfelder gives the chance of 1 in 3.5 million beside the excess of December 2015, which Chapter Three told. Hossenfelder writes that, for the excess of December 2015, ATLAS and CMS together "arrive at a chance of 3 in 10,000 that the excess is a random fluctuation" (*Lost in Math*, chapter 4, "Cracks in the Foundations", section "The Diphoton Diarrhea Begins"). When two routes of measurement rest on different instruments and different methods, so that a fault in one route does not pass into the other route, the sealed record calls the two routes two independent kinds of measurement.

A result established by the rule of decision bears on a prediction whether the result agrees with the prediction or goes against the prediction. *The Gravitational Passage* is this account's book that derives the law of gravity, and the book uses the same rule of decision for a prediction borne out: "confirmed means established at five standard deviations by at least two independent kinds of measurement". Some predictions say that a

thing will not be found. A prediction that a thing will not be found names a step of this account. The sealed record counts every search for the thing as bearing on the step that the prediction names, and this account says that none of the searches will find the thing. Suppose a search finds the thing, and the rule of decision establishes the finding. Then the finding counts against the step of this account that the prediction names. By the rule of decision, the excess of December 2015 was a measurement of interest. The data of 2016 showed that the excess of December 2015 was gone.

The questions of Chapters One and Two are settled by argument, so the sections of this appendix begin with Chapter Three. Some predictions bear on several chapters. Each prediction that bears on several chapters is set out in full once, under the chapter that the prediction bears on most, and the prediction is named again, with its content, under each other chapter that the prediction bears on.

Chapter Three: Why Did the New Particles Not Appear?

Prediction 30: no kind of particle beyond the closed list. What will be measured: every search for a new kind of particle, at colliders, the next and larger collider among them, in underground detectors, and in astrophysics. A *generation* is one family of the particles of matter. The three known generations are alike except in mass, each generation a heavier copy of the generation before. Every particle of matter has two parts, which physicists call the left-handed part and the right-handed part of the particle. The *right-handed neutrino* is the right-handed part of each neutrino, the part that lets the neutrino carry its small mass. The standard model is physics' established list of the particles and of three of the four forces among the particles. What this account says the searches will find: the kinds of particle of the standard model, with a right-handed neutrino in each generation, and no other kind. The closed list of kinds is the kinds of the standard model, with a right-handed neutrino in each generation, and no others.

The sealed record spells out the closed list by naming what lies outside the closed list:

> No further kind of particle will be found: no fourth generation, no supersymmetric partner, no X or Y boson or leptoquark, no W′ or Z′, no second Higgs boson, no axion, no species of dark matter, no sterile neutrino beyond the right-handed component of each neutrino, no dark photon, no mirror particle and no hidden sector.
>
> (*The Registered Predictions of Physics from Comparison*, Prediction 30)

Supersymmetry is a proposed symmetry that would give every known particle a heavier partner. A *supersymmetric partner* is the partner particle that supersymmetry would give a known particle. X and Y bosons and leptoquarks are proposed carriers of force that would turn quarks into electrons and into the relatives of the electron. W′ and Z′ (read "W prime" and "Z prime") are proposed heavier copies of the W and Z, the carriers of the weak force. The strong force has an angle of its own, and the strong force's own angle could have let the strong force treat a process differently from the mirror image of the process, with matter swapped for antimatter. An *axion* is the light particle that physicists proposed in 1977 and 1978 to drive the strong force's own angle to zero, as Chapter Four told. A *sterile neutrino* is a proposed neutrino that feels none of the forces of the standard model, and the sealed record allows the right-handed part of each known neutrino but no sterile neutrino beyond the right-handed part. A *dark photon*, a *mirror particle* and a *hidden sector* are proposed particles, or whole families of particles, that would touch the known particles only faintly or not at all.

The sealed record says two more things about the next collider: "The next collider will not find a new species. Heavier composites wait at higher energies; a new kind does not". A *composite* is a particle built of known particles, as a proton is built of quarks. So I expect heavier composites at higher energies, each heavier composite built of the known kinds. I expect

no supersymmetric partner at the energies of the next collider, and no supersymmetric partner at any heavier mass, because the closed list has no slot for a supersymmetric partner.

Where Hossenfelder and this account expect the same result. The register sets Predictions 30 and 35 beside Hossenfelder's own statement. Prediction 35, set out next, is that no new particle enters any loop. *Naturalness*, in Hossenfelder's sense, is the expectation that the pure numbers of a theory be neither very large, nor very small, nor very close to one another. Physicists who reasoned from naturalness called for new particles at the energies of the Large Hadron Collider. Hossenfelder holds that the new particles were not found. In January 2019, Hossenfelder wrote in an opinion piece in *The New York Times* that particle physicists "have no reliable prediction that there should be anything new to find" until energies about a million billion times above the energies now within reach. Hossenfelder's statement is that nothing gives reason to expect a new particle at a larger collider, while this account's statement is that there is no new kind of particle to be found. The register says: "The two agree on every search at the energies within reach".

Prediction 35: no new particle in any loop. In quantum theory, a particle can appear for a moment inside a process and vanish again. Physicists draw the passing appearance of the particle as a closed path in their diagrams and call the closed path a *loop*. A heavy unknown particle could show itself through loops in very precise measurements, before any collider made the particle. What will be measured: three things. The first thing measured is the strength of the tiny magnet carried by the muon, a heavier cousin of the electron. Physicists call the strength of the muon's tiny magnet the muon's *magnetic moment*. The second thing measured is the rare change of a bottom quark, one of the heaviest quarks, into a strange quark, one of the lightest quarks, together with a pair of electrons or muons. The third thing measured is any change of a muon into an electron. What this account says the three measurements will find: no particle beyond the standard model enters any loop. The muon's magnetic moment receives nothing from a new family of particles. The rare changes of

the bottom quark follow the standard model. Physicists now see small disagreements when the physicists combine the many measurements of the rare changes, and the small disagreements will resolve within the standard model. The sealed record gives the share of muon decays in which a muon turns into an electron and a particle of light as of the order of one in ten to the power fifty-five. The sealed record says: "No signal of charged-lepton flavor violation will be seen at any foreseeable experiment". The sealed record's words mean that no experiment will see one charged lepton (the electron, the muon or the tau) change into another charged lepton.

Prediction 31: exactly three generations. What will be measured: the number of generations of the particles of matter. What this account says will be found: exactly three, with no fourth generation at any mass.

Prediction 33: the proton does not decay. What will be measured: the lifetime of the proton, in the coming searches for proton decay. What this account says the searches will find: no proton decays. A quark can be in three states, and the strong force turns the quark from one of the three states to another. Physicists call the three states *color*. The weak charge is the label that the weak force turns. The electron and the relatives of the electron carry no color, and physicists call the electron and its relatives *leptons*. No carrier of force joins color to the weak charge, so no change turns a quark into a lepton. The proton is the lightest particle made of three quarks, so the proton has no route to decay. The sealed record states, together with Prediction 33, that there is no unifying group at any scale. No single larger symmetry holds the changes of all three forces in one set. No single larger force splits into the three forces of the standard model. Physicists can follow the strengths of the three forces to higher and higher energies. The strengths of the three forces meet at no single energy. No search will find the carrier particles of a single larger force.

Prediction 36: the running of the strengths changes only at known masses. The strength of each of the three forces changes slowly with the energy at which physicists measure the strength, and physicists call the change of a strength with energy the *running* of the strength. What will be

measured: the running of the three strengths, at higher and higher energies. What this account says will be found: the rates of running are fixed by the closed list of kinds. The rates of running change only at the masses of the known kinds and at the masses of the W and Z.

Chapter Four: Do the Unexplained Numbers Need Explaining?

Prediction 34: the strong force keeps CP, and there is no axion. *CP* is the symmetry that swaps a particle for its opposite charge (C) and for its mirror image (P) at once, as Chapter Four said. A force that keeps CP treats a process and the mirror image of the process, with matter swapped for antimatter, alike. What will be measured: the *electric dipole moments* of the neutron and of atoms, and every search for the axion. An electric dipole moment is a slight lopsidedness of charge inside a neutron or an atom, as Chapter Four described. The angle that experiments measure is the strong force's own angle plus a second part, the quarks' phase, which is an angle that the masses of the quarks carry with them. A nonzero measured angle would give the neutron and atoms the slight lopsidedness of charge. The sealed record names the dipole searches among the measurements that decide Prediction 34, and the dipole searches measure the whole measured angle: the strong force's own angle and the quarks' phase together. What this account says will be found: the strong force's own angle is zero. The structure of comparison needs no axion, and the searches for the axion will find none. The sealed record also states that the absence of the axion is a statement about the list of kinds: the absence of the axion holds whatever value of the measured angle the dipole searches find. The kinds break CP through two angles only, one angle in the mixing of the quarks and one angle in the mixing of the leptons, and each of the two angles is a different angle from the quarks' phase. The weak force changes a quark of one charge into a quark of the other charge, and the weak force can change a quark into a quark of any of the three generations. Physicists call the reach of the weak force across the three generations of quarks the mixing of the quarks. The mixing of the leptons is the same reach among the

leptons. The closed list of kinds holds one Higgs field. *CPT* is the symmetry that adds a reversal of time to CP. CPT holds: a particle and its antiparticle have equal mass, equal lifetime, and equal and opposite magnetic moments. The photon is the particle of light, and the gluons are the carriers of the strong force. The photon and the gluons have no mass.

Prediction 7: the matter fraction is 0.311. The *matter fraction* is the share of the universe's energy, today, that is in matter, dark and ordinary together. What will be measured: the matter fraction, by four surveys of the sky. The four surveys are the Dark Energy Spectroscopic Instrument (DESI), which maps galaxies from a telescope in Arizona; Euclid, a space telescope of the European Space Agency; the Vera C. Rubin Observatory, a survey telescope in Chile; and the Nancy Grace Roman Space Telescope of NASA. What this account says the four surveys will find: a matter fraction of 0.311, give or take 0.001. The cosmological constant is an energy of empty space itself, the same in every cubic meter, and the four surveys will find a share of 0.689 for the cosmological constant, together with the matter fraction of 0.311, in a space that is flat. The spread of 0.001 is the spread that the measured density of radiation gives. The number 0.311 depends on an identification that I make in Chapter Four. I identify the cosmological constant with the share of the vacuum energy that a measurement made inside empty space takes in, as distinct from the total vacuum energy. Given the identification, the count of the particle horizon fixes the share. The particle horizon is the edge of everything whose light has reached us, and in Chapter Four's picture the particle horizon carries tiles. The count of the particle horizon is the number of tiles on the particle horizon. The count is about two and three tenths times ten to the power one hundred twenty-three. Alexander Friedmann found an equation for the expansion of the universe in 1922. Friedmann's equation ties the rate of the expansion to the energy that each volume of the universe holds. The share and Friedmann's equation, taken together, give the matter fraction. The expansion rate and the strength of gravity cancel when the share and Friedmann's equation are taken together. So the matter fraction is a pure number.

The sealed record states Prediction 7 in three more ways, each way through one more measured quantity. The sealed record calls the four ways "one test, stated four ways". The first of the three more ways uses the density of matter measured from the microwave background, the oldest light in the sky. By the first way, Prediction 7 states the present rate of expansion, the *Hubble constant*, as 67.8 kilometers per second per megaparsec, give or take 0.3, and a megaparsec is about three and a quarter million light years. A *GeV* is a billion electron volts, the unit physicists use for the masses of particles. A proton weighs a little under one GeV. GeV to the fourth power is the unit particle physicists use for an energy packed into a volume. The second of the three more ways uses the measured radius of the particle horizon, and by the second way, Prediction 7 states the energy of empty space as 2.56 times ten to the power minus forty-seven GeV to the fourth power. A de Sitter time is one divided by the rate of expansion that the cosmological constant alone would give. A de Sitter time is about seventeen and a half billion years. By the third way, Prediction 7 states the present age of the universe, the age at which the cosmological constant is measured, as 0.792 de Sitter times.

Prediction 8: the equation of state of the energy of empty space is exactly minus one. Divide the pressure of empty space by the density of energy of empty space. Physicists call the result the *equation of state* of the energy of empty space. A value of exactly minus one means that each cubic meter of empty space keeps the same energy as space expands. What will be measured: the history of the expansion and the growth of the large structures of galaxies, by Euclid, the Vera C. Rubin Observatory and the Nancy Grace Roman Space Telescope. What this account says the three surveys will find: an equation of state of exactly minus one at every time, today and in the past alike. The cosmological constant is fixed once, as the constant term of one geometry. The field equations of gravity do not let a constant term of the geometry vary from place to place or from one time to another. No field that changes over time drives the speeding up of the expansion. The sealed record says: "The reported departure from -1 will

not be confirmed". The departure meant is the departure reported in 2026 from the final analysis of the Dark Energy Survey, combined with DESI and the microwave background.

Prediction 42, in part: the Higgs mass and the top mass. The Higgs field acts on itself. Physicists call the strength with which the Higgs field acts on itself the self-coupling of the Higgs field. The self-coupling is one eighth at the first level of calculation. In Chapter Four, I derive the value of one eighth given one stated identification. Quantum fluctuations add corrections to the calculation. I reach a Higgs mass of 125.17 GeV with the corrections and with the measured value of the Higgs field in empty space. When I reach a value in this account, and measurement also finds the value, and the reason for the agreement is still a question, I call the value a *measured agreement*. The Higgs mass of 125.17 GeV is a measured agreement. *The Measures of the Kinds* is this account's book on the masses and mixings of the particles. *The Measures of the Kinds* carries the calculation of the Higgs mass one order of precision further. *The Measures of the Kinds* writes the next correction in four forms, which differ only in how the correction enters the formula. The four forms give four values of the Higgs mass: 125.1715, 125.1888, 125.2064 and 125.2245 GeV. Each of the four values is a measured agreement. The top quark is the heaviest known particle. *The Measures of the Kinds* keeps six values of the mass of the top quark side by side, between 172.417 and 172.657 GeV. Each value of the top mass rests on different measured inputs, and each value of the top mass is a measured agreement as well. The measurements of 2026 do not choose among the four forms. The measurements of 2026 do not choose among the six values of the top mass either. What will be measured: the masses of the Higgs boson and of the top quark, more finely than physicists have measured the two masses so far. What the measurements must reach: a Higgs mass measured to about five thousandths of a GeV, either way, tells the four forms apart. Either of two measurements chooses among the six values of the top mass: a Higgs mass measured to three hundredths of a GeV, or a top mass measured to two hundredths of a GeV.

Prediction 10: no primordial gravitational waves. The microwave background is slightly polarized: the waves of the microwave background lean in preferred directions across the sky. Gravitational waves are ripples in the shape of space, and physicists call gravitational waves made in the first moments of the universe *primordial*. Primordial gravitational waves would leave a twisting pattern in the polarization of the microwave background. What will be measured: the polarization of the microwave background, by the Simons Observatory, a set of telescopes in the Atacama Desert of Chile, and by LiteBIRD, a satellite of the Japan Aerospace Exploration Agency. What the measurements will reach: the Simons Observatory will reach a ratio of about one part in a thousand between the power in primordial gravitational waves and the power in the ripples of density. LiteBIRD will reach below two parts in a thousand. What this account says the two instruments will find: no primordial gravitational waves. The early ripples of the universe are ripples of density. Waves of the shape of space arise from the ripples of density only weakly, at the next order. So waves of the shape of space carry far less than one part in a million of the power in the ripples of density. The sealed record says: "The Simons Observatory and LiteBIRD will find no primordial tensor signal". A *tensor* signal is the signal of primordial gravitational waves.

The Compactification is this account's book on the six small curled dimensions, on the starting conditions of the universe and on the first ripples. In chapter 6, section IX, *The Compactification* sets this account beside the favored models of inflation. This account and the favored models of inflation predict the same kind of early ripple, with every ingredient of the universe rippling together, and the two also predict the same flat space. The favored models of inflation, in addition, predict a slight tilt of the early ripples, in the direction that is measured: with the measured tilt, the ripples are a little stronger at large sizes than at small sizes. I take the sign of the tilt from measurement (Prediction 12, under Chapter Eleven).

This account and the favored models of inflation predict different values at one entry only, the strength of the primordial gravitational waves, and the Simons Observatory and LiteBIRD measure that strength. This account predicts an empty result. The favored models of inflation allow an empty result as well. If either instrument detects primordial gravitational waves, and the rule of decision establishes the detection, then the detection would count against Prediction 10.

Prediction 13: no long inflationary phase. *Inflation*, as Chapter Five told, is a proposed burst of very fast expansion in the first moments of the universe. In eternal inflation, the burst never stops everywhere at once, and bubble universes keep forming inside the inflating space. What will be measured: the measurements of Predictions 9 to 12 together. Predictions 9, 11 and 12 are set out under Chapter Eleven, and Prediction 10 is set out under Chapter Five, above. The measurements of Predictions 9 to 12 measure four things: the flatness of space, the absence of primordial gravitational waves, the single form of the early ripples for every ingredient of the universe, and the single pattern of the early ripples across the whole sky. The earliest horizon is the distance light could have crossed in the first moments. What this account says will be found: no inflation long enough to stretch the lengths we see today from within the earliest horizon to beyond the earliest horizon. An *epoch* is one whole span of the universe's history, from one turn to the next (as Chapters Ten and Eleven gloss the word). Our epoch began at the Big Bang. *The turn* is the boundary between two epochs. At the turn, the interiors of all the black holes of the ending epoch end together, as one end, and the next epoch begins. No comparison spans the turn. Physicists proposed inflation to solve two puzzles: why distant parts of the sky match, and why space is flat. The sealed record states that the turn from the previous epoch answers both puzzles, with no inflation. *Side by Side*, Volume Two, states what follows for eternal inflation: with no long inflation, there is no eternal inflation to make the bubble universes.

The many-worlds account and this account. In the many-worlds account of quantum theory, every possible outcome of a measurement happens, each outcome in a world of its own. Appendix D of *Side by Side*, Volume One, is a register that sets this account beside the work of the physicist David Deutsch. The register beside Deutsch states that the many-worlds account and this account "predict the same output of every quantum computer". The register beside Deutsch also counts the multiverse among the differences of kind that no measurement decides. So no result counts for or against either account on the multiverse, whether the result comes from a quantum computer or from any other measurement. In Chapter Five, I exclude the many worlds, taken as an account of a whole world, by argument.

Prediction 7, set out under Chapter Four, states one value of the matter fraction for this one universe, 0.311, and the coming surveys of the sky will measure the matter fraction against the value 0.311.

Chapter Six: What Happens When a Quantum System Is Measured?

Prediction 2: gravity alone ends no superposition. A *superposition* is a combination of two alternatives held together, such as a mass here and the same mass there, until a measurement finds one alternative. What will be measured: whether a mass held in two places at once loses the superposition of its own accord, with no interaction that records which place the mass is in. The deciding experiment is the experiment of Prediction 1, set out under Chapter Thirteen. Two small masses are each held in two places for two and a half seconds in the experiment of Prediction 1. What this account says the experiment will find: no mass, however large, no separation, however wide, and no length of time ends a superposition of its own accord. An interaction that registers which alternative is the case is a *finding*. A superposition ends only through a finding. *Decoherence* is the fading of a thing's quantum behavior as the surroundings of the thing keep touching the thing. Each touch is a comparison made by the surroundings. The only decoherence is the ordinary kind, made by the

touches of the surroundings. The physicists Lajos Diósi and Roger Penrose proposed a collapse by gravity, in which gravity itself would end a superposition, and the collapse by gravity gives a lifetime of about twelve thousandths of a second for the masses of the experiment of Prediction 1. This account says that the superposition does not end by a collapse by gravity.

Prediction 27: no signal faster than light, and none backward in time. What will be measured: whether anything found in one place depends on which measurement was chosen at a distant place, before a signal at the speed of light could carry the news. A local statistic is the pattern of outcomes found in one place. What this account says will be found: "every local statistic follows quantum theory unchanged, whatever measurement was chosen far away". News of a distant finding enters a record only at a place and time that a signal from the finding can reach, traveling at the speed of light or slower, and physicists call the set of places and times that the signal can reach the future *light cone* of the finding. A finding changes no geometry, here or anywhere. No body arrives anywhere outside the future light cone of the place and time that the body left. Prediction 27 allows travel within the light cone. Prediction 27 also allows distant galaxies to move apart faster than light, because the moving apart of distant galaxies is a growth of the space between the galaxies, and not a signal across the space.

Prediction 25, set out under Chapter Seven, bears on Chapter Six as well. Prediction 25 states that repeated measurements on systems prepared alike settle to the weights of the Born rule, the rule of quantum theory that states the chance of each outcome.

Chapter Seven:
Could Everything, the Experimenter's Choice Included, Have Been Fixed in Advance?

Prediction 25: the statistics of quantum theory hold. The *Born rule*, named for Max Born, is the rule of quantum theory that states the chance of each outcome of a measurement. The chances that the Born rule states

are the *weights* of the Born rule. What will be measured: repeated measurements on systems prepared alike, in every kind of quantum system; interference among three open paths; tests of Bell's limit; and experiments that join systems from independent sources.

What this account says the measurements will find, in the sealed record's words:

> Repeated measurements on identically prepared systems settle to the weights of the Born rule, in every sector and on the full space, including in the tests proposed for superdeterminism, which look for departures from those weights. The interference among three paths has no term that the pairs of paths do not account for. Tests of the CHSH inequality reach $2\sqrt{2}$ and go no further, and stay at 2 or below whenever either party's two observables commute. Experiments with independent sources find the complex, not the real, composition of independent systems.
>
> (*The Registered Predictions of Physics from Comparison*, Prediction 25)

In every case, the chances found settle to the Born weights, and the tests proposed for superdeterminism are among the cases. A quantum system can be in any of a range of states. A *sector* is one part of the range of states, and the *full space* is the whole range. The Born weights hold in each sector and in the full space. When light or particles pass through three open paths, the resulting pattern is built from the patterns of the pairs of paths, with nothing left over. The CHSH inequality is the form of Bell's limit that experimenters test. The CHSH inequality is named for John Clauser, Michael Horne, Abner Shimony and Richard Holt. In the picture of Chapter Seven, the CHSH inequality is a score that no answer sheet can raise above 2. Quantum theory raises the score to two times the square root of two, about 2.83, and this account says that the score in every test will stay at or below two times the square root of two. An *observable* is a quantity that a measurement can ask about. When two questions can be answered together without disturbing each other, physi-

cists say that the two questions *commute*. The score stays at 2 or below when either party's two questions commute. Quantum theory describes a system with numbers that include the square root of minus one, which physicists call the *complex numbers*. Experiments that join systems from independent sources find the description with complex numbers, and not a version built of ordinary numbers alone.

Hossenfelder's own test, beside Prediction 25. Sabine Hossenfelder has designed the experiment in which her account and this account expect different results. Hossenfelder set out the experiment in her paper of 2011, "Testing Super-Deterministic Hidden Variables Theories", in *Foundations of Physics*. With Tim Palmer, she also set out the experiment in section 6 of "Rethinking Superdeterminism", in *Frontiers in Physics* in 2020. What the experiment will measure: consecutive measurements of two quantities that do not commute, made on states prepared as nearly alike as possible, with devices as small and as cold as possible, at the shortest intervals the apparatus allows. *Superdeterminism* is the view that the world is fixed in advance in every detail, the experimenters' choices included. A correlation in time is a dependence of each outcome on the outcome just before it. What she predicts: superdeterminism will show itself in the experiment as correlations in time, beyond the weights of the Born rule. Hossenfelder's estimate of 2011 places the effect beyond the large-scale experiments done so far. Her estimate places the effect within reach of a suitably designed experiment on the small scale. What this account says the experiment will find: the weights of the Born rule, at every sensitivity and every interval, with no correlation in time beyond those weights. The first sentence of Prediction 25 names Hossenfelder's tests. What the experiment must reach: small devices and short intervals. Hossenfelder's estimate names a range in which the effect could lie, and the result of the experiment covers more of the range when the devices are smaller and the intervals are shorter. The register says: "The experiment is hers, and it is the one place where her account and the collection's meet on the same meas-

urement with opposite expectations". No experiment built to Hossenfelder's design had yet reported a result on 4 November 2026, the date of the register.

Prediction 28: no world is perfectly deterministic, and no process is perfectly reversible. The sealed record says: "No superdeterministic completion of quantum mechanics will be found, and no world is purely and completely deterministic". A *claim of logical form* is a claim that a conclusion follows from its starting points, as in a proof. Prediction 28 is a claim of logical form, and the exclusion in Prediction 28 comes from the structure of comparison. Prediction 28 is decided by argument, and Chapter Seven gives the argument. The sealed record assigns to Prediction 25 the outcome of every search for departures from the quantum predictions, Hossenfelder's test among them.

Chapter Eight: Has Physics Ruled Out Free Will?

Chapter Eight asks whether the future is fixed by the past. The coming measurement that bears on Chapter Eight is the measurement that bears on Chapter Seven: Hossenfelder's test, set beside Prediction 25. This account says that, in Hossenfelder's test, consecutive measurements on states prepared alike settle to the weights of the Born rule at every sensitivity and interval, with no correlation in time beyond those weights. Prediction 28, also set out under Chapter Seven, states that no world is purely and completely deterministic, and Prediction 28 is a claim of logical form, decided by argument. The forty-two predictions of the sealed record concern measurements of physics. What a person will choose lies outside the scope of the forty-two predictions.

Chapter Nine: Are You Only a Bag of Atoms?

Prediction 29: a discrete rule shows itself to a fine enough measurement. A *discrete rule* is a rule that advances the world in fixed steps, as a computer program does. In Prediction 29, a discrete rule means a rule in fixed steps offered as the foundation of physics. What will be measured: the

statistics of quantum measurements, at a precision finer than the least step of any discrete rule. What this account says will be found: for any one fixed discrete rule, a sensitive enough measurement tells the statistics of the rule apart from the statistics of the world, and a measurement is sensitive enough when the measurement reaches below the least step of the rule. Prediction 29 bears on the simulation of Chapter Nine. If a simulation cuts its numbers off at a fixed precision, whatever the precision is, then the simulation parts from the world.

Prediction 5: space and time have no least length, area or duration. What will be measured: two things. The first thing measured is the arrival times of light of different energies from many distant sources, such as the bursts of gamma rays from far galaxies, and the measurements tell any effect of the source apart from the effect sought by how each effect grows with distance. The second thing measured is every observation that could show area or volume coming in separate steps. The observations that could show separate steps include the faint echoes of gravitational waves from merging black holes. What this account says will be found: the speed of light in empty space does not depend on the energy of the light through any step of space and time, and no observation shows area or volume coming in separate steps. *Content*, as Chapter Three glossed the word, is what the verdict of a comparison is about, and in physics, content is quantum matter. Quantum matter is a name that takes in every particle found within space and time, light included, with the charges and the fields of every particle. The sealed record says: "Discreteness belongs to the content, the charges and the kinds of particle, and the account predicts it there".

Where Hossenfelder and this account expect the same result. The register sets Prediction 5 beside a result of Hossenfelder's. In 2010, Hossenfelder showed that if the speed of light depends on the energy of the light, in the same way for every observer, the dependence brings effects that are not confined to one place. Physicists call effects that are not confined to one place non-local. The Planck energy is the energy at which gravity and the quantum act on equal terms. Hossenfelder showed further that one

dependence is ruled out, a change of the speed of light in simple proportion to the energy of the light measured against the Planck energy, because the non-local effects of the dependence would conflict with known particle physics. The register says that her result "reaches the class of models it addresses, and within that class it agrees with the collection's prediction".

Chapter Ten:
Does the Past Still Exist, and Why Does Time Run One Way?

Prediction 28, on the direction of time. Chapter Ten found that time runs one way in every single interaction. The second half of Prediction 28 states the finding of Chapter Ten: "Some asymmetry of time must exist in the laws, and no process at any scale is perfectly reversible; a reversal of evolution, by an inverse in a formalism or by a pulse in a laboratory, does not remove a finding from the order of findings". The spin echo told in Chapter Ten is a reversal of evolution made by a pulse in a laboratory. The second half of Prediction 28 is a claim of logical form, decided by argument, like the first half. The first half of Prediction 28 is set out under Chapter Seven. The sealed record also states how far the claim of Prediction 28 reaches: the claim is that time has an asymmetry, and the claim does not state the size of the asymmetry. The sealed record notes that the measured breaks of the symmetry of time are consistent with the asymmetry that the sealed record requires. By a general theorem, the break of CP found in 1964 is also a break of the symmetry of time. Direct breaks of the symmetry of time were seen by the CPLEAR experiment in 1998 and by the BaBar experiment in 2012.

Prediction 27, on later choices. Prediction 27, set out under Chapter Six, also says what an experiment will find when the experimenter chooses the test after the preparation: "The probabilities of a preparation's outcomes do not depend on which test is chosen later, and no later finding comes to precede an earlier one".

Chapter Eleven: How Did the Universe Begin, and How Will It End?

What the Beginning Left Behind is this account's plain-words book on the first moments. *What the Beginning Left Behind* names five things the beginning left: the faint pattern in the oldest light, one settled state of empty space, the dark matter, the excess of matter over antimatter, and a faint hum of gravitational waves. Chapter Eleven gives the five things too. Four of the five things are already in our measurements. Next I set out the coming measurements of the four things and of the fifth thing, the hum. This account's statements about the kind of early ripple, the flatness of space, the energy of empty space, the dark matter and the hum are Predictions 7 to 15 and 20 of the sealed record.

Prediction 9: space is flat to the size of the early ripples. What will be measured: the bending of space on the largest scale, which DESI and Euclid measure together with the matter fraction. What this account says DESI and Euclid will find: space flat, with only the bending that the early ripples themselves carry, of the order of one part in a hundred thousand. Each epoch begins with space flat, and within one horizon the bending measured is the bending of the departures from evenness.

Prediction 11: every ingredient ripples together. What will be measured: whether any ingredient of the universe, such as the dark matter, carries a pattern of early ripples of its own in the microwave background, apart from the other ingredients. Physicists call a separate pattern of early ripples, carried by one ingredient alone, an *isocurvature* mode. What this account says will be found: every ingredient departs from evenness together, as one form carried across from the epoch before, and the dark matter carries no separate pattern of its own.

Prediction 12: the ripples are one pattern across the whole sky. What will be measured: every finer map of the microwave sky. What this account says will be found: the early ripples correlated across the whole sky, with nearly the same strength at every length. Separate, unconnected pieces would make a pattern that physicists call white noise. White noise is excluded. I take two numbers of the ripples from measurement, the

strength of the ripples and the sign of the slight tilt of the ripples from large sizes to small: this account does not fix the two numbers. Each prediction uses the measured values of the two numbers wherever the prediction needs the two numbers.

Prediction 14: the hum of the settling, and no hum where others expect one. What will be measured: gravitational waves that fill the whole sky, by LISA and by the *pulsar-timing arrays*. LISA is a planned observatory of gravitational waves in space. The pulsar-timing arrays watch the steady ticks of spinning dead stars for the slight stretch that a passing wave gives the ticks. Measurements of the microwave background also measure the count of kinds of particle light enough to have moved at nearly the speed of light in the early universe. What this account says will be found: the six small dimensions form again at each turn. The settling of the six small dimensions just after the turn leaves a hum of gravitational waves. The hum peaks today above about five hundred billion vibrations per second, and no instrument now built or proposed reaches a frequency that high. Chapter Twelve calls the six small dimensions, taken as a context, the setting of possibility. The strength of the hum has an upper limit and no lower limit, and the upper limit is an addition of less than about nine hundredths to the count of light kinds of particle. LISA will find no hum from a sudden change of state of the early universe, for two reasons. First, the changes of state of the early universe were gradual: the change of the joined electric and weak force, and the change of the strong force. Second, there is no further kind of particle to make a sudden change of state. The pulsar-timing arrays have found a hum. The hum found by the pulsar-timing arrays comes from pairs of giant black holes orbiting each other, on one condition: the early ripples keep, at short lengths, about the strength measured at long lengths. Cosmic strings, domain walls and monopoles are thin lines, sheets and points of trapped energy, and some theories predict that the early universe left cosmic strings, domain walls and monopoles. The early universe made no lasting network of cosmic strings, and

the early universe made no domain walls or monopoles from the breaking of the symmetry of the joined electric and weak force. So the early universe left no hum from cosmic strings, domain walls or monopoles.

Prediction 15: the excess of matter has one sign everywhere. What will be measured: searches for stars, galaxies or whole regions made of antimatter, and for nuclei of antihelium among the cosmic rays, the fast particles that rain on the Earth from space. What this account says will be found: the particles of ordinary matter outnumber their antiparticles everywhere in the observable universe, and there is no region of antimatter in the observable universe.

The other statements of Chapter Eleven are predictions set out under earlier and later chapters of this appendix. The energy of empty space is measured through Predictions 7 and 8, under Chapter Four: a matter fraction of 0.311 and an equation of state of exactly minus one at every time. Predictions 10 and 13, under Chapter Five, state the absence of primordial gravitational waves and of a long inflation. Prediction 33, under Chapter Three, states that the proton lasts. The dark matter was made as our epoch formed from the turn, and the predictions under Chapter Twelve are about the dark matter.

Chapter Twelve:
What Is the Dark Matter, If Every Search Comes Back Empty?

The predictions of this section depend on an identification that I make in Chapter Twelve. Chapter Twelve puts the identification in these words: "I identify the dark matter with a ringing of the setting itself: a lasting vibration of the six small dimensions, taken as the setting of what could be found". In the picture of the balance, the dark matter shows in the result of a weighing only as extra pull. The dark matter is never a thing set in a pan. The dark matter is not matter of any kind on the list of particles.

Prediction 19: the dark matter acts only through gravity. What will be measured: every search for the dark matter by any route other than the weight of the dark matter. The routes are scattering in underground de-

tectors, light or particles that the dark matter might give off, and the making of dark matter in a collider. What this account says will be found: the dark matter is found by its weight alone, at every sensitivity. The sealed record says: "No search will detect the dark matter through any interaction but gravity, at any sensitivity: not by scattering in an underground detector, not by light or particles it gives off, and not by its production in a collider".

Prediction 16: the dark matter outweighs the ordinary matter by six minus two over pi. What will be measured: the densities of the dark matter and of the ordinary matter, by a second, independent kind of measurement at the precision that measurements of the microwave background reach. The Planck satellite was the European satellite that mapped the microwave background. What the measurement must reach: the Simons Observatory, together with the maps of the Planck satellite, would measure the ratio of the two densities to about 0.6 percent. What this account says will be found: the dark matter outweighs the ordinary matter by six minus two divided by pi, 5.3634 to one, at every time since helium formed. Combined with the matter fraction of Prediction 7, the ratio of 5.3634 to one gives the ordinary matter 0.0486 of the universe's energy and the dark matter 0.2608.

Prediction 17: one number shared with the cosmological constant. The curvature of the six small dimensions enters both the matter fraction of Prediction 7 and the ratio of Prediction 16, through one coefficient. What will be measured: the ratio of Prediction 16, together with an independent measurement of the matter fraction. In the sealed record, k is the curvature of the six small dimensions, in the units built from the constants of gravity, of quantum theory and of light. What this account says will be found, in the sealed record's words: "Both observables will find k = 1". The two observables are the ratio of Prediction 16 and the matter fraction, two routes that rest on different measurements, and the two routes will meet on one value of k.

Prediction 20: the dark matter does not decay. What will be measured: the ratio of the dark matter to the ordinary matter when the microwave background was released, set beside the same ratio today. What this account says will be found: the dark matter does not decay. The density of the dark matter falls exactly as the density of matter does, and the ratio is the same at both times. *Gyrations* are the units of the dark matter that Chapter Twelve described. The gyrations of each epoch are made only as the epoch forms from the turn that begins the epoch. No gyration passes from one epoch into the next.

Prediction 21: the dark matter is perfectly cold. What will be measured: how finely the dark matter clumps, which the faintest small galaxies circling large galaxies show. The bending of light by mass reveals small lumps, and the small lumps also show how finely the dark matter clumps. What this account says will be found: the dark matter clumps on every small scale, with no smallest size of clump set by the motion of the dark matter.

Prediction 22: the gyrations have about the Planck mass. What will be measured: the mass of the gyrations, the units of the dark matter. What this account says will be found: each gyration has a mass of the order of the Planck mass, the mass at which gravity and the quantum act on equal terms. The lightest gyration has the square root of two Planck masses, about seventeen billion billion GeV, at the classical level of the calculation, before any quantum correction, and with the first quantum correction added, the lightest gyration has about 0.6 Planck masses. So there is about one gyration for every one and a half to three and four tenths billion billion particles of ordinary matter of the kind made of three quarks.

Prediction 24: a galaxy feels a larger neighbor only through its tide. Chapter Twelve told of Mordehai Milgrom's rule for faint pulls, which physicists call modified Newtonian dynamics. Modified Newtonian dynamics predicts an *external field effect*: the inner motions of a galaxy falling freely in the field of a larger galaxy change with the strength of the outer field. What will be measured: the inner motions of galaxies that fall freely in the field of larger galaxies. The *tide* of a galaxy is the difference of the

outer pull from one side of the galaxy to the other. What this account says will be found: a galaxy falling freely in the field of a larger galaxy feels the outer field only through the tide of the galaxy. The sealed record says that "the external field effect that modified Newtonian dynamics predicts will not be found".

Prediction 30, under Chapter Three, lists the kinds of particle that will not be found. The list of Prediction 30 includes any species of dark matter, the axion, the dark photon and any hidden sector. Prediction 34, under Chapter Four, states again that there is no axion.

Chapter Thirteen:
Is Gravity's Meeting with the Quantum the One Real Problem?

Prediction 1: gravity entangles two masses. What will be measured: two small masses. Each mass is held in a superposition of two places, and the two masses are related to each other only through gravity. The two masses are kept so well isolated that ordinary decoherence stays well below the effect sought. When two masses are linked so that neither mass can be described alone, physicists say that the two masses are *entangled*. What this account says will be found: the two masses become entangled, with the phase that Newton's law of gravity between the two masses gives. A *phase* is an angle carried by each alternative in the quantum description. The entangling phase is the angle by which gravity turns the alternatives relative to one another. The phase is measured in radians. A full turn is a little under six and three tenths radians. In 2017, Sougato Bose and his colleagues proposed a design for the experiment. The phase is 0.314 radians for the design of Bose and his colleagues. A micrometer is a millionth of a meter. The design of Bose and his colleagues holds two masses of a hundred-thousandth of a billionth of a kilogram for two and a half seconds, each mass in two places 250 micrometers apart, and the centers of the two masses 450 micrometers apart. Two standard measures of entanglement apply to the state of the two masses in the design of Bose and his colleagues. The first measure is the concurrence, which reads 0.156. The

second measure is the entanglement witness of Chevalier, Paige and Kim, which reads minus 0.22. A witness below zero shows entanglement. For any other design, the phase is the phase that Newton's law gives for the masses, distances and time of the design.

The experiment of Prediction 1 also sets this account apart from two kinds of account, and every account of either kind predicts no entanglement. Accounts of the first kind keep one geometry of space for all the alternatives of the matter, and examples of the first kind are the accounts of Christian Møller and Léon Rosenfeld and of Jonathan Oppenheim in 2023. Accounts of the second kind are accounts of collapse by gravity, such as the collapse by gravity that Diósi and Penrose propose. Below the Planck scale, the quantum description of gravity's small waves predicts the same phase as this account.

Prediction 3: gravity is not quantized. What will be measured: every effect that could show the geometry of space and time carrying quantum states of its own, such as the scattering of gravitational waves, and every detection of gravitational waves. What this account says will be found: no effect shows the geometry carrying quantum states of its own, beyond the quantum states tied to the alternatives of the matter. The Planck curvature is the extreme bending at which gravity and the quantum act on equal terms. Below the Planck curvature, a description of the small waves of the geometry by quanta holds. The quanta belong to the description, never to space and time themselves. If a detector registers a gravitational wave in single clicks, the single clicks agree with this account. The single clicks do not show that gravity is quantized.

Prediction 4: everything falls alike, and nothing shields gravity. The *Eötvös parameter*, named for Loránd Eötvös, is the fractional difference between the free falls of two materials. What will be measured: the Eötvös parameter, by tests such as the proposed satellite STEP (Satellite Test of the Equivalence Principle), which aims at one part in a billion billion; the free fall of antimatter; and every search for a shield against gravity. What this account says will be found: the Eötvös parameter is zero for every

pair of materials at every precision. Antimatter falls with the acceleration of matter. No arrangement of matter shields gravity, and nothing will be found that gravity leaves untouched.

Prediction 2, under Chapter Six, says that gravity alone ends no superposition. Prediction 5, under Chapter Nine, says that space and time have no least length.

Chapter Fourteen: Whom Can We Trust When Scientists Agree?

In Chapter Fourteen, I point to the sealed record as a whole: the sealed record contains every claim of this account about what the world will show, beside the measurement that bears on the claim. The register sets the predictions of the sealed record beside Hossenfelder's predictions. On one measurement, Hossenfelder's account and this account expect opposite results, and the experiment for that one measurement is Hossenfelder's own: her test of consecutive measurements, set beside Prediction 25 under Chapter Seven. On two measurements, Hossenfelder's account and this account expect the same result. The first shared result is no new kind of particle at the energies within reach (Predictions 30 and 35, under Chapter Three). The second shared result is a speed of light that does not depend on the energy of the light (Prediction 5, under Chapter Nine), within the class of models that Hossenfelder's result of 2010 addresses. Three matters are decided by argument, not by measurement: superdeterminism itself, the update of the quantum state on measurement, and choice. The register states that each of the three matters is decided by argument, and states the kind of claim that each matter is. Every entry in this appendix falls under the one rule of decision stated at the start of the appendix: a result counts when the result is established at five standard deviations by at least two independent kinds of measurement.

The Reach of the Record

The sealed record states the reach of its predictions as plainly as the sealed record states the predictions themselves. The sealed record says: "A record of predictions is exact only if it also says what is not predicted, so that no later measurement is counted for or against the account where the account makes no claim". The ninth section of the sealed record states the reach of the predictions, as follows.

Four numbers are measured inputs, taken from measurement. The first measured input is Newton's constant, which sets the strength of gravity, and the second measured input is the strength of light, the strength with which light acts on electric charge. The third measured input is the strength of color, the strength of the force that binds quarks, and the fourth measured input is the value of the Higgs field in empty space. This account predicts the Hubble constant only through the matter fraction, because the Hubble constant cancels from the identity on which Prediction 7 rests. This account does not fix the strength of the early ripples or the sign of the tilt of the early ripples, so each prediction uses the measured strength and the measured sign of the tilt wherever the prediction needs the two numbers. This account does not predict the change of the tilt with length: the books of this account give the change of the tilt only on a condition that the books do not adopt. The books of this account do not compute the workings of the passage from one epoch to the next, and the books also do not compute the way the gyrations are made as a new epoch forms from the turn. The excess of matter over antimatter has had its size from the start: the excess is a residue that no process among the kinds makes. The kinds fix only the share of the excess held in particles made of three quarks. The books that reason out the kinds fix the kinds and not the values of the kinds. Two further books carry the masses, mixings and strengths: *The Strengths of the Kinds*, this account's book on the strengths of the forces among the kinds, and *The Measures of the Kinds*. Where the two books carry two values side by side, the two books state that measurement has yet to choose between the two values. This account

predicts that time has an asymmetry, but the size of the asymmetry lies outside the prediction. Below the Planck curvature, this account and the description of gravity's small waves by quanta predict the same result for every experiment now proposed. Gravitons are the proposed quanta of gravity. A detection of single gravitons would not show that gravity is quantized. Detecting a primordial background of gravitational waves would not show that gravity is quantized either. *Two Theories, One World* is this account's book on gravity and the quantum, and *The Unquantized Arena*, the companion of *Two Theories, One World*, gives the same argument in technical form. For the information that falls into a black hole formed from a star, *The Unquantized Arena* and *Two Theories, One World* assert neither that the information returns to the outside world nor that the information is lost to the outside world. *The Gravitational Passage* follows the information through the interior of the black hole: in *The Gravitational Passage*, the information is lost to every observer who stays outside the horizon, and the information is not destroyed. The information re-emerges in the starting conditions of the next epoch. *At the Edge of Reality* is the plain-words form of *The Gravitational Passage*. *At the Edge of Reality* tells, in plain words, the passage of the information that *The Gravitational Passage* follows. This account claims nothing, either way, about whether travel within the light cone can be made practical.

Appendix B

For the Specialist

This appendix is for the specialist who wants to follow each claim of the chapters to the book of this account that carries its argument, and to see in their exact form the values and the algebra that the chapters state in words. For each chapter it lists the claims in the order the chapter makes them. Each entry gives the claim in one plain sentence, at the strength the chapter states it, which is the strength the carrying book states it; then the carrying book, with its chapter and section as that book prints them; and, where the chapter states a value or a relation in words, the exact value, symbol or formula that the carrying book gives. Where an entry uses a symbol, the entry says in words what the symbol stands for at its first use. Where the carrying book states a step as my identification, a stated step from the structure of comparison to something in the world, the entry states it as an identification, in the first person, as the book and the chapter do. Where a chapter says that two routes arrive at one result, the entry names both routes and the books that carry them, and the two books stand on different ground; where one book restates in plain words an argument made in another, the entry names the restating book as a restatement. The chapters are complete without this appendix.

Preface

Comparison is setting one thing beside another and finding how they stand, and every measurement is an act of comparison: a ruler is set beside an edge, one clock's ticks beside another clock's, a detector's count against a threshold. Carried by *Physics Is Not Math*, chapter 1, "What It Is to Compare", section I, "Two Stones" ("A comparison is the act of finding whether two things are the same or different, in some respect"), and sec-

tion III, "The Tide Gauge" ("A length is compared with a measuring rod, a duration with the ticking of a clock, the weight of a sample with a standard mass").

I identify every finding of physics, every result that physics has found, with an act of comparison made from inside the world. Carried by *Physics Is Not Math*, chapter 1, section V, "A Premise Used by Every Attempt to Deny It", in the words "I identify every finding of physics with an act of comparison made from inside the world". The same section names the observation that bears on the identification: every measured value has the form of a count against a threshold, a measure against a standard or a frequency against a reference.

Inside the world means that whoever or whatever does the comparing is itself a part of the world it compares, with no place outside the world to stand. Carried by *Physics Is Not Math*, chapter 1, section V, where every measured value is "delivered by an instrument that is itself part of the world it measures"; and by *Home in the World*, chapter 1, "Properties Are Relations", section "No Place Outside" ("There is nothing outside the world for anything to be still against, and nowhere outside it for anyone to stand").

In the balance's picture, the things set in the pans are what is compared and the tip of the beam is the result; the setting is the two places the things weighed occupy, the left pan and the right pan, with the floor and the room that hold those places, and the moment of the weighing; the beam that joins the two pans carries the comparison, and it is part of the setting too. Within the picture, the weighing divides one way into what the result is about, here how heavy the things in the pans are, and the setting; Chapter Three names these two the content and the context. The same weighing can also be divided in a second way: by this second division, the instrument, with whoever reads it, is the side from which the weighing is made, and the things in the pans are the side about which it is made. The two divisions are distinct: by the first, the pans and the beam belong to the setting; by the second, they belong to the instrument. Carried by *Measurement; The Steps from Comparison to Physics*, chapter 1, "What

This Book Takes from the First Two", section I, "The Ground of the First Volume" ("Content and context are what the verdict is on, and the respect in which the two things compared are two"; "The subjective and the objective are the side from which the comparison is made and the side about which it is made"; "The pairs are distinct, and none can stand in for another"; "The context is the respect in which they are two: two pans, two places, one moment"; "The subjective is the side from which the comparison is made, the balance and whoever reads it, and the objective is the side about which it is made, the apples"); the beam's place in the setting, the floor and the room are this book's picture.

Metaphysics, in this account, is the study of what must be so for anything at all to be known, and immanent means within: the Immanent Metaphysics works from inside the act of knowing, here and now, and never from a place outside the world. The account asks what every comparison must contain, whatever is compared and whoever or whatever compares it, and its ground takes nothing from physics: no measurement, no law, no result of any experiment. Carried by *Home in the World*, Prelude, "Two Crews, One Tunnel", section "The Crew from Knowing", whose words are: "Metaphysics here means the study of what must be so for anything at all to be known; immanent means within: it works from inside the act of knowing, here and now, as it happens, and never from a place outside the world. Its ground takes nothing from physics: no measurement, no law, no result of any experiment".

From that ground the Immanent Metaphysics works out a physics, set out in a series of books; in this book, "this account" names the Immanent Metaphysics together with that physics. Carried by *Home in the World*, Prelude, section "The Crew from Knowing" ("What it finds there, it works out from what every comparison must contain"); the name "this account" is this book's own term.

Two routes from separate ground that arrive at one place give more reason to trust that place than either route gives alone. Carried by *Physics Is Not Math*, chapter 12, "Chains and Cables", section V, "Two Routes to One Value", and section VI, "Merit and Truth" ("Its truth is then sought

through measurement and through the convergence of independent routes"); and by *Side by Side*, Volume One, "What Beauty Cannot Decide", section II, "Where She Is Right: Beauty Is No Evidence". The exact probability is given under Chapter One below.

On beauty Sabine Hossenfelder is right, and the account this book sets beside hers reaches the same place by a route of its own. Carried by *Side by Side*, Volume One, "What Beauty Cannot Decide", section II, "Where She Is Right: Beauty Is No Evidence": "The collection agrees that a feeling of beauty is no evidence about nature", and "The collection adds the reason the critique is right".

Chapter One: Can Beauty Tell Us Which Laws Are True?

An act of comparison is setting one thing beside another and finding how they stand: the same, or different, in some respect. Carried by *Physics Is Not Math*, chapter 1, "What It Is to Compare", section I, "Two Stones": "A comparison is the act of finding whether two things are the same or different, in some respect".

Every measurement is an act of comparison: a length is found by setting an edge beside a measuring rod, a duration by setting an event beside a clock, a weight by setting a load beside a standard mass; a measured result says how the thing measured stands against its standard, and a pan balance is one such comparer. Carried by *Physics Is Not Math*, chapter 1, section III, "The Tide Gauge" ("A length is compared with a measuring rod, a duration with the ticking of a clock, the weight of a sample with a standard mass"), and section II, "Instruments Compare Too" ("A pan balance sets two loads against each other, and it tips, or it stays level"); and by *Home in the World*, chapter 3, "Three Parts in Every Finding", section "One Event, Three Names".

By this account the chapter means, as the Preface does, the Immanent Metaphysics and the books of physics built on it; the word immanent means within: the Immanent Metaphysics works from inside the act of knowing, here and now, and never from a place outside the world. Car-

ried by *Home in the World*, Prelude, "Two Crews, One Tunnel", section "The Crew from Knowing" ("immanent means within: it works from inside the act of knowing, here and now, as it happens, and never from a place outside the world").

The orrery that runs as easily backward as forward shows a property of the model, and the Moon in fact moves away from the Earth by about 3.8 centimeters a year. Carried by *Physics Is Not Math*, chapter 11, "Why the Order Surprises", section I, "A Clockwork Solar System", which also carries the history (John Rowley's instrument of about 1712 for Charles Boyle, fourth Earl of Orrery). The value of 3.8 centimeters a year is measured, by laser light returned from the reflectors left on the Moon.

Mathematics writes from one view only: the third person, the same for every reader, with the result laid out whole and no one in it doing the comparing; made with mathematics, the visitor's mistake is to take that view for the whole of what is, and so to take a property of the description for a property of the world. Carried by *Physics Is Not Math*, chapter 3, "Truth Has a Frame", section VII, "Mathematics Works as if Only the Objective Existed" ("Mathematics works as if only the objective existed, and as if there were no subjective side at all"), and section VIII, "Taking the Frame of Mathematics for Everything" ("The frame of mathematics is a frame too: the third person, with the stance left unnamed and the result laid out"); chapter 11, "Why the Order Surprises", section IV, "Why the Laid-Out Seems to Come First" ("Chapter 3 met it as the frame of mathematics taken for everything, and the order of depth is its correction"); and *Side by Side*, Volume One, "What Beauty Cannot Decide", section II ("taking the frame of mathematics for the whole is the error Physics Is Not Math, Chapter 3, names").

A property of a mathematical description of the world (its symmetry, its economy, the absence of large unexplained ratios in it) is a property of the description, and whether the world shares it is found by measurement; naturalness is a case of the visitor's mistake made with mathematics, the mistake in a precise form; the world is under no obligation to the instrument. Carried by *Side by Side*, Volume One, "What Beauty Cannot

Decide", section II, "Where She Is Right: Beauty Is No Evidence", whose words are: "a property of a mathematical rendering (its symmetry, its economy, the absence of large unexplained ratios in it) is a property of the rendering"; "Naturalness is that error in a precise form: the demand that the numbers of nature be of a size the mathematics finds unremarkable"; "The world is under no obligation to the instrument".

A finished description reaches us after the act that found it, already laid out and the same for everyone, and so the most shareable, most exact and most finished description is easily taken for the deepest. Carried by *Physics Is Not Math*, chapter 11, section IV, "Why the Laid-Out Seems to Come First".

Circles riding on circles can follow any path whatever, so a close fit of circles to the path of Mars says nothing about why Mars takes that path. Carried by *Physics Is Not Math*, chapter 15, "The Descent", section I, "Circles Riding on Circles", and section II, "A Question the Circles Cannot Reach".

Kepler kept in charge the question of what moves the planets; that question decided which mathematics was worth doing, and one more circle was not worth doing, because no circle could answer it. Carried by *Physics Is Not Math*, chapter 15, section II, "A Question the Circles Cannot Reach" ("Every answer the method gives is a better fit, and no answer it gives touches the cause"), and section VI, "The Outcome Table".

Kepler found the shape of the path and proposed a cause, a force from the Sun; Newton then found the one law of gravity that gives that shape; the question of what moves the planets was answered by physics reasoning that used mathematics at every step, and the circles kept their use as a way to calculate where a planet will be seen on a given night. Carried by *Physics Is Not Math*, chapter 15, section V, "Kepler Turns Back to the Physics Question" ("In 1687 Isaac Newton, in the Principia, showed that one law of gravity, the same pull that makes a stone fall, gives the planets

paths of exactly Kepler's shape"), which also carries the history the chapter tells: the miss of eight minutes of arc against Tycho Brahe's measurements, the ellipse, and the *Astronomia Nova* of 1609.

The Basis of Physics compares the theory of the particles to an old inherited program, with running code, input numbers, outputs and a manual; the running code is the machinery of calculation that turns those input numbers, such as the masses and strengths of the particles, into predictions that can be set beside measurement; naturalness belongs to the manual, which is "consulted for orientation but trusted for nothing", and the rule that *The Basis of Physics* gives for an old program is to trust nothing in the manual until the running code confirms it. Carried by *The Basis of Physics*, Introduction, "Physics at the Boundary of Comparison", section VIII, "What Physics Is, on This Account", subsection "The Standard Model as Inherited Code": "Category A: Action machinery. This is the code that runs"; "Category B: Configuration", whose free parameters are the "coupling constants, masses, mixing angles, CP-violating phases", and whose step is to "Isolate the set of inputs that define the system's operating state"; naturalness and the hierarchy arguments are listed under "Category D: Documentation"; and the rule is to "trust nothing in it until confirmed by the code".

None of the books of this account uses naturalness or fine-tuning as an argument. Carried by *Side by Side*, Volume One, "What Beauty Cannot Decide", section II.

Truth is found in the way things actually are, and beauty in the here and now, the meeting of one particular person with what is before them; *The Last Turtle* counts truth and beauty as two of a triple whose third is goodness, found in values and virtue, and holds the three distinct, never found apart, and never standing in for one another. Carried by *The Last Turtle*, chapter 1, "What Metaphysics Is", section VIII, "The Good, the True and the Beautiful" ("Truth goes with the omniscient: logic, mathematics, the way things actually are. Beauty goes with the immanent: the finite, the here and now, the relational in the personal and intimate sense. Goodness goes with the transcendent: values, virtue, the goodness that is

not fixed in any one instance"), where "is found in" renders the book's "goes with", each term set under one role of comparison (section VI, "The Relationship as the Starting Point"); the relation "distinct, inseparable, and non-interchangeable" is Axiom III, stated in that section VI. The step from there to Hossenfelder's finding (who a person is changes what that person meets as beautiful, so her finding that a sense of beauty is formed partly by education fits where that book places beauty) is my own step, stated in the first person in the chapter ("Because who a person is changes what that person meets as beautiful, I say ..."); it is not a sentence of *The Last Turtle*.

Before any mathematics is done for a physics question, a table is written that gives, for each possible result of the mathematics, what changes in the answer to the question about the world; the mathematics is done for a question only when some result of it would change the answer. For one more circle in the model of Mars, the two possible results are that the fit becomes closer and that the fit stays as it was; neither changes the answer to "what moves the planets?", so for that question the circle is not added. Carried by *Physics Is Not Math*, chapter 15, section VI, "The Outcome Table" ("Both rows read "Nothing", so for this question the circle is not added").

An identification is a stated step from the structure of comparison to a quantity measured in the world; *Comparison; The Necessary Basis* states each of its own identifications in the first person ("I identify ...") and checks each one against measurement. Carried by *Comparison; The Necessary Basis*, chapter 2, "Comparison as the Ground of Science", section IV, "Identifications, in the First Person" ("An identification is a stated step from the structure of comparison to a physical quantity, made in the first person, with the observation that would test it"), and chapter 10, "Reasoning", section II, "The Real and the Abstract".

Elegance, taken as "a sign of understanding and not of style", has three parts that anyone can check: parsimony, many results from few starting points, of which Newton's one law of gravity, giving the path of every planet, is the plain case; structural inevitability, whether the form a

body of work takes could not have been otherwise, so that it shows why its conclusions hold, and not only that they do; and economy of means, whether everything present does work; of structural inevitability, *Physics Is Not Math* adds that "independent thinkers arriving at the same structure is evidence of it". Carried by *Physics Is Not Math*, chapter 19, "A Right Method of Evaluation", section VII, "Merit Has Many Measures" ("Parsimony is many results from few premises"; "Economy of means is whether everything present does work"); the Newton example rests on chapter 15, section V.

Two independent routes to one value make the value surer than either route alone; independent routes resting on different premises and arriving at one value is convergence, the strongest evidence that inquiry into the world can have; so where no measurement has yet been made, independent routes that arrive at one result, which anyone can lay side by side and check, give firmer ground than taste. Carried by *Physics Is Not Math*, chapter 12, "Chains and Cables", section V, "Two Routes to One Value", which also carries Jean Perrin's thirteen procedures for counting molecules (1913). Exact form, as that section gives it: for two independent arguments to one value, each right nine times in ten, the chance that both are wrong at once is $(1/10) \times (1/10) = 1/100$, so the shared value is right 99 times in 100; the same two arguments joined as links of a chain, each of which must hold, give $(9/10) \times (9/10) = 81/100$.

Elegance taken as a sign of understanding is the convergence of independent routes on one result, which anyone can check; elegance in the sense the field gives it, simplicity joined with surprise, is a preference of the theorist and no evidence about the world, and in that sense this account agrees with Hossenfelder. Carried by *Side by Side*, Volume One, "What Beauty Cannot Decide", section II ("Elegance in that sense is the convergence of independent routes on one result, a convergence anyone can check (as distinct from a preference of the theorist)"), and section IX, "Summary" ("Elegance counts for it only as the convergence of independent routes, which can be checked").

Elegance is not simplicity: "elegance is not simplicity; a theory need not be simple to be called elegant. To call a theory elegant is to say that it is profoundly clear". Carried by *The Last Turtle*, chapter 4, "How a Triple Is Found and Tested", section VIII, "Reifying Power and Resolving Power". The passage speaks of elegance; it states nothing about beauty, and it is not the convergence sense of elegance.

Chapter Two:
If Physics Is Written in Mathematics,
Why Is Physics Not Mathematics?

A finding made by the balance is complete in itself: it needs no law of nature, no rule and no theorem. Carried by *Physics Is Not Math*, chapter 9, "Metaphysics Is the Act", section I, "The Two Stones Again": "So the act of comparison is complete with no law, no program and no theorem".

The mark stamped on a weight is the record of an earlier weighing against a standard. Carried by *Home in the World*, chapter 4, "The Circle and the Floor", section "Six Parts of Every Comparison" ("A unit is a standard to compare against"), and by *Physics Is Not Math*, chapter 9, section II, "All Three Are Made of the Act".

Metaphysics, the study of what must be so for anything at all to be known, is in this account the account of the act of comparison itself, since every act of knowing is an act of comparison or is built from acts of comparison. Carried by *Physics Is Not Math*, chapter 5, "What Depth Means", section V, "The Order of the Four" ("Metaphysics, in this book, is the account of the act of comparison itself"), and chapter 2, "Two Things That Cannot Both Be Perfect", section VI, "The Theorem" ("Every act of knowing is an act of comparison or is built from acts of comparison").

Arranged by what each presupposes, deepest first, the four fields run: metaphysics, physics, computation, mathematics; I call that arrangement the order of depth; depth here means presupposition and nothing else, and says nothing about which field is more exact, more useful or more admired. Carried by *Physics Is Not Math*, chapter 5, section II, "Depth Is the

Order of Presupposition", section III, "Depth Is Not Certainty", and section V, "The Order of the Four". Exact form of the definition: one discipline is deeper than another when the second cannot be carried out, stated or checked without the first, and the first can be carried out without the second.

Mathematics stands after computation because every proof is checked by a computation; computation stands after physics because every computation that is carried out is a physical process; physics stands after the act of comparison because every finding of physics is an act of comparison made from inside the world; and each of the three needs runs one way only (holding two stones is an event in the world, and their bare comparison needs nothing that physics states about such events). Carried by *Physics Is Not Math*, chapter 5, section V, "The Order of the Four", whose words for the three one-way steps are: "a computation runs without waiting on any proof"; "physics happens whether or not anything is computed"; and a single comparison "is complete with no law of physics, no program and no theorem".

Mathematics keeps all of its certainty, and it is the finest instrument there is for what is laid out as structure. Carried by *Physics Is Not Math*, chapter 5, section III, "Depth Is Not Certainty" ("The certainty of mathematics stands"); chapter 4, "Truth Above True and False", section X, "Summary"; and chapter 11, "Why the Order Surprises", section VII, "What Each Discipline Keeps".

A field that rests on another cannot set conditions on the one it rests on: where the two disagree, the field that rests on the other is the one at fault. Carried by *Physics Is Not Math*, chapter 5, section VI, "Why the Order Matters" ("A discipline that rests on another cannot set conditions on the one it rests on"), whose picture is a photograph of a cake that disagrees with the cake: "a poor picture, not a poor cake".

What a theorem guarantees is the connection between its premises and its conclusion, in the form "if these premises, then this"; whether the premises hold of the world is a second question, and measurement an-

swers it. Carried by *Physics Is Not Math*, chapter 6, "Mathematics, the Science of the Timeless", section IV, "If These Premises, Then This", and section V, "Two Questions Answered Elsewhere", which also carries the history of the parallel postulate (Euclid; Lobachevsky, 1829 and 1830; Bolyai, 1832; Riemann, 1854) and the finding of Einstein's theory of gravity that near heavy bodies the geometry of space is not exactly Euclid's.

Each measurement made of Einstein's theory of gravity, from the turning of Mercury's orbit to the ripples in space sent out when two black holes merge, found space and time smooth and shaped by what they hold. Carried by *Physics Is Not Math*, chapter 2, "Two Things That Cannot Both Be Perfect", section X, "Two Characters, Two Theories".

An argument has merit when its claims follow from its premises, and it is true, in the sense used for arguments, when it has merit and its premises are also true of the world; mathematics certifies merit, and truth is sought through measurement and through independent routes that arrive at one result. Carried by *Physics Is Not Math*, chapter 12, "Chains and Cables", section VI, "Merit and Truth" ("Mathematics certifies merit"), and the chapter "Relevance, Merit and Truth", section IV, "Merit Before Truth" ("it is true, in the sense used for arguments, when it has merit and its premises are also true of the world").

The coal sphere "perhaps represents the simplest possible physical object", and the coal sphere lets no light through. The diamond is complex, and light passes through the diamond. The light stands for understanding. In thinking about metaphysics, clarity of essence is asked for in place of simplicity of appearance. To call a theory of physics elegant is less to say that the theory is demonstrably simple than to say that the theory is profoundly clear. Carried by *An Immanent Metaphysics*, chapter 1, "Foundations", section "Simplicity, Clarity, and Metaphor", aphorism 1.1-5: "In thinking about metaphysics, one must proceed with an emphasis on a clarity of essence rather than submit to a desire or drive for a simplicity of appearance"; "the ability to transmit light (a metaphor for understand-

ing) is not dependent on complexity"; "To say that a concept of metaphysics, or a theory of physics, has 'elegance' and grace, is not to say that it is demonstrably simple so much as it is to say that it is profoundly clear".

I identify a law of physics with a statement of what stays the same when the setting of a comparison changes (the setting being the places, the moment and the conditions in which the comparison is made), and the continuity physics assumes, its smoothness, with a statement of what stays the same when the setting stays the same; both are statements about comparison, so the account of comparison studies the assumptions physics already makes, and the order of depth places it before physics, as the ground physics rests on; metaphysics "is about the foundations of physics: the structural conditions that must obtain for physics to be possible at all", where structural conditions are conditions set by the structure of comparison itself. Carried by *Comparison; The Necessary Basis*, chapter 14, "Science as Formalized Comparison", section II, "What Physics Actually Does" ("The laws of physics are statements of symmetry, what remains the same when context changes, and the continuity assumptions of physics are statements of continuity, what remains the same when context stays the same"; "These are identifications: when physics asserts a symmetry, it asserts something about comparison, and when physics assumes continuity, it assumes something about comparison"), and section III, "What Metaphysics Actually Is" ("It is about the foundations of physics: the structural conditions that must obtain for physics to be possible at all"; "It studies the structure of comparison").

"No theory will ever be able to completely explain, predict, or model all observable behavior and phenomena in a domain", and the account says this of its own framework too. Carried by *Comparison; The Necessary Basis*, chapter 14, section VI, "The Scope of Theory" ("This includes the Epistemic Process itself").

A comparison can find four characters: symmetry, the same under every change of place or setting; continuity, with no gaps, so that a small change of setting gives a small change in what is found; asymmetry, different from place to place; discontinuity, in steps with gaps between, so

that in one unchanged setting what is found jumps from one value to another, with no value between; weighing with a box of stamped weights is symmetric and discontinuous, and watching a beam settle is continuous and asymmetric. Carried by *Physics Is Not Math*, chapter 2, section II, "Four Characters" ("The content changes though the context has not"). Exact form, as that section gives it: continuity is a sameness of content where there is a sameness of context; symmetry is a sameness of content where there is a difference of context; discontinuity is a difference of content where there is a sameness of context; asymmetry is a difference of content where there is a difference of context. The box of weights and the settling beam are this book's pictures.

A change of setting too small for any comparison to register is, for that comparison, no change of setting at all; so perfect continuity says that where the setting is the same, what is found is the same. Carried by *Physics Is Not Math*, chapter 2, section II, where a sameness of context includes settings "so close together that no difference between them is found".

A comparison perfected at its foundation in symmetry and continuity together would find "same" whatever the setting, at every moment and in either pan (the two pans being two places in the setting), and one perfected in asymmetry and discontinuity together, by the same reasoning with "same" and "different" exchanged, would find "different" always; since sameness and difference come together in every comparison, both of those pairings fail, and two kinds survive, continuous and asymmetric or symmetric and discontinuous, with no third. Carried by *Physics Is Not Math*, chapter 2, section III, "Ten Ways to Pair Them", section IV, "Three Tests" (of continuity with symmetry, both perfected: "Sameness of content appears twice, and difference of content not at all"), and section V, "The Two That Survive"; and, as a restatement in plain words, by *Home in the World*, chapter 4, "The Circle and the Floor", section "Two Cannot Both Be Perfect". Exact count: four characters can be paired in ten ways (four pairings of a character with itself, and six pairings of two different characters); three tests are applied to each of the ten.

The Incommensuration Theorem: "Symmetry and continuity cannot both be applied, simultaneously and fundamentally, to any event or comparison; and neither can asymmetry and discontinuity". It is a structural fact about the nature of knowing, and it holds with no condition of any kind. Structural here means that it belongs to the make-up of every act of knowing: every act of knowing is an act of comparison or is built from acts of comparison, and the theorem holds of every comparison. Carried by *Physics Is Not Math*, chapter 2, section VI, "The Theorem", which also defines the two words ("To apply a character fundamentally is to hold it at the foundation of a description, and to apply two simultaneously is to hold both in one and the same comparison"), and says of structure: "the theorem, together with the intrinsics of comparison from which it is built, is inherent in every single act of knowing"; and by chapter 9, "Metaphysics Is the Act", section VI, "Unconditional in the Immanent".

The name comes from an old word: two lengths are incommensurable when no unit, however small, fits a whole number of times into each, as with the side and the diagonal of a square; the theorem names a gap of that kind between two characters, since symmetry and continuity have no common perfection. Carried by *Physics Is Not Math*, chapter 2, section VI ("The diagonal of a square is incommensurable with its side, since their ratio is the square root of two, which no ratio of whole numbers can express"; "symmetry and continuity have no common perfection").

The proof uses nothing but the meanings of sameness, difference, content and context and the inseparability of sameness and difference; no step of it rests on any fact about the physical world; it is settled as a count is settled, by the count itself. Carried by *Physics Is Not Math*, chapter 2, section VII, "Settled as a Count Is Settled", which quotes *Incommensuration; The Theorem and the Three Axioms*, where the full proof stands (chapter 6, "The Incommensuration Theorem: Statement and Proof").

The theorem applies to every measurement that physics has made or will make, and every challenge to it is itself a comparison. Carried by *Physics Is Not Math*, chapter 2, section VII.

The theorem forbids symmetry and continuity both perfected at the foundation of one and the same comparison; it allows them together where they hold nearly, as on a ripple, and where they are kept apart by level, by phase or by scope, so that the mathematics of a theory, which is written down as structure and is no finding, can carry together what its findings never show together, since the theorem concerns what a comparison finds; these are statements of what the theorem is about, and none of them is a condition on whether it holds. Carried by *Physics Is Not Math*, chapter 2, section IX, "What the Theorem Allows", which quotes *Incommensuration* ("because a physical theory has two levels, its mathematics and its findings, and the theorem concerns what a comparison finds"), and chapter 9, section VI, "Unconditional in the Immanent".

This account establishes that the world that comparisons find is not a mathematical structure: a mathematical structure can be smooth and perfectly symmetric at once, like the circle of geometry, and no comparison ever finds a thing that is both. Carried by *Side by Side*, Volume Two, "The Structure and the Act", section III, "The Step at Which They Part" ("A mathematical structure can be smooth and perfectly symmetric at once, like the circle of geometry; no comparison ever finds a thing that is both").

Mathematics can write the circle down because its frame leaves out the one who compares: a theorem names no one who proves it, no place where it is proved and no moment at which it is checked, and its objects do not change; the number 31 is not on its way to becoming 32. Carried by *Physics Is Not Math*, chapter 2, section IX, "What the Theorem Allows" ("its frame has set aside the stance from which every comparison is made"); chapter 3, "Truth Has a Frame", section VII, "Mathematics Works as if Only the Objective Existed"; and chapter 6, section II, "Objects That Do Not Change".

"In a domain from which temporal comparison is removed, symmetry and continuity can be written down together". Carried by *Incommensuration; The Theorem and the Three Axioms*, chapter 6, "The Incommensuration Theorem: Statement and Proof", section XIII, "Scope".

Every mathematical structure, smooth or jagged in its parts, taken as a whole is laid out at once and is the same in every instance, so it holds perfect sameness and gapless completeness together, which no act of comparison can hold; so the world that comparisons find, the only world physics has, is not a mathematical structure, and a mathematical description of it, however exact, is never complete. Carried by *Side by Side*, Volume Two, "The Structure and the Act", section III ("the circle shows it, and a structure that is discrete and irregular in its parts is no exception"; "So the world that comparisons find, the only world physics has, is not a mathematical structure, and a mathematical description of it, however exact, is never complete"). The staircase drawn on a page, jagged in its parts and whole as a drawing, is this book's picture of that sentence.

To exist is to stand as structure: timeless, the same in every instance, able to be held in view as a whole; to be real is to be given in an actual act of comparison: here, now, with the future still open; a law exists, and a measurement is real; every physical theory has both, its mathematics, which exists, and its findings, which are real. Carried by *Home in the World*, "For the Specialist", section "Exists and Real; Causation and Determinism", whose words are: "To exist is to stand as structure: timeless, the same in every instance, able to be held in view as a whole"; "To be real is to be given in an actual act of comparison: here, now, with the future still open"; "The mathematics of a physical theory exists; its findings are real". The same two glosses, in the chapter's plain form, stand in chapter 8, "The Bottle, the Note and the Living", section "What "Exists" Means"; the sentence "A law exists; a measurement is real" stands in *Comparison; The Necessary Basis*, chapter 10, "Reasoning", section II, "The Real and the Abstract".

Tegmark's argument has two steps: that there is a world which does not depend on human beings, and that this world is a mathematical structure; this account agrees with the first step and parts from him at the second. Carried by *Side by Side*, Volume Two, "The Structure and the Act", section II, "The Ground the Two Share" ("The collection agrees with the first half of Tegmark's argument, the External Reality Hypothesis, read

plainly: the world does not depend on human beings"), and section III, "The Step at Which They Part" ("The collection denies the second half of Tegmark's argument, the Mathematical Universe Hypothesis that the world is a mathematical structure").

Hossenfelder's example of a consistent theory that describes nothing we see, a universe that is "a perfect, empty, two-dimensional sphere", is a universe no comparison could find, since a perfect sphere is smooth and the same under every turn, both exactly; the claim that the world is mathematics, which she leaves outside what science can decide, this account excludes by that argument about what any comparison can find. Carried by the theorem's entry above and by *Side by Side*, Volume Two, "The Structure and the Act", section III; the application to her sphere is this book's own (her example: *Existential Physics*, chapter 7, section "Will We Ever Know It All?").

Mathematics is timeless, and *Physics Is Not Math* calls it the science of the timeless; what is timeless is laid out by acts, in sequence, in the world: the curve of a falling stone on a page was drawn by someone, from measurements made by comparing. Carried by *Physics Is Not Math*, chapter 6, section II, "Objects That Do Not Change", and chapter 11, section III, "One Source" ("The curve of the falling stone was drawn by someone, from measurements made by comparing").

The theorem about acts of comparison is held in every act: every attempt to doubt it is a comparison, and so uses it. Carried by *Physics Is Not Math*, chapter 9, section III, "Three Ways a Claim Can Be Held", and section IV, "The Theorem Is Held in the Act" ("The Incommensuration Theorem is a performed claim").

Mathematics fits the world for the same reason that it never becomes the world: a physical theory sets its mathematics beside what is found, so the mathematics and the findings are the two things compared in one act of comparison, made of the same parts, sameness and difference and the same four characters. Carried by *Measurement; The Steps from Comparison to Physics*, chapter 14, "The Consequences of the Theorem", section XII,

"Why Mathematics Is Effective in Physics, and Why It Is Never Complete"; and, as a restatement in plain words, by *What Cannot Be*, chapter 20, "What Physics Cannot Reach", section "Why Mathematics Works in Physics, and Why It Is Never Complete".

The number π stands for the symmetry of turning, and it appears wherever that symmetry does, in a spread of errors over two directions that can be exchanged for each other as much as in a circle. Carried by *What Cannot Be*, chapter 20, section "Why Mathematics Works in Physics, and Why It Is Never Complete". Exact form: the bell curve of errors in one variable x, the density $e^{-x^2/2}/\sqrt{(2\pi)}$, has the constant $\sqrt{(2\pi)}$ because the square of the integral of $e^{-x^2/2}$ over all x is an integral over the plane of $e^{-(x^2+y^2)/2}$, a function unchanged by turning about the origin; written in polar coordinates (distance r and angle θ from the origin) that integral is $2\pi \times 1 = 2\pi$. The round cloud of darts is a standard theorem, which the chapter states in words: if the misses in two perpendicular directions are independent of each other and have the same spread, the joint spread is unchanged by every turn about the mark exactly when each is the bell curve centered on the mark. It was given by J. F. W. Herschel in his review of Quetelet's letters on the theory of probabilities, *Edinburgh Review* 92 (July 1850), 1 to 57, and by J. C. Maxwell, "Illustrations of the Dynamical Theory of Gases", *Philosophical Magazine* 19 (1860), 19 to 32. The integral and the theorem of the round cloud are standard mathematics, not claims of this account.

The theory of the electron and the laboratory agree on the strength of the electron's magnetism to about one part in a trillion. Carried by *What Cannot Be*, chapter 20, section "The Standard Model as Inherited Code" and section "Why Mathematics Works in Physics, and Why It Is Never Complete", citing the measurement of Fan, Myers, Sukra and Gabrielse (2023). That figure is measured.

Findings come in the two kinds that survive the theorem, each with two of the four characters: the countable kind is symmetric and discontinuous, coming in steps, each exactly like the last; the smooth kind is continuous and asymmetric, with no gaps, differing from moment to mo-

ment; mathematics has structures of both kinds, and for findings of either kind there is a mathematics of the other kind, smooth mathematics for countable findings and symmetric mathematics for smooth findings; that mathematics comes as close to each finding as anyone likes and never covers all the findings, since a mathematics that matched its findings exactly would perfect symmetry and continuity together, which the Incommensuration Theorem forbids; "The power of the description and its incompleteness come from one source, and neither can be had without the other". *What Cannot Be*'s own words for the pairing are "smooth mathematics for countable findings, symmetric mathematics for a smooth setting" and "for findings of either character it has a mathematics of the opposite character"; there "character" names a kind's pair of characters, so the chapter's "a mathematics of the other kind" and its "for smooth findings" state the same claim. Carried by *Measurement; The Steps from Comparison to Physics*, chapter 14, section XII, and, as a restatement in plain words, by *What Cannot Be*, chapter 20, section "Why Mathematics Works in Physics, and Why It Is Never Complete".

The world is under no obligation to the instrument. Carried by *Side by Side*, Volume One, "What Beauty Cannot Decide", section II.

Chapter Three: Why Did the New Particles Not Appear?

On 4 July 2012 ATLAS and CMS each reported a new particle, and in their full reports, published later that year, ATLAS measured its mass as 126.0 billion electron volts and CMS as 125.3. Carried by the two discovery papers: ATLAS Collaboration, "Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC", *Physics Letters B* 716 (2012), 1 to 29; and CMS Collaboration, "Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC", *Physics Letters B* 716 (2012), 30 to 61. The masses that ATLAS and CMS reported are measured values. I give the standing of the Higgs mass in this account further on, under the Higgs field.

The content of a comparison is what its verdict is about, and its context is the respect in which the two things compared are two. Carried by *Physics Is Not Math*, Appendix C, "Glossary", entries "Content" and "Context"; and by *Home in the World*, chapter 4, "The Circle and the Floor", section "Six Parts of Every Comparison".

The content and the context of one comparison cannot be one respect, since a verdict fixed in advance is no verdict. Carried by *Comparison; The Necessary Basis*, chapter 4, "The Six Intrinsics of Comparison", Summary of Part One, Key Concepts; and by *Home in the World*, chapter 4, section "Six Parts of Every Comparison".

In physics, the content is quantum matter, a name that here takes in every particle found within space and time, light included, with its charges and its fields (at the scale of single particles, which the next entry takes up, the content is the fermions alone and the context is the bosons, the carriers of force, so that there Hossenfelder's two families divide as content and context); in physics the context is the arena that quantum matter is found in, space and time, together with the setting of possibility: the range of states in which a thing could be found. Carried by *Side by Side*, Volume One, "Terms of the Collection", entry "Content and context" ("in physics, quantum matter and the geometry of general relativity"); by *The Story of the Particles*, Level 0, "The Three Carriers", section II, "The Comparing Act" ("every field this book names, light included, is content in a wider sense: something found within the arena"); by *The Alphabet of Particles*, "How to Read the Alphabet", section II, "The Structure the Derivation Starts From", for the first of its three scales, the scale of single particles ("It acts at three scales. At the first, content is matter (the fermions) and context is the carriers of force (the bosons)"); and, for the setting of possibility, by *The Story of the Particles*, Overture, "The Scientists", section III, "What Comparison Requires" ("space, time and possibility, which are its context"), and *The Weight of Possibility*, chapter 1, "The Question and Its Ground", section III, "What This Book Takes from the Passage, and What It Does Not" ("The internal space is content relative to the open dimensions, and context relative to what is found in it").

At the scale of single particles the line between content and context falls a second time, inside that wider content: the particles of matter are content, and the carriers of force, light among them, are context, since a carrier of the act of comparing is not one of the things compared. Carried by *The Story of the Particles*, Level 0, "The Three Carriers", section II, "The Comparing Act": "The act of comparing is not one of the things compared; it belongs with the framework within which comparison takes place, which is context"; "content means the separated instances of matter and context means the carriers of the act"; "Within the arena of space and time, every field this book names, light included, is content in a wider sense"; "The partition at the first scale is a partition inside that wider content". The beam of the balance, which carries the pull of one pan to the other, is in neither pan and is part of the setting, is this book's picture of the carrier.

The Incommensuration Theorem: "Symmetry and continuity cannot both be applied, simultaneously and fundamentally, to any event or comparison; and neither can asymmetry and discontinuity". It is a structural fact about the nature of knowing; a comparison held perfectly at its foundation takes one of two forms, and only two: symmetric and in steps, or continuous and uneven. In every actual comparison, content and context each lean toward one of those two forms: content toward the symmetric form in steps, and context toward the continuous and uneven form. Carried by *Side by Side*, Volume One, "Terms of the Collection", entry "Incommensuration Theorem"; and by *The Alphabet of Particles*, "How to Read the Alphabet", section II, "The Structure the Derivation Starts From" ("any comparison, perfected at its foundation, is either continuously asymmetric or discontinuously symmetric"; "Comparison therefore divides into a content pole, which is symmetric and quantized (coming only in whole, separate steps), and a context pole, which is continuous and asymmetric"), where a pole is one of the two ends of the division.

Content leans toward the symmetric form in steps: two pieces of content of one kind in one state would be one piece, which is why two electrons cannot share one state; context leans toward the continuous form:

carriers of force in one state add to one another, which is why any number of particles of light can share one state. Carried by *Non-Commutative Geometry and the Immanent Metaphysics*, chapter 19, "The Particle Content", section III, "The Two Statistics", Postulate P-Id: "Two instances of content in one state are one instance"; "Two contributions of context in one state are one contribution of twice the amount"; with the premise it quotes from *An Immanent Metaphysics*, aphorism 1.46-12 ("Content is local and interexclusionary, and understood in terms of symmetry ... Context is non-local and intercompositional, and understood in terms of continuity"). Exact form: in the n-fold product $V^{\otimes n}$ of a one-particle space V, the content clause is the projection onto the antisymmetric part, which sends every product with two equal factors to zero, and the context clause is the symmetric part, which contains every product $\psi \otimes \cdots \otimes \psi$ of one state with itself.

Content, taken to perfection, is symmetric and comes in steps, and context, taken to perfection, is continuous and uneven; the division of comparison into these two poles is the partition between content and context, and the Incommensuration Theorem asserts it. Carried by *The Alphabet of Particles*, "How to Read the Alphabet", section II ("Comparison therefore divides into a content pole, which is symmetric and quantized"; "This division is the content/context partition"); and by *The Story of the Particles*, Level 9, "The Composites and the Boundary", section IV, "What the Zoo Does Not Contain".

Heavier composites of the known kinds wait at higher energies; a new kind is not on the list. Carried by *The Story of the Particles*, Coda, "What the Scientists Learned", section II, "The Two Surprises" ("What has no continuation is the list of kinds").

The closed list of kinds is the kinds of the standard model, with a right-handed neutrino in each generation, and no others; the right-handed part lets the neutrino carry its small mass. Carried by *Side by Side*, Volume One, Appendix I, "The Registered Predictions Beside Sabine Hossenfeld-

er", Terms, entry "Closed list of kinds"; and, for the neutrino mass, by Appendix B, "The Sealed Record", Prediction 32 ("Every neutrino mass is a Dirac mass, joining two components of one state").

Every comparison has three positions: the thing compared, the thing it is compared against, and the act of comparing; the strong force belongs to the position of the thing compared, the weak force to the position of the thing compared against, and the third force, met at everyday energies as electricity and magnetism, to the act; every particle of matter stands toward both compared positions at once, and from each position the force of that position either acts on it or leaves it alone. Carried by *The Particular Evidence*, Glossary ("The three positions of comparison: the act of comparing (immanent), the thing compared (omniscient), and the thing compared against (transcendent)"; among the forces, "the force on the phase (met at low energy as electromagnetism), the strong force and the weak force"), and Case 15, "Is That All?", section IV, "With the Story in Hand" ("every state of matter stands toward the two conjugate positions, the thing compared and the thing compared against, and the algebra acts on it from each direction. Toward one, a state carries the doublet or not; toward the other, color or not").

Each force has its position by what it acts on, its label, the property of a particle that the force acts on; color, the physicists' name for three states a quark can be in, among which the strong force turns it, carries the mark of the thing compared: the three colors stand for the three positions of comparison, held together inside the content and available at once, a pattern held whole in view; each quark carries one of the three colors, and in a baryon, a particle of three quarks such as the proton or the neutron, one quark sits at each position; the doublet carries the mark of the thing compared against: it has one side that faces the act of comparing and one that does not present itself to it, and what the act reaches toward without containing is that mark. Carried by *The Kinds of Particle*, chapter 4, "The Gauge Factors", section III, "The Three Rows", Premise 2 ("A force and the label it acts on stand at one position: the binding of each force to its modality follows from what it acts on"), and section VI, "Three Colors"

("The three colors are the labels of the three positions of comparison held inside the content"; "one quark sits at each position in a baryon"); and by *The Spectral Chain*, chapter 2, "The Modalities, the Intrinsics and the Three Forces", section IV, "One Force for Each Position" ("color is the whole pattern of comparison held inside content, the three positions together, available at once, and the omniscient position is the thing fully available to knowing, the pattern held whole in view"; that each quark carries one of the three colors, after *The Story of the Particles*, Level 6, section III; and, after *The Story of the Particles*, Level 7, section III, "every doublet has a side that faces the comparing act and a side that does not present itself to it"), and its Summary, where in the frame of measurement each force is "placed by what it acts on". The pear held whole in the pan and the weights standing for a standard the weighing reaches toward and does not hold in the pan are this book's picture of the two marks.

Each state of matter carries the doublet of the weak force or not, and color or not, and carries the phase toward both; that gives four kinds of matter and no fifth: left-handed up and down quarks in three colors, $2 \times 3 = 6$ fields; right-handed up and down quarks in three colors, $2 \times 3 = 6$; the left-handed electron and neutrino, 2; the right-handed electron and the right-handed neutrino, 2; sixteen fields in each generation, all occupied. Carried by *The Particular Evidence*, Case 15, "Is That All?", section IV, "With the Story in Hand", in three steps. First, a fact of mathematics: the finite-dimensional algebras that can serve as an algebra of observables are sums of matrix algebras over the real numbers, the complex numbers and the quaternions only (Frobenius; Artin and Wedderburn). Second, a selection: the three forces must carry $1 + 3 + 8 = 12$ transformations (one on the phase, three between the two sides of the doublet, eight among the colors), and the algebra that supplies exactly these is $\mathbb{C} \oplus \mathbb{H} \oplus \mathrm{M}_3(\mathbb{C})$, that is, the complex numbers $\mathbb{C}$, the quaternions $\mathbb{H}$ and the three-by-three complex matrices $\mathrm{M}_3(\mathbb{C})$, with the count $1 + 3 + 9 - 1 = 12$ once every overall phase is tied to the unit's. Third, a count: the doublet acts toward one term of the comparison only, color toward the other only, and the

phase toward both, which gives the four kinds (doublet with color, the left-handed quarks; color alone, the right-handed quarks; doublet alone, the left-handed leptons; neither, the right-handed electron and the right-handed neutrino), sixteen fields in a generation when colors and sides are counted.

Every particle ever observed belongs to a kind on the list, and the Large Hadron Collider found the Higgs boson that the structure requires, and no new kind. Carried by *The Grand Synthesis*, chapter 13, "The Cosmological Constant and the Completeness of the Kinds", section III, "The Completeness of the Kinds".

The account fixes the Higgs field and its properties, and the field's mass is measured. Carried by *The Particular Evidence*, Case 14, "The Last Field", section IV, "With the Story in Hand". The standings of the Higgs values, exactly as the books of this account give them: the Higgs self-coupling of one eighth at tree level is "derived given a stated identification" (*Side by Side*, Volume One, Appendix B, Prediction 42); the Higgs mass of 125.17 GeV (giga-electron-volts) is a measured agreement, "a value the account reaches that measurement finds, and it carries the question of why it lands" (*The Spectral Chain*, chapter 1, "The Axioms and the Standings", section V, "The Six Standings"; *Why These Numbers*, chapter 18, "The Higgs Mass, the Top's Readings, and What Measurement Supplies", section "The Higgs Mass beyond Tree Level"); and *Non-Commutative Geometry and the Immanent Metaphysics* "derives no value of the Higgs mass" (chapter 15, "The Standard Model Parameters", section IV, "The Higgs Mass").

The particles naturalness called for were absent because the structure of comparison has no slot for them. Carried by *Side by Side*, Volume One, "What Beauty Cannot Decide", section II, "Where She Is Right: Beauty Is No Evidence".

Each of the leading proposals for new particles at the collider assumed that the known particles are part of a longer list, and the list is whole. Carried by *The Grand Synthesis*, chapter 13, section III, "The Completeness of

the Kinds", which names four proposals (supersymmetry, extra dimensions with Kaluza–Klein resonances, composite Higgs models, technicolor) and says that "each proposal assumed that the particle content of the Standard Model is a subset of a larger list of kinds, and the list of kinds is whole". The chapter's three (partners; extra dimensions; new strong forces) are those four in plain words, composite Higgs models and technicolor being the new strong forces.

Hossenfelder's statement, that particle physicists "have no reliable prediction that there should be anything new to find" until about fifteen orders of magnitude above the energies now within reach, and this account's, that there is no new kind to be found, agree on every search at the energies within reach. Her statement is from her opinion piece "The Uncertain Future of Particle Physics", *The New York Times*, 23 January 2019, not from her two books ("To date, particle physicists have no reliable prediction that there should be anything new to find until about 15 orders of magnitude above the currently accessible energies"). Carried by *Side by Side*, Volume One, Appendix I, section III, "Where the Two Accounts Agree", entry "Hossenfelder 2. No new kind at the next collider", which cites the same piece ("Hossenfelder 2019, The New York Times; Lost in Math, 2018").

There is no supersymmetric partner at all: a supersymmetry by definition carries every field of content to a field of context, and the Incommensuration Theorem forbids that exchange, since it would perfect symmetry across the partition between content and context. Carried by *The Story of the Particles*, Level 9, section IV, "What the Zoo Does Not Contain" ("There is no supersymmetric partner"); by *Non-Commutative Geometry and the Immanent Metaphysics*, chapter 19, section IV ("The reason from comparison is that a supersymmetry would carry the content pole onto the context pole and so perfect symmetry across the one partition on which the Incommensuration Theorem forbids it"); and, as a restatement in plain words, by *Why These Numbers*, chapter 2, "What There Is, and Why It Is Built So", section "What Has No Place Among the Kinds". The change of sign the chapter pictures is the standard statement of the two statistics: ex-

changing two identical particles of matter multiplies their joint state by -1, and exchanging two identical carriers multiplies it by $+1$ (*Non-Commutative Geometry and the Immanent Metaphysics*, chapter 19, section III, "The Two Statistics").

Every field that enters the theory is a field of matter, a carrier of force, or the Higgs field, and there is no fourth sort; and the field space of the standard model admits no supersymmetry: the label sets of matter and of the carriers share only two types, and the quarks and the right-handed electron are left unmatched; since the theory holds no other fields, a partner has nowhere to come from, and the two propositions together exclude a partner at any mass. The two common types, in plain words: no label at all, carried by the right-handed part of the neutrino and by the carrier of the third force; and the labels of the left-handed electron and neutrino, carried also by the Higgs field, which comes as a doublet with the same labels. Carried by *Non-Commutative Geometry and the Immanent Metaphysics*, chapter 19, "The Particle Content", section IV, "The Field Space and Its Content": Proposition 19.7(iii), "No field enters the theory that is not a spinor field, a gauge one-form or the Higgs doublet" ("Proposition 19.7(iii) is the statement, on the triple, that there is no fourth"); and Proposition 19.8. The route of this count is separate from the route of *The Story of the Particles*: one starts from a count of labels, the other from the theorem. Exact form: a supersymmetry is a linear map Q on the field space that commutes with the gauge transformations $\mathrm{SU}(\mathrm{A_F})$ of the finite algebra $\mathrm{A_F}$, exchanges the odd (matter) and even (carrier) sectors, and is one-to-one on the odd sector. The types, written (color, weak, hypercharge), are $(3, 2, 1/6)$, $(3, 1, 2/3)$, $(3, 1, -1/3)$, $(1, 2, -1/2)$, $(1, 1, -1)$, $(1, 1, 0)$ and their conjugates in the odd sector, and $(8, 1, 0)$, $(1, 3, 0)$, $(1, 1, 0)$, $(1, 2, \pm 1/2)$ in the even sector. The common types are $(1, 1, 0)$, shared by the right-handed neutrino ν_{R} and the $\mathrm{U}(1)$ gauge field, and $(1, 2, \pm 1/2)$, shared by the lepton doublet and the Higgs doublet; so Q vanishes on the left-handed quark doublet $\mathrm{Q_L}$ and on $\mathrm{u_R}$, $\mathrm{d_R}$ and $\mathrm{e_R}$, the right-handed up quark, down quark and electron, and is not one-to-one.

A turning moves a thing within the structure the thing already carries: a quark carries color and a lepton none, so no turning makes a quark a lepton; no force acts on another force's label; a simple symmetry cannot be split into parts; so no unifying symmetry exists at any energy. Carried by *The Kinds of Particle*, chapter 4, "The Gauge Factors", section I, "The Gauge Group". Exact form: the algebra of a simple Lie group is not a sum of two or more parts that commute with one another, so no simple Lie group is the gauge group at any scale, and no gauge boson joins a quark to a lepton, as the X and Y bosons of a grand unified group would.

The proton is stable: no route to decay exists in the structure; the absence of a carrier that joins quark to lepton is reached by two routes that meet (the symmetry of the state space, a direct product, has no generator acting on both factors; and the gauge group of the finite algebra is a product of its factors at every scale), and the other proposed routes (through hidden extra dimensions, and through rare events of the strong and of the weak force) are closed as well. Carried by *The Branches of the Kinds*, chapter 2, "The Stable Proton", section II, "Baryon Number" ("The proton is stable: no route to decay exists in the structure"); section I, "The Product and Its Consequence" ("The two routes are independent and converge on the same conclusion"); the Chapter Overview, for the other routes (Kaluza–Klein states, the instantons of the strong force, the sphalerons of the weak force); and section V, "What Measurement Says" ("On the content reading, the argument gives a lifetime that is not finite"). Exact value of the past measurement: the Super-Kamiokande Collaboration (A. Takenaka and others, 2020, arXiv:2010.16098) found the partial lifetime of the proton for the decay into a positron and a neutral pion to exceed 2.4×10^{34} years, more than 10^{24} times the present age of the universe.

This account holds that the three forces belong to three distinct positions of comparison, and so they were never one force, at any energy: no single larger force splits into them; the weak force and the third force do mix, light being the one mixture of their carriers that the Higgs field leaves without mass, and that mixing is the joining of the electroweak the-

ory, which makes no larger force from which the three split. Carried by *The Particular Evidence*, Case 12, "The Heavy Messengers", section IV, "With the Story in Hand" ("a structure of three distinct, non-interchangeable positions gives a single broken force no footing"), and section V, "The Confession" ("They were never one force"; the photon "is the one mixture of the phase and the neutral weak carrier that the edge field lets pass"); and by *The Kinds of Particle*, chapter 4, "The Gauge Factors", section I, "The Gauge Group" ("The photon, the carrier of electromagnetism, is the massless combination of the hypercharge boson and the neutral weak boson"). Her words on the electroweak theory, which the chapter quotes, are in *Lost in Math*, chapter 7, "Converging Lines": it "is not a satisfactory unification because it still has two different groups".

The strengths of the three forces, measured at the energies within reach and carried upward by the standard model's own rules for how strengths change with energy, draw close and meet at no energy: they draw close because the three forces are inseparable, and they never become one force because they are distinct. Carried by *The Strengths of the Kinds*, chapter 3, "Where the Couplings Cross", section III, "Where the Crossings Are" ("Run upward with the Standard Model's own rates, the three measured couplings draw close to one another, and they meet at no scale"; "Because the three forces are inseparable, their strengths draw close; because they are distinct, they never become one force"). Exact values: run at three loops from the couplings of the 2024 compilation of the Particle Data Group, the three pairwise crossings lie at 54.259 halvings ($\alpha_1 = \alpha_2$), 58.200 halvings ($\alpha_1 = \alpha_3$) and 65.521 halvings ($\alpha_2 = \alpha_3$) above the electron's mass, where α_1, α_2 and α_3 are the strengths of the force on the phase, the weak force and the strong force, and an energy μ stands at $h = \log_2(\mu/m_e)$ halvings above the electron's mass m_e, so that one halving is one doubling of the energy (same book, chapter 3).

The width of the Z particle counts the light neutrinos: three, and not four. Carried by *The Particular Evidence*, Case 15, section I, "The Mystery: The Silence After the Higgs". Exact value: the count is 2.996, with an uncertainty of 0.007; the sealed record gives $N_\nu = 2.9963 \pm 0.0074$ light neut-

rino species from the invisible width of the Z (Janot and Jadach, 2020), 0.5 standard deviations from three (*Side by Side*, Volume One, Appendix B, section VII, Prediction 31, "Exactly three generations"). The measurement behind it: the collider measured how often Z particles were made at energies around the peak from 1989 to 1995, and P. Janot and S. Jadach, "Improved Bhabha cross section at LEP and the number of light neutrino species" (*Physics Letters B*, 2020; arXiv:1912.02067, December 2019), corrected the calculation of the number of collisions behind those measurements, which removed an earlier tension of two standard deviations with three.

I identify the dark matter with a ringing of the setting itself, a vibration of context: a vibration of the setting of possibility, the range of states in which a thing could be found; in the balance's picture it shows in the result only as extra pull, and it is never a thing set in a pan; it is not matter of any kind on the list of particles. Carried by *The Weight of Possibility*, chapter 1, "The Question and Its Ground", section III, "What This Book Takes from the Passage, and What It Does Not" ("the dark matter is an excitation of possibility as the context of what could be found, and it is not an item of the actual content that measurements register"), and section IV, "The Identification" ("The dark matter is a conserved excitation of the six dimensions of possibility, made at the turn"; "This statement is an identification, and this section gives its argument"; "in role it is a vibration of context"); the entries under Chapter Twelve give its argument.

The three neutrinos of the Z, the empty searches for supersymmetry, the empty detectors of dark matter and the missing graviton are four observations of one fact: the list is complete because the structure it comes from is finite and fully used. Carried by *The Particular Evidence*, Case 15, section IV, "With the Story in Hand".

"Our world's method closes cases by finding things. It has no method for closing a case by showing that nothing more is there". A search can show only that it has not yet found something, and every search run since 1989 has agreed with the count. Carried by *The Particular Evidence*, Case 15, section II, "The Detective Work: What Was Expected", section III, "The Resolution: Not Yet, in Our World", and section IV.

"First the argument. Then the instrument". The argument points the instruments at what the structure leaves to measurement: the masses, the strengths of the forces and the mixings of the known particles, measured ever more finely, and the heavier composites built from them. Carried by *The Story of the Particles*, Overture, "The Scientists", section I, "An Empty World", and Coda, section II, "The Two Surprises" ("What has no continuation is the list of kinds").

This account writes down its predictions, and seals them, before the measurements that will decide them, and then leaves them alone: the sealed record, which Chapter Fourteen explains in full. Carried by *Side by Side*, Volume One, "Twenty-Four Models, One Record"; "Terms of the Collection", entry "Sealed record"; and Appendix B, "The Sealed Record". The count of predictions, the date of sealing and the rule of decision are given under Chapter Fourteen below and in Appendix A.

Chapter Four: Do the Unexplained Numbers Need Explaining?

In 1885 Johann Balmer found a rule that gives the four visible lines of hydrogen, and the rule gives, for the next whole number, a fifth line that had already been observed. Carried by *Physics Is Not Math*, chapter 13, "A Value That Lands", section III, "A Formula Waiting for Its Reason". Exact form: the wavelength λ of a line is $\lambda = 364.56 \text{ nm} \times n^2/(n^2 - 4)$, where nm is the nanometer and n a whole number; n = 3, 4, 5 and 6 give 656.2, 486.1, 434.0 and 410.1 nm, and n = 7 gives 397.0 nm.

Bohr's account of 1913 made the lines the drops of the electron from the third, fourth, fifth and sixth levels to the second, so that the four in Balmer's rule is two squared, and it gave Balmer's constant from the electron's charge and mass, the speed of light and Planck's constant. Carried by *Physics Is Not Math*, chapter 13, section III. *Physics Is Not Math* states the relation in words; in the standard notation it is $364.56 \text{ nm} = 4/R_H$, where R_H is the Rydberg constant of hydrogen, which Bohr's account computes from the electron's charge e, its mass m_e, the speed of light c and Planck's constant h.

This account reaches the result Hossenfelder reaches about fine-tuning: only a reason, once found, explains an agreement of numbers, and the account never counts the agreement, by itself, as evidence for any particular reason, such as a new particle. Carried by *Side by Side*, Volume One, "What Beauty Cannot Decide", section III, "What the Collection Puts in Place of Beauty" ("The collection agrees that an agreement of numbers is not, by itself, an explanation, and the collection never counts such an agreement as evidence for any particular reason").

The account takes every number at the size that the structure, a stated step or a measurement gives it, and gives no number a natural size that it ought to have had; a number that is measured is said to be measured. Carried by *Side by Side*, Volume One, "What Beauty Cannot Decide", section III.

Every number carries a stated standing, a statement of where the number comes from: from the structure of comparison, from that structure with one stated step, from measurement, or from the account and measurement both; *Why These Numbers* groups the standings into four, each with its own picture (set by the structure; set by the structure once a stated step is taken; measured; and reached by the account and found by measurement, with the reason it lands still a question), and none of the standings is a degree of being sure. Carried by *Why These Numbers*, chapter 1, "Numbers Physics Cannot Explain", section "Four Ways a Number Can Stand" ("There are four standings, and each has its own picture"; "The standings are different relations between a number and the world, and not degrees of confidence"). *The Spectral Chain*, chapter 1, "The Axioms and the Standings", section V, "The Six Standings", divides the same ground more finely into six: measured input, structural value, derived, derived given a stated premise or identification, measured agreement, and fork. *Why These Numbers* is the plain-words restatement of *The Spectral Chain* and of the companion books of *The Spectral Chain*, so *Why These Numbers* is not a second route. The chessboard, the surveyor's deed, the tailor's pattern and the two clocks are this book's pictures.

A measured agreement is a value the account reaches that measurement finds, with the reason it lands still a question. Carried by *The Spectral Chain*, chapter 1, section V, "The Six Standings": "A measured agreement is a value the account reaches that measurement finds, and it carries the question of why it lands".

Among the particles there are twenty-six numbers to account for (nineteen in the standard model, and seven more for the neutrinos), and each carries one standing. Carried by *The Spectral Chain*, chapter 1, section V, Table 3; and by *Why These Numbers*, chapter 1, section "Counting the Numbers". Exact count: $9 + 3 + 1 + 3 + 2 + 1 = 19$ numbers in the standard model as first written, and $19 + 7 = 26$ with the neutrino masses and mixings.

No step in the account rests on a probability distribution over the constants, or on any sense of what size a number should have. Carried by *Side by Side*, Volume One, Appendix I, "The Registered Predictions Beside Sabine Hossenfelder", section VI, "What the Collection Does Not Predict Here": "the values carry a stated standing, derived or measured, and none rests on an expectation of their natural size".

A value that lands is a number that agrees with measurement before anyone knows why; it is a question, "why does it land?", and it is evidence of a reason not yet known, before anyone knows which reason it is; the agreement is explained once that reason is found. Carried by *Physics Is Not Math*, chapter 13, "A Value That Lands", opening and section IV, "A Value That Lands Is a Question"; the question "why does it land?" is section II, "Why Does It Land?".

Balmer's whole numbers and his square of two pointed to something in the atom that comes in whole steps; the equality of the two kinds of mass pointed Einstein to his theory of gravity. Carried by *Physics Is Not Math*, chapter 13, section I, "Two Kinds of Mass", section II, and section IV. Exact form: a body's inertial mass and its gravitational mass are in the same proportion in every body measured, and in the usual units that proportion is 1.

A value is fitted when someone chose it to match, as a dial is turned until the needle points where it should; then the match has a reason, the turning of the dial, and a question stays, why the world needs the dial at that position; Balmer chose the form of his rule and one number, 364.56, by looking at four lines; he did not choose that so simple a rule gives all four as closely as they were measured, and then the fifth, and that agreement landed. Carried by *Physics Is Not Math*, chapter 13, section IV.

The label "coincidence" says that an agreement has no reason, which no one has shown; what anyone has shown of such an agreement, before its reason is found, is only that no reason is yet known; held as a question, Balmer's rule became a door into quantum theory. Carried by *Physics Is Not Math*, chapter 13, section V, "A Grade Closes; a Question Opens".

Hossenfelder and this account each reject a verdict reached before the reason is found: she rejects the verdict that a number needs a new explanation because it looks unlikely, and this account rejects the verdict that an agreement is a coincidence. Carried by *Side by Side*, Volume One, "What Beauty Cannot Decide", section III.

The account holds that every pure number among the particles has a reason, whether or not the reason is yet found, and the reason is one of two things, a law that fixes the number or a proof that no law fixes it; the account's target for each such number is one of those two ends (after a proof that no law fixes it, the number is taken once from measurement); the strength of light is a number of the second kind: an argument shows that no law fixes it, and its value is read once from measurement; some numbers have reached their end already, and each number not yet at either end carries the question that settles it. Carried by *The Strengths of the Kinds*, chapter 1, "What Is Measured", section VI, "Why the Strength of Light Stays Measured" ("This book also holds that no pure number among the particles is a brute constant (a number with no reason). Every pure number not yet derived carries the question that settles it: the law that fixes it, or the proof that no law does"; "What remains of a pure number after the unit, the setting and the history are removed is fixed by its law, or it is shown independent of comparison, as α_{em} is", where α_{em} is

the strength of light). The same section states the scope of that result for the strength of light: "The independence of α_{em} is thus derived for the comparisons the argument examined, with the circle's rule as its stated hypothesis"; "No concept or set of concepts fixes the value of α_{em}; its independence is derived for the comparisons the argument examined, under the circle's rule"; and the step that carries it is "that the comparison structure is the same at every value of α_{em}". Also carried, as a restatement in plain words, by *Why These Numbers*, chapter 1, section "Two Ends for Every Number" ("Every number of the Standard Model is to reach one of two such ends").

Symmetry is a sameness of content where there is a difference of context, and asymmetry belongs to context; the context of a measurement has three measures, space, time and possibility: the arena holds the first two, and the setting of possibility, the range of states in which a thing could be found, is the third; each reversal is a difference of one of them (P reverses space, T time, and C possibility, because swapping a particle for its antiparticle reflects the range of states it could be found in, every charge it could be found with turning to its opposite); so a force can break a reversal by its own form only if its act carries a state of matter across, from the content into the context and back; the weak force's act, which turns a particle across its doublet, does, and so it cannot treat a state and its mirror image alike; the weak force is the one force whose own form breaks a reversal: its form breaks P and C, each taken alone, and keeps CP, the two taken together, and T; the difference between a process and its mirror image with matter swapped for antimatter that some weak decays show comes from one further angle in the mixing of the quarks, beside the mixing angles, which the mixing of the quarks can carry only because the quarks come in three generations, and without which the weak force would treat the two alike; the strong force's act, which turns a quark among its three color states, keeps every state in the content. Carried by *The Branches of the Kinds*, chapter 3, "The Discrete Symmetries", Rule 1 ("the weak way keeps T"), Rule 2 ("for the weak way, C and P"), Rule 3 ("Only the weak way breaks a reversal by its form; color and the phase

row break none by their form") and Box 3.3, "The premise of Rule 3" ("Each reversal is a difference of one context measure: T reverses time, P space, C possibility"; "Asymmetry belongs to context; so a form can be asymmetric only if its act involves the context pole, which is to carry a state across the content-to-context partition"; "The weak way's form keeps T and CP"; "The one phase of the quark mixing that three generations allow is how that remaining possibility is realized"; "with no complex phase in the quark mass matrices, or with fewer than three generations, the electroweak couplings conserve CP"), where the further angle in the mixing of the quarks is "the CKM phase, the irremovable phase of the quark mixing matrix of Cabibbo, Kobayashi and Maskawa", a different angle from the quarks' phase, the part of the measured angle that the masses of the quarks carry, and from the phase the third force turns; by *The Spectral Chain*, chapter 2, "The Modalities, the Intrinsics and the Three Forces", section IV, "One Force for Each Position" ("a transformation across the doublet carries a state from the content pole, which is symmetric, to the context pole, which is not, and back"); by *The Story of the Particles*, Level 4, section II, which gives the reason for C ("C reverses possibility, the measure of context, because it reflects the internal space in which a particle's possible states lie"), with the six measures of a measurement in the Overture, section III; and by *The Last Turtle*, "The Three Boundaries of Knowing", section VII, "How the Constants Join the Measures" ("The measures of context are space, time and possibility"). That an antiparticle carries each charge of its particle with the opposite sign is standard physics. The weighing seen in a mirror is this book's picture of symmetry of content.

The strong force's own angle is zero, and the reason is the structure of comparison: the strong force moves a pattern among its own positions and carries nothing across to the context; the law of symmetry applies to all that is content; and CP violation, the different treatment of a process and its mirror image with matter swapped for antimatter, is an asymmetry, which belongs to context. Carried by *The Branches of the Kinds*,

chapter 3, section V, "The Strong CP Angle", Box 3.6 ("CP violation is an asymmetry, and asymmetry belongs to context"). Exact form: $\theta_{\text{bare}} = 0$, where θ_{bare} is the coefficient of the topological term of the color field.

A second argument starts from the rules by which the strong force's turnings combine (the algebra of the strong force): the part of the force that could tell a process from its mirror image with matter swapped for antimatter is closed on itself, its turnings combined give only turnings of that part, and they carry nothing of it into the rest of the force, so no effect that tells a process from its mirror image with matter swapped for antimatter can pass from that part to the rest of the force; the two arguments are independent and meet on one result: the strong force keeps CP "not by fine-tuning or by accident, but by the architecture of comparison itself". Carried by *The Geometric Route*, chapter 29, "The Real Structure of the Color Algebra", section IV, "The Physical Meaning of the Division" ("This self-containment is what prevents the CP-odd sector from coupling to the CP-even sector at the algebraic level"), and section VI, "Two Routes to One Conclusion" ("a closed subalgebra with no mechanism for amplifying or communicating CP-odd effects to the rest of the color force"; "The two arguments are independent, they are complementary, and they converge on the same structural conclusion"), with the scope of its identification in section V, "The Standing of the Identification" ("The J-splitting alone does not derive $\theta = 0$": the zero of the force's own angle is the first argument's). The two routes are therefore *The Branches of the Kinds*, chapter 3, from the partition of content and context, and *The Geometric Route*, chapter 29, from the real structure of the color algebra.

The measured angle is the strong force's own angle plus the quarks' phase, an angle that the masses of the quarks carry (a different angle from the further angle in the mixing of the quarks that some weak decays show, and from the phase that the third force turns); the structure fixes the first at zero and does not fix the second. The phase has two values at which the strong force would treat a process and its mirror image with matter swapped for antimatter alike, zero and a half turn, and which of the two it takes comes from the signs of the quark masses: in the working of *The*

Measures of the Kinds each mass is a number with a sign, measurement finds the size of each mass, the sign enters only the quarks' phase, and each minus sign adds a half turn to it; I take the quark masses as that book's ladder takes them, with one minus sign among the three quarks with charge plus two thirds and one among the three quarks with charge minus one third, so the two half turns make one whole turn and the phase is zero; zero, and not a half turn, is also the value that measurement supports. That the phase lands on zero is a measured agreement: the account reaches zero through the ladder's two minus signs, and measurement finds it; its question is: why do the quark masses add no angle to the strong force's own angle, whose zero the structure sets? Carried by *The Branches of the Kinds*, chapter 3, section V, Box 3.7, "The measured angle" ("That phase is carried as zero, a measured agreement"); by *The Geometric Route*, chapter 25, "Electric Dipole Moments and the Quark-Mixing Floor", section I, "The Strong CP Question and the Answers Proposed for It" ("The phase from the quark masses is carried as zero, and this is a measured agreement"; "With hermitian mass matrices the determinant of each sector is the product of its real eigenvalues, so arg $\det(M_u M_d)$ is 0 when the number of negative eigenvalues over both sectors is even and π when it is odd. The mass ladder takes the quark mass matrices as hermitian with one negative eigenvalue in each sector, so that $\det(M_u M_d)$ is positive"; "the zero rather than π is the choice that measurement supports"; "The structure fixes the first part of θ; it does not fix the second"); by *The Measures of the Kinds*, chapter 10, "Quark Mixing", section II, "The Cabibbo Angle", Box II-2, premises 2 and 5 ("A Hermitian matrix has real eigenvalues, and its determinant is their product"; "The quark mass matrices of the ladder are Hermitian, and each has one negative eigenvalue, so the product of their determinants is positive"); and by *Why These Numbers*, chapter 1, section "Four Ways a Number Can Stand" ("That phase is carried as zero rather than as a half turn"). A sector, in these quotations, is one of the two sets of three quarks: the up-type quarks, with charge plus two thirds, and the down-type quarks, with charge minus one third; an eigenvalue of a quark mass matrix is one of the signed masses.

Exact form: $\theta = \theta_{bare} + \arg\det(M_u M_d)$, where θ is the measured angle and $\arg\det(M_u M_d)$ is the phase of the determinant of the product of the mass matrices of the up-type quarks, M_u, and of the down-type quarks, M_d.

The structure calls on no axion: the angle it sets is already zero, and the closed list of kinds of particle has no slot for one. Carried by *The Branches of the Kinds*, chapter 3, section V, Box 3.7, and chapter 4, "The Carriers", section III, "What Is Not a Particle", subsection "No axion; no dark-matter species" ("the absence of the axion is a statement about particle content and would hold for any value of the angle"). The history (Peccei and Quinn, 1977; Weinberg and Wilczek, 1978) is carried by *The Alphabet of Particles*, "Names Without an Entry", entry N8, "Axion", subsection "What Was Proposed".

The strong force's whole angle is less than about two ten-billionths of a radian, measured with very slow neutrons at the Paul Scherrer Institute (reported 2020). Carried by *The Branches of the Kinds*, chapter 3, section V, and by *Side by Side*, Volume One, Appendix B, section VII, Prediction 34, "The strong force breaks no reversal; no axion". Exact values: the neutron's electric dipole moment d_n is below 1.8×10^{-26} e cm, where e is the charge of the proton and cm the centimeter (Abel and others, 2020); the angle gives the neutron a dipole moment of order $\theta \times 10^{-16}$ e cm (Baluni, 1979; Crewther, Di Vecchia, Veneziano and Witten, 1979); so θ is below 1.8×10^{-10} radians (one radian is about 57.3 degrees).

The Higgs field comes as a doublet, two sides between which the weak force turns it, and each side carries a number that says which side it is, plus one half for one side and minus one half for the other; the size of that number, one half, is the doublet's half, and it is set by the structure; I identify the self-coupling of the Higgs field with half the square of the doublet's half, so at the first level of calculation, before the loop corrections, the self-coupling is one eighth, derived given that one identification. Carried by *The Spectral Chain*, chapter 1, section V, Table 3 (the standing "derived given a stated identification", as *Side by Side*, Volume One, Appendix B, Prediction 42, also gives it); and, as a restatement in plain

words, by *Why These Numbers*, chapter 17, "The Vacuum Value, the Top and the Higgs", section "The Doublet's Half", and chapter 1, section "Four Ways a Number Can Stand" ("Its step is that the self-coupling is half the square of one half, the number Chapter 17 calls the doublet's half"). Exact form: $\lambda = ½ \times (½)^2 = 1/8$ at tree level, where λ is the Higgs self-coupling and ½ is the doublet's half.

With the loop term added, and with one measured number, the value at which the Higgs field settles in empty space (the vacuum value v), the account reaches a Higgs mass of 125.17 GeV; measurement finds 125.13 GeV, give or take 0.11 (Particle Data Group, current listing, consulted November 2026); the mass is a measured agreement. Carried by *The Spectral Chain*, chapter 1, section V, Table 3 ("the mass with its loop term, 125.17 GeV, is a measured agreement"), and chapter 16, "The Top's Coupling and the Higgs Self-Coupling", section VI, "The Tree Mass" ("with which the Higgs mass computed from the measured v is 125.17 GeV, a measured agreement"). Exact values: *Side by Side*, Volume One, Appendix B, section VIII, "The Values of the Particles", Prediction 42, gives the measured $M_H = 125.13 \pm 0.11$ GeV and four forms of the second order, 125.1715, 125.1888, 125.2064 and 125.2245 GeV, and states that the measured excess of the self-coupling over $1/8$ agrees with $1/(24\pi^2)$.

Non-Commutative Geometry and the Immanent Metaphysics derives no value of the Higgs mass; the value the account reaches comes by the route set out in *The Spectral Chain*. Carried by *Non-Commutative Geometry and the Immanent Metaphysics*, chapter 10, "Classification of Comparison Triples", section I, "The Classification of Chamseddine and Connes", and chapter 15, "The Standard Model Parameters", section IV, "The Higgs Mass". The reason given there: that book's Majorana matrix is zero, so the extra scalar field by which Chamseddine and Connes bring their Higgs mass near 125 GeV does not arise in it.

In 1998 two teams of astronomers, measuring exploding stars of one kind as standard candles, found that the expansion of the universe is speeding up. Carried by *The View from Inside*, chapter 1, "The Emptiest Space Is Not Empty", section "A Strange Discovery".

The energy of empty space is small: about the mass of three or four hydrogen atoms in each cubic meter of space. Carried by *What the Beginning Left Behind*, chapter 8, "The One Edge That Sets the Vacuum", section "The Number, Seen Two Ways". Exact value: about 5.8×10^{-27} kilograms in each cubic meter, measured.

The cosmological constant is no free number: its value rests on steps of mine, each stated in the first person where I make it, and, given those steps, the structure of comparison sets the value together with two measured things, the strength of gravity and the size of the particle horizon, the edge of everything whose light has reached us; the steps are three identifications (the constant with the share that a measurement inside empty space takes in; the channels with the three things a measurement registers; the count of an edge assigned to the particle horizon) and two takings (the first part of the total taken as the Planck density; one tile taken in by each channel). Carried by *What the Beginning Left Behind*, chapter 8, "The One Edge That Sets the Vacuum": section "Measuring Empty Space from Inside" ("I identify the cosmological constant with the share of the vacuum's energy that a measurement inside the vacuum engages, and not with the total"; "I take this part to be the Planck density of Chapter 4"); section "Three Tiles Out of All the Tiles" ("I identify the channels through which the vacuum reaches a measurement with the three contents a measurement registers"; "I take each channel to take in one tile"; "The count of three is set by the structure. The trim is set by the structure. The share itself, three parts out of the count, is an identification: mine, made in the three steps above. The Planck density comes from Newton's constant, the one measured constant on gravity's side. The radius of the particle horizon is measured"); section "Why the Edge of What Has Reached Us" ("So I assign the particle horizon the count of Bekenstein and Hawking, by an identification"); and section "Five Choices, Each with Its Reason", which gives a reason from the account for each of the share's five choices (the edge, the count of channels, the trim, the floor counted inside the Planck density, the full Planck mass): "Every choice in the share is fixed by a reason, so nothing is left to adjust. The share rests

on five choices, and each reason is drawn from the account itself, with no reference to the measured value". Its standing in *The Spectral Chain*, chapter 1, section VII, is "derived given an identification, from a measured S".

A measurement of empty space is made from inside it, by one made of the very fields whose lowest energy is measured, and it receives only a share of their total, as a cup dipped in the sea holds actual sea water and never holds the sea; I identify the cosmological constant with the share of the vacuum energy that a measurement made inside empty space takes in, as distinct from the total. Carried by *What the Beginning Left Behind*, chapter 8, section "Measuring Empty Space from Inside"; by *The View from Inside*, "On the Purpose of This Book" ("I identify the cosmological constant with that share"), chapter 1, section "A Different Kind of Question", and chapter 10, "Why the 10^{123} Never Arises", section "A Cup from the Sea". Exact value: the usual estimate of the total exceeds the measured energy of empty space by a factor of about 10^{123}.

Space and time bend under what comparisons find in them, in proportion to the energy found, so energy that no comparison ever finds bends nothing; and the total, reckoned as a whole (*What the Beginning Left Behind*'s "as it would be found from outside, if there were an outside"), is the same at every place, the same for everyone moving steadily, and without a break, so it would be perfectly symmetric and perfectly continuous, which no comparison finds; so the total bends no space, whatever its size, and the factor of 10^{123} needs no canceling. Carried by *The View from Inside*, chapter 10, section "What Curves Space" ("It bends in proportion to energy, because energy is the rate at which findings can be made"; "What no comparison finds places no strain on the arena, and so bends nothing") and section "The Shape That No Comparison Finds" ("Taken as one whole, it would be perfectly symmetric and perfectly continuous at once"; "So the total curves nothing"); and by *The Grand Synthesis*, chapter 13, "The Cosmological Constant and the Completeness of the Kinds", section I, "The Cosmological Constant", which quotes *The View from Inside*, chapter 10.

The share is found as a count: what a measurement takes in comes in whole pieces, each taken in or not, as a marble is in the cup or not, the same for every comparer, so it is symmetric and comes in steps, the pairing the theorem allows; so the share is found, and the share bends space. Carried by *The View from Inside*, chapter 10, section "The Share and the Total" ("A whole degree of freedom is taken in or it is not, as a marble is in the cup or it is not"; "What is found in countable steps, and is the same for every comparer, is discontinuously symmetric, the stack of coins: one of the two characters the theorem allows").

Our particle horizon now lies about forty-six billion light years away; Jacob Bekenstein and Stephen Hawking found in the 1970s that the edge of a black hole carries a count, one tile for every four squares a Planck length on a side; I assign that same count to the particle horizon, because it bounds everything a present measurement has compared. Carried by *What the Beginning Left Behind*, chapter 8, sections "Edges That Signals Cross One Way", "What the Count of an Edge Counts" and "Why the Edge of What Has Reached Us" ("So I assign the particle horizon the count of Bekenstein and Hawking, by an identification: the bound of what has been compared is the bound of the information available to the comparison"). Exact values: the particle horizon has a radius R of about 46.1 billion light years, and its count is $S = \pi R^2 / l_{Pl}^2 = 2.29 \times 10^{123}$, where l_{Pl} is the Planck length, which the chapter gives in words as about two and three tenths times ten to the power one hundred twenty-three.

The total that is shared has two parts: the energy of all the fields at their lowest, at the smallest scale there is, which I take to be the Planck density, fixed by Newton's constant; and the energy of the curvature of the six small dimensions, which draws space together and takes away three divided by eight pi of the Planck density, about twelve hundredths of it; what remains, a little under nine tenths of the Planck density, is the trimmed total. Carried by *What the Beginning Left Behind*, chapter 8, section "Measuring Empty Space from Inside" ("I take this part to be the Planck density of Chapter 4"; "It takes away three divided by eight pi (eight pi is about twenty-five) of the Planck density, about twelve hundredths of it";

"The trim is set by the structure: the curvature of the six at their derived size fixes it"). Exact form: $f = 1 - 3/(8\pi) = 0.8806$, the trim. The estate shared among heirs after a fixed charge is this book's picture.

The world has six small dimensions besides the three of space and the one of time, the same in size and shape at every place, and their shape fixes what kinds of particle there can be, the closed list of Chapter Three; they differ from the extra dimensions proposed for the collider, which would have added new particles to the list: read as a space of the states of matter, the six have no size, no field lives on them and no tower of new particles forms on them, so they fix the list and add nothing to it. Carried by *The Compactification*, chapter 1, section XI, "Conclusion", and chapter 2, "One Vacuum"; and by *What Comes After the Dark*, chapter 4, section "The Six Small Dimensions"; for the six read as a space of states, by *What the Beginning Left Behind*, chapter 5, "One Vacuum", section "Two Readings, Two Meanings of the Word" ("On the content instance, the six are the space of all the states that the choices of matter can take, and that space has no size"; quoting *The Kinds of Particle*, the internal space "is the product of the carriers' spaces of states: it has no size and no fields live on it"), and by *The Compactification*, chapter 7, "The Gravitational Waves of an Epoch", section III, "The Settling at the Turn as a Source" ("It is not a tower of Kaluza–Klein modes on the content instance").

Each tile holds an equal part of the trimmed total, because the total is the same at every place and nothing makes one tile different from another. Carried by *What the Beginning Left Behind*, chapter 8, section "Three Tiles Out of All the Tiles" ("Nothing makes one tile different from another in what it holds, and tiles that nothing distinguishes hold equal parts").

Every measurement registers three kinds of thing, a pattern in space, a force in time and a probability over what could be found; I identify the channels through which empty space reaches a measurement with these three things it registers; that there are three such things is set by the structure, so a measurement has three channels; I take each channel to take in one whole tile, and a different tile for each, because the three things the channels carry are distinct; and the one who measures is one stance, so a

telescope and a thermometer used together take in three tiles, not six. Carried by *What the Beginning Left Behind*, chapter 8, section "Three Tiles Out of All the Tiles" ("I identify the channels through which the vacuum reaches a measurement with the three contents a measurement registers, one in each of the three roles"; "the comparer is one stance, one place from which every finding is made, so the tiles it takes in are counted once"). Exact form: $c_1 = 3$, the Euler count of the complex projective plane, the larger of the two factors of the six small dimensions.

So the cosmological constant is three parts, out of the count of the particle horizon, of the trimmed total, and three tiles out of about 2.3×10^{123} hold about one part in 10^{123} of it. Carried by *What the Beginning Left Behind*, chapter 8, sections "Measuring Empty Space from Inside" and "Three Tiles Out of All the Tiles"; and by *The Spectral Chain*, chapter 1, section VI, "Where the Observer Enters a Constant", equation (11). Exact form: $\rho_\Lambda = c_1 \, f \, {M_{Pl}}^4 / S$ and $\Lambda = 8\pi G_N \rho_\Lambda$, where ρ_Λ is the energy density of empty space, Λ the cosmological constant, G_N Newton's constant, $c_1 = 3$ the number of channels of one measurement, $f = 1 - 3/(8\pi) = 0.8806$ the trim, $M_{Pl} = 1.221 \times 10^{19}$ GeV the (unreduced) Planck mass, so that ${M_{Pl}}^4$ is the Planck density, and S the count of the particle horizon.

With the measured size of our particle horizon, the share gives an energy of empty space that agrees with the measured energy of empty space to within about two percent. Carried by *What the Beginning Left Behind*, chapter 8, section "The Number, Seen Two Ways"; and by *The Spectral Chain*, chapter 1, section VI. Exact values, in the units of energy to the fourth power that particle physicists use for an energy packed into a volume: $\rho_\Lambda = 2.56 \times 10^{-47}$ GeV^4 from the share, against the measured 2.52×10^{-47} GeV^4, a difference of 1.6 percent, both from the Planck 2018 parameters $h = 0.674$ (the Hubble rate in units of 100 km/s per megaparsec), $\Omega_m = 0.315$ (the matter fraction), $\Omega_r = 9 \times 10^{-5}$ (the radiation fraction), and a spatially flat universe.

There is a second way to the same energy, through the equation Alexander Friedmann found from Einstein's theory in 1922: for a universe whose space has no overall bend, the rate of the expansion fixes how

much energy each volume of the universe holds, in three parts (matter, ordinary and dark together, the dark matter counting here by its weight, though it is not matter of any kind on the list of particles; the energy of empty space; and a thin sliver of light and other fast particles), which in such a universe make up the whole, the sliver of light being measured; with the size of the particle horizon counted in the unit the expansion sets, the distance at which the expansion carries things away at the speed of light, the rate of the expansion enters the share as its square, because the count of tiles on the edge grows with the square of the edge's size; the rate enters Friedmann's equation as its square too, and the strength of gravity enters both alike, so both drop out; one statement in pure numbers remains, and since the horizon's size in that unit depends only on how the energy has been divided among the three parts over the history of the expansion (matter and light thin out at different rates as space grows, and the energy of empty space does not thin out), it has one unknown, the matter part, which it gives as 31.1 percent, against a measured 31.5 percent, give or take 0.7; the energy of empty space and the matter part are one measured agreement, seen two ways. Carried by *What the Beginning Left Behind*, chapter 8, section "The Number, Seen Two Ways" ("The part that is matter, ordinary and dark together, is the matter fraction"; "In a flat universe the parts fill the whole: matter, the energy of empty space, and a thin sliver of radiation, which is light and other fast particles, about nine parts in a hundred thousand today, measured"; "Both grow with the square of the expansion rate, and both carry the strength of gravity in the same way, so the expansion rate and the strength of gravity (the Planck mass) both cancel"; "The horizon's size in Hubble radii depends only on how the energy has been divided over the history of the expansion"); and by *The View from Inside*, chapter 16, "The Observer Inside", section "Two Answers" ("Measurement finds 31.5 percent, give or take 0.7"). That the count of tiles grows with the square of the edge's size follows from the count given above, one tile for every four squares a Planck length on a side of the edge's area. Exact form: the identity $I^2\,\Omega_\Lambda = 8 - 3/\pi \approx 7.05$, where I is the radius of the particle horizon in Hubble radii (the Hubble

radius being the distance at which the expansion carries things away at the speed of light) and Ω_Λ the vacuum's fraction of the whole, and $8 - 3/\pi = 8\text{f}$; solved with Friedmann's equation, it gives $\Omega_m = 0.311$ and $\Omega_\Lambda = 0.689$, against the measured $\Omega_m = 0.315 \pm 0.007$. The two surveyors are this book's picture.

The energy of empty space is small because the edge of what has reached us is large. Carried by *What the Beginning Left Behind*, chapter 8, section "Three Tiles Out of All the Tiles". Exact form: the particle horizon spans about 10^{61} Planck lengths, so three tiles of its count hold about one part in 10^{123} of the trimmed Planck density.

The particle horizon grows a little every year, and the constant stays one number, fixed once: Einstein's equations require their constant term to be one number throughout one geometry, the one shape of space and time that holds the whole history of our epoch, which is a theorem of the geometry and uses no measurement; the measurement that fixes that one number is the present one, and the records of an astronomer who lived when the universe was half its present size carry the same constant; in this account the speeding up of the expansion is driven by the one constant, the same at every place and every time of our epoch, and by no field whose strength changes over time. Carried by *What the Beginning Left Behind*, chapter 8, section "Fixed Once" ("The other terms of the equations balance on their own, by a property of the geometry called the contracted Bianchi identity"; "A road carries one speed limit along its whole length, posted once; one geometry carries its one constant in the same way"; "Picture an astronomer who lived when the universe was half its present size"; "A law exists; a measurement is real"; "no field that changes over time drives the acceleration of the expansion"); the road and the astronomer are that book's pictures; and, for the constant's sameness within our epoch, by *What Comes After the Dark*, chapter 3, section "Binding Lives Where the Matter Is" ("Within our epoch, the cosmological constant is the same at every place and every time"). Exact form: $w = -1$ exactly, where w is the ratio of a form of energy's pressure to its energy in each unit of

volume; and the contracted Bianchi identity makes the divergence of the left side of Einstein's equations equal to the gradient of Λ, which the equations set to zero.

Chapter Five:
Was the Universe Tuned for Us, or Is Ours One of Many?

Along a row of worlds that differ only in the strength of light, the same arrangements are possible, impossible and certain everywhere; changing that strength changes only how often and how strongly things happen, so the constant is independent of comparison and stays measured; a constant fixed by its idea is fixed as pi is: every circle on a flat page, of any size, has one and the same ratio of the distance around it to the distance across it, and that ratio is pi; the digits of pi can be computed one by one, with no measurement. Carried by *Why These Numbers*, chapter 3, "The Electron and the Strength of Light", sections "Why the Strength of Light Stays Measured" and "The Comparison of Worlds" ("as pi is the one ratio at which a figure on a flat page is a circle"; "as there are procedures for the digits of pi"), which derives the independence with the circle's rule as its stated hypothesis. That every circle on a flat page has one and the same ratio of the distance around it to the distance across it is a theorem of the geometry of the flat page; pi is defined as that ratio. Exact value: $1/\alpha_{em} = 137.035999177$, where α_{em} is the strength of light (the fine-structure constant), a measured input (*The Strengths of the Kinds*, chapter 1, "What Is Measured", section VI, "Why the Strength of Light Stays Measured").

A value chosen by our being here cannot be predicted and cannot be derived from first principles; it stops being a consequence of law and becomes an accident of location. Carried by *The View from Inside*, chapter 3, "Why Nothing Else Has Worked", section "Strategy Two: Accept the Landscape" ("an accident of location").

To exist is to stand as structure: timeless, the same in every instance, able to be held in view as a whole, as a printed calendar is; to be real is to be given in an actual act of comparison: here, now, with the future still

open, as this morning is. Carried by *Home in the World*, "For the Specialist", section "Exists and Real; Causation and Determinism", and chapter 8, "The Bottle, the Note and the Living", section "What "Exists" Means"; the calendar is this book's picture.

A rule stated from outside, which surveys the whole history of the universe at once, can say how likely a comparer is to stand at each time in it, and it cannot single out any one of those times as real, since to do so it would have to take the present of every time as given together. Carried by *The Gravitational Passage*, chapter 13, "Λ as a Prediction; Information Cost at the Horizon", Questions ("A criterion stated from outside, which surveys all epochs at once, can give a distribution of the epochs at which comparers stand. It cannot single out one of them as real, since that would take the presents of all epochs as given together"); by *The Gravitational Companion*, "Open Questions as Research", section I, "Why This Epoch, Asked from Outside" ("A distribution singles out no epoch as real"); and by *Side by Side*, Volume Two, "The Open Future", section VI, "The Multiverse". So Hossenfelder's result, that a distribution is no explanation of the value we see, stands on two grounds in this account: the ground of *The View from Inside* (a value selected by our being here is no consequence of law) and the ground of *The Gravitational Passage* (a distribution laid out from outside cannot say which time is real).

The Incommensuration Theorem, exactly: "Symmetry and continuity cannot both be applied, simultaneously and fundamentally, to any event or comparison; and neither can asymmetry and discontinuity". Symmetry is being the same under every change of place or setting; continuity is having no gaps, so that a small change of setting gives a small change in what is found. Carried by *Physics Is Not Math*, chapter 2, section VI, "The Theorem", and by *Causality Without Determinism*, chapter 1, "Two Concepts, Three Differences", section VII, "The Incommensuration Theorem".

Mathematics can write symmetry and continuity down together because it has no one comparing in it and no time: "In a domain from which temporal comparison is removed, symmetry and continuity can be written down together. Such a domain is not a real world, precisely because the

real world has a temporal element and that domain does not"; so a collection of universes that no comparison could ever find is a structure of the same kind as the circle: mathematics lays it out whole, all at once, with no one comparing in it, and no act of comparison gives it. Carried by *Physics Is Not Math*, chapter 3, "Truth Has a Frame", section VII, "Mathematics Works as if Only the Objective Existed", which quotes *Incommensuration; The Theorem and the Three Axioms*, chapter 6, section XIII, "Scope"; the step to a collection of universes is the chapter's application of that sentence, with *Side by Side*, Volume Two, "The Structure and the Act", section III.

In 1953 Fred Hoyle inferred from the carbon in the world that carbon-12 must have an excited state just above the energy of three helium-4 nuclei together, and the state was found where he said; the account tells this step as an inference from carbon, with no appeal to life. Carried by *The Matter We Know*, Volume One, chapter 6, "Where the Elements Come From", section III, "Across the Gaps: Three Alpha Particles Make Carbon". Hossenfelder counts Hoyle's prediction as "The first successful use of the anthropic principle"; she reports that Hoyle "is said to have exploited the fact that carbon is central to life on Earth, hence stars must be able to produce it", and that "Some historians have questioned whether this was indeed Hoyle's reasoning"; and she calls the reference to life in connection with the anthropic principle "a common but superfluous verbal decoration" (*Lost in Math*, chapter 5, "Cosmic Poker"). Exact values, measured: the state lies about 7.65 MeV (million electron-volts) above the ground state of carbon-12, and 0.38 MeV above the energy of three helium-4 nuclei. The finding of the state: D. N. F. Dunbar, R. E. Pixley, W. A. Wenzel and W. Whaling, "The 7.68-Mev State in C12", *Physical Review* 92 (1953), 649 to 650, from Ward Whaling's group in William Fowler's laboratory at the California Institute of Technology; the further measurements: C. W. Cook, W. A. Fowler, C. C. Lauritsen and T. Lauritsen, *Physical Review* 107 (1957), 508 to 515.

George Ellis holds that a collection of universes that cannot be tested should not be called physics, and *Side by Side* agrees with him and with Hossenfelder; it adds a reason of its own: this account has one world, with

one settled state of empty space, so there is no collection of worlds from which ours could be selected; a collection of other worlds could be laid out only from a place where no comparison can stand, since every comparison is made from inside a world. Carried by *Side by Side*, Volume Two, "The Open Future", section VI, "The Multiverse"; and Appendix H, "The Registered Predictions Beside George Ellis", section V, "Where No Measurement Decides" ("This is a claim of logical form").

String theory's threaded fields give its six curled dimensions some ten to the five hundred valleys, or settled states, and beyond; the six of this account have one valley. Carried by *What the Beginning Left Behind*, chapter 5, "One Vacuum", sections "A Ball Among Valleys" and "What the Turn Gives Back"; and by *The Compactification*, chapter 2, "One Vacuum", section I, "The Question of Vacuum Uniqueness". Exact value: estimates of the number of valleys run to 10^{500} and beyond (Douglas, 2003; Douglas and Kachru, 2007).

This account also has ten dimensions, with six curled small, each count found from the structure of comparison: one of time, three of space and six of possibility. Carried by *Side by Side*, Volume Two, "Time Is Real", section II, "What the Collection Shares", subsection "The string theory critique", which cites *Measurement; The Steps from Comparison to Physics*, chapter 4, for the counts.

The account builds gravity from the geometry of space and time alone, so no field winds through the six and there is no whole number to count the windings; the only whole numbers the six carry are counts of their own shape, whole numbers that no smooth stretching of the shape can change, as no stretching changes the number of holes in a ring, and each of those counts has one value; and two separate routes, starting from different premises, arrive at one and the same shape for the six, so neither route picks the shape from a list of candidates. Carried by *The Compactification*, chapter 2, section VI, "No Flux, No Flux Integers" ("The integers that the internal space does carry are topological counts of its own, not flux quanta"; "Such counts have one value each, fixed by the topology of the one space, and no choice among them is possible"), and sec-

tion IX, "One Algebra, One Space"; the gloss of such counts is *Two Theories, One World*'s, chapter 21 ("whole-number counts that no smooth stretching of a geometry can change, such as the number of holes in a surface"). Exact values of the counts: the Euler characteristic of the six is $3 \times 2 = 6$, and $c_1 = \chi(\mathbb{C}P^2) = 3$. The two walkers who reach one summit by different roads are this book's picture. The two routes are: first, the algebraic route of *Non-Commutative Geometry and the Immanent Metaphysics*, Theorem 12.1, where the algebra is $\mathbb{C} \oplus \mathbb{H} \oplus M_3(\mathbb{C})$ and the pure states of $M_3(\mathbb{C})$ form the complex projective plane $\mathbb{C}P^2$ while the ray space of the quaternions $\mathbb{H}$ is the sphere S^2; second, the route of *The Gravitational Passage*, chapter 9, section VII, which uses no algebra and finds the space as "the only compact homogeneous product that satisfies the conditions". Exact form: the shape is $\mathbb{C}P^2 \times S^2$; its count of channels is $c_1 = 3$, equal to the Euler characteristic of $\mathbb{C}P^2$.

With one shape and one valley, the energy of empty space has one value; I identify the cosmological constant, the energy of empty space as gravity feels it, with the share of that energy which a measurement made from inside takes in; with that identification, its value is set by the structure of comparison, together with the measured strength of gravity and the measured size of the particle horizon; *The View from Inside* derives its value, and the value agrees with the measured one to within about two percent; no selection among universes takes part in it. Carried by *The View from Inside*, "On the Purpose of This Book" ("I identify the cosmological constant with that share"); and by *The Compactification*, chapter 2, section IX ("The cosmological constant is then not selected from a distribution of vacua; it is fixed by the identity of Chapter 4, from the external value (2.5), the count of channels c1 = 3 and the particle horizon of the present measurement"). Exact values: 2.56 derived against 2.52 measured, in units of 10^{-47} GeV^4 (*Side by Side*, Volume One, Appendix B, Prediction 7); the formula and the identity $I^2\,\Omega_\Lambda = 8 - 3/\pi$ are given under Chapter Four above.

Inflation was proposed to explain several puzzles, among them why regions of the sky that no signal could ever have joined share one temperature; this account answers that puzzle without inflation: those regions are alike because they all come from one beginning, the one end of all the black-hole interiors of the epoch before ours, from which the new outside world re-forms; it answers the other puzzles without inflation as well; and since I identify the first ripples in the sky with the form of the content carried through the turn, it excludes a long burst of inflation, and endless inflation would be the longest of all, so the endless inflation that would bud off other universes does not happen in this account. Carried by *What the Beginning Left Behind*, chapter 13, "No Inflation Needed" (the three puzzles), section "The Sameness and the Flatness, Answered From the Turn" ("Two towns far apart may share an accent without ever having spoken to each other, if they were founded from one place"; "Regions of the sky that no signal within this epoch's history has connected are alike because they come from one domain"), and section "A Long Inflation Is Excluded" ("In Chapter 11 I identified the first ripples with the form of the content carried through the turn"; "So, on that identification, the account excludes a long inflation"; a shorter one it neither requires nor excludes); and by *Side by Side*, Volume Two, "The Structure and the Act", section VI, "The Four Levels, Level by Level", Level II ("It needs no inflationary phase and excludes a long one, so there is no eternal inflation to make the regions").

The other universes of the string landscape and of eternal inflation are not real. No comparison could ever find the other universes, since every comparison is made from inside a world, and the structure of comparison gives one world. No structure of this account holds the other universes either, since the structure of comparison gives one shape, one valley and no long inflation, and leaves no place for the other universes. What string theory writes down of the other universes exists as the mathematics of string theory, as the circle does. Carried by *Side by Side*, Volume Two, "The Structure and the Act", section VI, Level II ("The collection excludes this level by three routes"), and Level IV ("A mathematical structure exists; a

world is real, given in acts of comparison made from stances inside it. Structures that no comparison could ever find are not further worlds"), and "The Open Future", section VI; and by *The Compactification*, chapter 2, "One Vacuum". This account states the second of the two statements Hossenfelder calls ascientific (*Existential Physics*, chapter 5, "The MultiWorse"), that the other universes are not real, on the ground that every comparison is made from inside a world.

The regions beyond our particle horizon, and those beyond our event horizon (the boundary past which no event, now or later, can ever send us a signal, which an accelerating expansion gives every observer), are parts of the one arena, the one space and time that holds them and us; each interacts with the regions next to it, so they belong to our one world; they are not another universe; comparisons are made in them all the time, wherever one thing there meets another, and they are real wherever those comparisons are made. Carried by *Side by Side*, Volume Two, "The Structure and the Act", section VI, Level I ("In an accelerating universe every observer has a cosmological event horizon, a boundary beyond which no event can ever send a signal to that observer"; "Regions beyond it are parts of the one arena, related to their own neighbors as our region is to ours"; "Regions beyond a horizon interact with what is near them"). The same passage gives the principle that fixes their standing, quoted from *Incommensuration; The Theorem and the Three Axioms*, chapter 9, section I: "Existence without any interaction whatsoever is indistinguishable from non-existence, and therefore is non-existence". The same section reaches that principle from the principle of identity ("that which is indistinguishable must be the same"), which "says only that to be something (rather than nothing) requires being distinguishable from nothing, and distinguishability requires comparison, and comparison is interaction". I state the far regions' standing as belonging to our one world and as real where comparisons are made in the far regions. Hossenfelder's position is in *Existential Physics*, chapter 5, "The MultiWorse": of what lies beyond what

we can observe, “Science doesn’t say anything about whether it exists or doesn’t exist”. The villages trading with their neighbors are this book’s picture.

A world fixed completely by one law needs the same law carrying every state into the next, everywhere and always, which is symmetry perfected, and every state fixed at every point, with no gap in what the law fixes, which is continuity perfected; “A whole world completely fixed by a law perfects symmetry and continuity together, whichever account describes it, and the theorem forbids that pairing”; so, taken as an account of a whole world, the many-worlds account is excluded, and its other branches exist as structure in its mathematics and are not real. Carried by *Physics Is Not Math*, chapter 8, “Physics Has the Arrow”, section VII, “Three Grounds” (“It needs the same law carrying every state into its successor everywhere and at every time, which is symmetry perfected; and it needs every state specified at every point, with no gap left open anywhere, so that each passes into the next with nothing unfixed between them, which is continuity perfected”). Whether the other branches are there is a difference between the many-worlds account and this account that no measurement reaches, and the two predict the same output of every quantum computer; the one place where they predict differently that a measurement can reach, whether gravitation itself is quantized, no experiment now proposed separates (*Side by Side*, Volume One, Appendix D, “The Registered Predictions Beside David Deutsch”, Abstract: “The two accounts predict differently at one place a measurement can reach: whether gravitation itself is quantized”; “The deepest differences, the multiverse, the determinism of the whole, ... are differences of kind that no measurement decides”; and section V, “Where No Measurement Decides”: “Both predict the same output of every quantum computer”); Hossenfelder finds that the many-worlds account and the standard interpretation make the same predictions (*Existential Physics*, chapter 5, “Many Worlds”); so the exclusion rests on the structure of comparison, and on no experiment. This account states its claim about the many-worlds account at two scopes, and both hold. As a description of a whole world, the

many-worlds account is excluded, because a whole world completely fixed by one law would perfect symmetry and continuity together (*Physics Is Not Math*, chapter 8, section VII). As an account of knowing, it is limited without being refuted: a theory that removes all first-person structure can be a complete account of the third-person physics, and it cannot, by the theorem, also be a complete account of the conditions under which that physics is known (*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"). *Side by Side*, Volume One, "Tasks, Runs and Worlds", section V, "The Multiverse", states the two parts together.

The form of physics could not have been otherwise, because any form that supports comparison must have this form, and that form includes the kinds of force and the shape of the six; the anthropic principle is a selection effect, which explains what we see by what our being here lets us see, and the self-descriptive closure is a uniqueness theorem applied to the structure of comparison itself: there is exactly one self-consistent structure of comparison, and so one form. Carried by *The Geometric Route*, chapter 32, "Self-Descriptive Closure in the Physics", section IV, "The Physical Analogue" ("This is not the anthropic principle"; "The anthropic principle is a selection effect. The self-descriptive closure is a uniqueness theorem applied to the structure of comparison itself"). The gloss of "selection effect" is the chapter's, resting on the same section ("The anthropic principle says: we observe this universe because we are here to observe it"). Exact form: the condition $c^2 + (c + 1)^2 = (2c - 1)^2$ has exactly one positive whole-number solution, $c = 3$, which gives the Pythagorean triple $\{3, 4, 5\}$; an alternative internal space would violate this condition, and an alternative gauge group would alter the modality structure; the gauge group is $\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1)$.

No pure number among the particles (a number with no units, such as the ratio of one mass to another) is a number with no reason; each such number has a reason of one of two kinds, a law that fixes its value or a proof that no law does, and each not yet derived carries the question that

settles which of the two it has; so finding a number's reason means answering one question with two possible answers, a law that fixes the number or a proof that no law does, and no probability enters that question. Carried by *The Strengths of the Kinds*, chapter 1, section VI ("This book also holds that no pure number among the particles is a brute constant (a number with no reason). Every pure number not yet derived carries the question that settles it: the law that fixes it, or the proof that no law does"), and its Summary ("Every number of the Standard Model is to reach one of two ends"); and, as a restatement in plain words, by *Why These Numbers*, chapter 1, section "Two Ends for Every Number".

A value that lands, before its reason is found, is a question, and it is evidence of a reason not yet known. Carried by *Physics Is Not Math*, chapter 13, section IV, "A Value That Lands Is a Question".

String theory's founding discovery, that its consistent forms describe gravity by quanta, with the particle of gravity among the string's vibrations, and the count by Strominger and Vafa (1996) of the hidden states of a class of idealized black holes, which matched the entropy of Bekenstein and Hawking exactly, are "two of the most striking results in modern physics". Carried by *Two Theories, One World*, chapter 22, "What Each Program Found", section "Four Programs That Quantize the Arena", subsection "String theory".

String theory's first step is to begin from quanta and build the arena of space and time out of them; "A discrete starting point, however rich, has fixed no single smooth world; that is what multiplicity means"; the many valleys are the difficulty that first step predicts, since building the smooth arena exactly out of identical quanta would ask one description to carry symmetry and continuity together, both perfect, which the Incommensuration Theorem excludes. Carried by *Two Theories, One World*, chapter 22, section "One Error, Four Expressions"; the table of the three difficulties is given in the next entry. The bricks stacked into a hillside are this book's picture.

Starting with pieces and building the smooth arena out of the pieces predicts the first difficulty, which is many possible worlds, with no principle that selects ours. Starting with the smooth arena and dividing the arena directly into quanta predicts the second difficulty, which is an equation of change that will not give back the changing world. Giving up one of the two characters, the smoothness or the sameness with gaps, and hoping to rebuild the lost character from the other character, predicts the third difficulty, which is the need for a further principle to bring the lost character back. If a line of research keeps gravity as the arena, never asks one description to carry both characters, and never treats the arena itself as made of quanta ("It excludes one thing: a quantum of the arena itself"), then that line of research meets none of the three difficulties. Treating the arena itself as made of quanta would give space and time a smallest step. So a line of research that meets none of the three difficulties meets no landscape, because the landscape of many possible worlds is the first of the three difficulties. This account is a line of research of that kind. Carried by *Two Theories, One World*, chapter 21, "Four Questions for Any Theory", the table of first steps and difficulties ("Derive the smooth arena from discrete structure", multiplicity; "Quantize the smooth arena directly", dynamics; "Give up one character and rebuild it from the other", recovery), with its pictures of the ledger ("Make the dates themselves into entries of the account, to be added and subtracted like the sums, and the ledger still holds every number. It no longer says which entry came first") and of the mosaic ("The tiles alone never decide that a circle is wanted"); the passage on what the theorem admits ("The theorem admits the quanta of the content: matter and light, and everything else that moves through the arena"; it allows the small waves of the geometry to be described by quanta, "as a description", and it admits "whole-number counts that no smooth stretching of a geometry can change"; "It excludes one thing: a quantum of the arena itself, at any scale, which would give space and time a least step"); and section "The Questions Judge Commit-

ments, Not People" ("Such a program keeps gravity as the arena, never asks one description to carry both characters, and quantizes only what the theorem admits. It therefore meets none of the three difficulties").

The correspondence between a gauge theory and gravity is two exact descriptions of one system, joined by a dictionary: correspondence, not emergence. Carried by *Two Theories, One World*, chapter 23, "Two Descriptions That Translate", sections "The Strongest Objection" and "Neither Side Comes First"; and by *The Unquantized Arena*, chapter 15, "AdS/CFT as Cross-Modal Correspondence", section VI, "Neither Side More Fundamental". *Two Theories, One World* and *The Unquantized Arena* are one argument in two forms.

On beauty Hossenfelder and this account stand together: beauty, like symmetry or economy, is a property of a mathematical description, and such a property is no evidence about the world the description describes. Carried by *Side by Side*, Volume One, "What Beauty Cannot Decide", Abstract ("a property of a mathematical rendering cannot decide what is true of the world it renders"), and section II, "Where She Is Right: Beauty Is No Evidence" ("But a property of a mathematical rendering (its symmetry, its economy, the absence of large unexplained ratios in it) is a property of the rendering").

A test can settle something only where its outcome can be compared again, by another person, at another time, along another route; an outcome is what *Physics Is Not Math* calls objective when it comes from an actual comparison, can be compared again in those three ways, with every finding consistent with the others, and could have come out against what was expected: "a test applies exactly where the outcome of a comparison can be objective, and nowhere else", and there "it is a valid and powerful tool"; a universe that no comparison could ever find gives no outcome to compare, so no test reaches it, either to confirm it or to rule it out. Carried by *Physics Is Not Math*, chapter 19, "A Right Method of Evaluation", section III, "Where a Test Applies", which names the second condition consistency ("The second is consistency: the interactions must close into consistent rings, one person's finding agreeing with another's, a photograph

with a memory, today's reading with last year's") and states the three conditions of an objective outcome together ("A test is these three rings at work: an actual comparison, repeated and agreed across many, whose outcome could have gone against the expectation"). The same chapter of *Physics Is Not Math* adds, in section VI, "What Physics Already Weighs", that physicists have never chosen between theories by a test alone: where the evidence does not decide, they choose on other grounds, which the historian Thomas Kuhn named in 1977 (accuracy, consistency, scope, simplicity and fruitfulness).

Physics Is Not Math names three ways in which anything can be validated, measurement, agreement among people and proof; measurement and proof validate truth, and "Agreement among people validates nothing by itself"; so a loss of interest among physicists tells about the physicists, and only measurement and proof can tell whether a theory is true. Carried by *Physics Is Not Math*, chapter 19, section IV, "Three Ways of Validation".

This account keeps the test for its own claims about the world. Carried by *Side by Side*, Volume One, "The Wave Function and the One Who Finds", section VII, "What Lies at the Ground" ("The collection keeps the criterion where it applies, for claims about the world, and states its own predictions there"); its predictions are the sealed record, Appendix B of the same volume.

"A law exists; a measurement is real": so mathematics does not turn into the world at some first moment; the pattern of the law stands as structure, and what is real is each weighing, made now, in which the pattern is met. Carried by *The Gravitational Passage*, chapter 5, "Reason, the Real and the Abstract", section II, "The Real and the Abstract"; the step from that sentence to a first moment is the chapter's application of it; her words on a moment "at which the math becomes real" are in *Existential Physics*, "Other Voices #1: Is Math All There Is?", the box "The Brief Answer".

Chapter Six: What Happens When a Quantum System Is Measured?

No experiment has ever contradicted the predictions of quantum mechanics. Carried by *Why the Quantum Is the Way It Is*, chapter 1, "Six Rules Nobody Chose", section "Why These Rules?" ("No experiment has ever contradicted the predictions of the six rules"). *Why the Quantum Is the Way It Is* restates in plain words the derivation of *The Quantum Passage*.

A finding is any comparison that lays down a record, an interaction after which some part of the world carries a record of the outcome; the finding is made by the comparer that finds, the screen or the counter, as an interaction, and no mind is needed. Carried by *Why the Quantum Is the Way It Is*, chapter 17, "Why a Measurement Has an Outcome", section "Every Comparison Has a Cut" ("The finding is made by the comparer that finds, the screen or the counter, as an interaction, and no mind is needed"). The print of a hoof in wet sand is this book's picture.

A comparer, in this account, is whatever makes a comparison; the comparer is a role, and a mind, an instrument or a thermostat can fill it. Carried by *Measurement; The Steps from Comparison to Physics*, chapter 1, "What This Book Takes from the First Two", section I, "The Ground of the First Volume" ("A comparer is whatever makes a comparison"; "The comparer is a structural role, the role of relating, and a mind, an instrument or a thermostat can fill it").

Von Neumann showed in 1932 that the line between the measured system and the chain of measuring instruments can be drawn at any link without changing any predicted count; so nothing special happens at the last link, where a person looks, and laying down a record is the whole of what makes an interaction a finding. Carried by *Why the Quantum Is the Way It Is*, chapter 17, sections "Two Things Go by One Name" and "Every Comparison Has a Cut". Hossenfelder reaches the same result, that a measurement needs no conscious observer, from the calculation of how quickly the surroundings wash out quantum behavior. In this account I

reach the same result from the structure of comparison. Hossenfelder's calculation and the structure of comparison are two separate grounds for the result.

Measurement divides every comparison in a second way, distinct from its division into content and context: with two apples on the two pans of a balance, the side about which the weighing is made is the apples, and the side from which it is made is the instrument itself together with whoever reads it, which *Measurement* calls "the balance and whoever reads it"; on that side the instrument alone is enough, as in a locked shop where the beam tips and a pen on the pointer marks the paper with no one there. Carried by *Measurement; The Steps from Comparison to Physics*, chapter 1, section I ("The subjective and the objective are the side from which the comparison is made and the side about which it is made"; "The pairs are distinct, and none can stand in for another"; "The subjective is the side from which the comparison is made, the balance and whoever reads it, and the objective is the side about which it is made, the apples"); the locked shop and the pen are this book's picture.

In 2003 molecules of carbon seventy sent through a grating in Vienna lost their bands of interference as gas was let in, because each gas molecule carried away a trace of the path; the surroundings act as a notebook in which each alternative writes. Carried by *Why the Quantum Is the Way It Is*, chapter 17, section "What the Surroundings Do" (Hornberger, Arndt, Zeilinger and colleagues).

Decoherence stops short of one outcome: the living and dead possibilities of the cat stop interfering long before anyone opens the chamber, and each then carries its own record; the finding settles which of the two records the opened chamber will show; decoherence prepares the measurement, and the act of comparison completes it, with one outcome. Carried by *Why the Quantum Is the Way It Is*, chapter 17, section "What the Surroundings Do" ("Decoherence prepares the conditions for the measurement, by selecting the pointer basis; the immanent act completes the measurement, by giving one outcome").

"The weirdness is an artifact of the starting point, and not a feature of quantum mechanics": the surprise is a fact about the expectations that a classical starting point produces, and from the structure of comparison superposition, entanglement and the odds follow. Carried by *Why the Quantum Is the Way It Is*, chapter 19, "Where the Derivation Stops, and Why", section "Why the Quantum Seemed Strange".

Whenever two particles interact directly with one another, as quantum systems, their states become linked: they are entangled. Carried by *The Last Turtle*, chapter 28, "Correlation Without a Cause", section IX, "What the Correlation Is".

The outcomes at each place, taken alone, are random; the agreement appears only when the two records are brought together, by signals no faster than light; nothing passes between the places to make the agreement. Carried by *Why the Quantum Is the Way It Is*, chapter 15, "Entanglement and Bell's Limit", sections "Why No Message Can Be Sent" and "In Any Order, and at Neither Place".

The quantum state is like a forecast in that it is smooth and gives odds, and it differs from a forecast in that no further knowledge sharpens it, since there is no state beneath it. Carried by *Why the Quantum Is the Way It Is*, chapter 17, section "What Remains, and Where the Born Rule Stands" ("The forecast is a picture; the quantum state differs from a forecast in that no further knowledge sharpens the quantum state, since there is no state beneath the quantum state"), which credits the picture to *Two Theories, One World*.

When a measurement is made, the comparison has occurred, and its result belongs to the record of the system; the update is the change of that laid-out record, "which is shared, and the same for everyone who has the outcome"; it is the change of what is known in that sense, and it is not one person's degree of belief, not a physical process, and not an extra law of motion. Carried by *Why the Quantum Is the Way It Is*, chapter 17, section "Why Collapse Is Not Physical", where the update is "an epistemic up-

date" and the sense of "epistemic" is fixed as the shared record; and by *The Quantum Passage*, chapter 9, "The Measurement Problem Dissolved", section IV, "Why Collapse Is Not Physical".

The update looks like a physical process, a collapse, only inside the narrower frame of the standard formulation, which has the space of states and its operations and lacks the division into content and context and the directed cycle of comparison; Hossenfelder, declining the word collapse because it suggests a physical process that quantum mechanics does not contain, already treats the update, within quantum mechanics as it stands, as no physical process. Carried by *Why the Quantum Is the Way It Is*, chapter 17, section "Why Collapse Is Not Physical"; her words are in *Existential Physics*, chapter 1, "Eternal Information".

The Incommensuration Theorem, exactly: "Symmetry and continuity cannot both be applied, simultaneously and fundamentally, to any event or comparison; and neither can asymmetry and discontinuity". Symmetry is being the same under every change of place or setting; continuity is having no gaps, so that a small change of setting gives a small change in what is found; the chapter's argument uses the first clause. Carried by *Physics Is Not Math*, chapter 2, section VI, "The Theorem"; and by *Causality Without Determinism*, chapter 1, "Two Concepts, Three Differences", section VII, "The Incommensuration Theorem".

The chance of an outcome belongs to comparison itself: a description that fixed every finding would carry one law into every state everywhere, which is symmetry perfected, and would fix every state with no gap in what the law fixes, which is continuity perfected; the theorem forbids the two together, so every lawful description leaves something over that its law does not fix, and in Schrödinger's chamber that something is the moment of the click; no hidden layer beneath the quantum state removes it. Carried by *Why the Quantum Is the Way It Is*, chapter 11, "Why Chance Enters", section "A Click Nobody Could Name in Advance" ("Physics gives the chance that it decays within the next minute, and that chance is all there is to know in advance; no record of the atom's past, however complete, names the moment") and section "The Residual" ("A descrip-

tion that fixed every finding would carry one law into every state everywhere, which is symmetry perfected, and would pass each state into the next with no break, which is continuity perfected, and the theorem forbids the two together"; "The single outcome of a quantum measurement is the plainest instance of the residual"); chapter 17, section "Why Collapse Is Not Physical"; and *The Quantum Passage*, chapter 7, "The Born Rule from the Structure of Comparison", section II, "Why Probability Is Necessary".

The Incommensuration Theorem guarantees the gap between the continuous description and the definite finding, "and no future theory removes that gap": the smooth mathematics comes as close to each finding as any measurement can resolve, and it never contains the finding itself. Carried by *Why the Quantum Is the Way It Is*, chapter 17, section "What Remains, and Where the Born Rule Stands": "a formalism that contained its findings exactly would perfect symmetry and continuity together in one mode".

A finding runs one way: before the chamber is opened there are two possibilities, a living cat and a dead one, and the opening is one act that gives one cat; many possibilities pass to one act, and many acts to one record; the step back from one record to many possibilities can be written down as a relation, and no act of comparison runs that way, so the passage from possibility to result cannot be undone. Carried by *Why the Quantum Is the Way It Is*, chapter 17, section "Why Collapse Is Not Physical" ("The measurement is the act, the immanent: a passage from the possible to the actual"; "a range of many possibilities leads to one act, and many acts to one record. The reverse step would be one to many, which is a relation and not a passage"); the cat as the example is this book's application.

Two different things go by the name of the measurement problem: a clash among the textbook rules, between smooth change and the jump; and the gap between a smooth description and a finding that comes in a step; Schrödinger's cat is the same difficulty. Carried by *Why the Quantum Is the Way It Is*, chapter 17, section "Two Things Go by One Name".

The rules were assembled from six separate traditions between 1906 and 1932, with refinements in 1935 and 1951, and "The measurement problem is the scar left by that assembly". Carried by *Why the Quantum Is the Way It Is*, chapter 1, section "The Scar Left by the Assembly", and chapter 17, section "Where the Contradiction Came From".

Derived from one source, the act of comparison, the two rules are said of different things, the rule of smooth change of the range of what is possible before any finding, and the jump of the act of finding itself, and so they do not clash; the remaining gap is no contradiction, and at it the rule for the odds, the Born rule, carries the smooth description over to how often each finding comes. Carried by *Why the Quantum Is the Way It Is*, chapter 17, sections "The Problem Dissolves" ("The third rule describes the pair before any comparison of it; a finding is a comparison; the two rules are said of different things, and they do not conflict") and "What Remains, and Where the Born Rule Stands" ("The Born rule carries a state of the formalism to the weights of findings").

A comparison stands on three legs, like a stool: the act of finding, here and now; the record it lays down, which anyone can read; and the place from which the question is asked, with its range of possible answers; none stands without the others, and none does another's work; *Why the Quantum Is the Way It Is* reads each interpretation of quantum mechanics by which leg it sets aside, and it finds each one's known difficulty exactly where the missing leg belongs. Carried by *Why the Quantum Is the Way It Is*, chapter 18, "The Interpretations, Each Missing a Role", sections "A Stool With Three Legs" ("the act itself, here and now, which is the immanent role; what is laid out as structure, the record that can be held in view as a whole and shared, which is the omniscient role; and the stance from which the act proceeds, with its range of what is possible, which is the transcendent role"; "Axiom III says that the three roles are distinct, that they are inseparable, and that none can do the work of another") and "The Map of the Roles". The three legs shown in Schrödinger's chamber (the opening as the act, the cat as found as the record, the chamber as set up as the place of the question) are this book's application.

The Copenhagen interpretation keeps the act and the record and treats measurement as the starting point, the order this account keeps, with the act first; it cannot say where the line between the measured system and the measuring instrument falls, because it gives no account of the range of possible answers. Carried by *Why the Quantum Is the Way It Is*, chapter 18, section "Copenhagen and the Cut" ("Copenhagen's order, with the finding first and the state as a tool for computing the odds of findings, is the order of Axiom I"; "The account keeps Copenhagen's order").

The many-worlds interpretation keeps the smooth change and removes the act, and its difficulties, which branches there are and what the odds mean, are the act returning: choosing how to divide the world into branches is choosing which outcomes count as having happened, and odds need someone who faces outcomes and weighs them. Carried by *Why the Quantum Is the Way It Is*, chapter 18, section "Many Worlds" ("choosing that way is choosing which outcomes count as having occurred"; "When every outcome occurs, a probability needs an agent who faces outcomes and weighs them"), section "The Map of the Roles", and its Summary. At the scope of a description of a whole world, this account excludes the many-worlds account; at the scope of an account of knowing, it limits what that account can claim without refuting it (the sources are named under Chapter Five).

Each interpretation is a partial view: as a description of the part it keeps, it is not wrong, and as an account of the whole, it sets one leg aside; the interpretations are placed by structure, by which part of every comparison each leaves out, and the account that keeps all three parts needs none of the interpretations. Carried by *Why the Quantum Is the Way It Is*, chapter 18, section "What the Interpretations Were Doing" ("The structure seen whole needs none of the interpretations, because it stands on all three roles from the start").

To exist is to stand as structure: timeless, the same in every instance, able to be held in view as a whole, as a train timetable is; to be real is to be given in an actual act of comparison: here, now, with the future still open, as a train's arrival is; "The mathematics of a physical theory exists; its

findings are real". Carried by *Home in the World*, "For the Specialist", section "Exists and Real; Causation and Determinism", which gives all three sentences in these words, without the timetable and the arrival, which are this book's picture; and by *Measurement; The Steps from Comparison to Physics*, chapter 14, "The Consequences of the Theorem", section V, "The Real Is the Triple of Causality, Change and Choice".

The smeared description of the cat exists; the cat that is found is real; the other branches exist as structure and are never found, so they are not real in this sense. Carried by *Side by Side*, Volume One, "The Wave Function and the One Who Finds", section III, "The Branches"; and by *Why the Quantum Is the Way It Is*, chapter 17, section "Each Claim Said of One Role".

Chapter Seven:
Could Everything, the Experimenter's Choice Included, Have Been Fixed in Advance?

Bell showed in 1964 that answer sheets have a limit: no account in which the answers are laid out at the source reproduces the agreement between entangled particles. Carried by *Causality Without Determinism*, chapter 3, "The Free Will Theorem", section I, "The Theorem". Exact values: in the combination S of four correlations of Clauser, Horne, Shimony and Holt, every local account stops at 2, and quantum mechanics reaches $2\sqrt{2}$, about 2.8 (Tsirelson, 1980); carried by *The Unquantized Arena*, chapter 13, section II, "Bell", and by *The Last Turtle*, chapter 28, "Correlation Without a Cause", section VII, "The Wizard's Decks".

If the settings are fixed along with the states, statistical independence fails, Bell's limit no longer applies, and an account in which each particle carries its own answers, with nothing outrunning light, can be kept. Carried by *The Basis of Physics*, Essay 9, section II, "Superdeterminism as Determinism Strengthened".

Determinism is the thesis that a complete specification of the state at one time, carried by the same lawful mapping in every context, fixes a unique state at every other time; statistical independence is the assumption of Bell's theorem that the settings of the measuring devices are independent of the hidden state of the systems measured; superdeterminism is a deterministic completion of quantum mechanics in which the settings are fixed together with the states, so that statistical independence fails. Carried by *Side by Side*, Volume One, "What Beauty Cannot Decide", Terms. The tea test with the coin is this book's picture of statistical independence.

Hossenfelder and Palmer identify the assumption of statistical independence exactly, so that a reader knows which step of Bell's argument a superdeterministic theory gives up, and they propose tests of it that bring the question into the laboratory; this account credits both, and its own argument, like theirs, assumes nothing about free will. Carried by *Side by Side*, Volume One, "What Beauty Cannot Decide", section IV, "Superdeterminism at Full Strength" ("and they propose tests of it"); by *The Unquantized Arena*, chapter 13, "Bell, Kochen and Specker, and PBR as Instances", section VII, "Questions"; and, for free will, by *The Basis of Physics*, Essay 9, "The Structural Impossibility of Superdeterminism", section III, "The Category Error: Choice Collapsed into Causality", subsection "On the Word "Free" in Free Choice". Their paper is S. Hossenfelder and T. N. Palmer, "Rethinking Superdeterminism", *Frontiers in Physics* 8 (2020), 139; her proposed test is S. Hossenfelder, "Testing Super-Deterministic Hidden Variables Theories", *Foundations of Physics* 41 (2011); the coming tests are gathered in Appendix A.

The early tests left two loopholes: the detectors might miss particles, so that the detected pairs were an unrepresentative sample, and the settings might be chosen too slowly, so that a signal at light speed could carry one setting to the other side. Carried by *The Basis of Physics*, Essay 6, "Hard Randomness", section IV, "The Loophole-Closing Tests and the Razor".

In 2015 three groups, in Delft, in Vienna and in Boulder, closed both loopholes together and found Bell's limit passed; tests with settings drawn from the choices of about a hundred thousand people, from the light of stars and from the light of quasars passed it again, and pushed any shared cause of settings and particles into those choices or far back in time. Carried by *The Last Turtle*, chapter 28, section VIII, "The Experiments" ("In 2017 and 2018 other groups chose the detector settings using light from distant stars and from quasars, and using the button presses of many thousands of people, and the inequality was still broken"); by *Side by Side*, Volume One, Appendix H, "The Registered Predictions Beside Anton Zeilinger", section III, "Where the Two Accounts Agree", entry "Zeilinger 5. No superdeterministic completion"; and by *The Unquantized Arena*, chapter 13, section II. Exact values, measured: $S = 2.42 \pm 0.20$ from 245 rounds over 220 hours, with electron spins 1.3 kilometers apart (B. Hensen and others, *Nature* 526 (2015), 682 to 686); the human choices of 30 November 2016, set into thirteen experiments in twelve laboratories (BIG Bell Test Collaboration, "Challenging Local Realism with Human Choices", *Nature* 557 (2018), 212 to 216); about 600 years for settings from Milky Way stars (Handsteiner and others, 2017); at least about 7.8 billion years for settings from quasars (Rauch and others, 2018).

In a superdeterministic world every result is fixed together with everything else, the settings included, so no result can rule such a world out; the experiments make superdeterminism very costly, a shared cause reaching back billions of years and into the choices of a hundred thousand people; they constrain it, and they do not exclude it by logic. Carried by *Side by Side*, Volume One, "What Beauty Cannot Decide", section V, "Why Superdeterminism Is Excluded"; by *The Last Turtle*, chapter 28, section VIII; and by *Measurement; The Steps from Comparison to Physics*, chapter 13, "Physical Law as Access, and Its Limits", section IV, "Signals Have a Limit" ("constrained by those tests and not logically excluded by them"). *Measurement* states superdeterminism at two scopes, and both hold. At the scope of what experiments can do, superdeterminism is constrained by the tests and not logically excluded by them (chapter 13, section IV). At

the scope of what the Incommensuration Theorem does, superdeterminism is excluded: "Superdeterminism falls with determinism" (chapter 14, "The Consequences of the Theorem", section II, "Determinism Is Impossible").

Of two hypotheses, that the whole past has been arranged so that the experimenters' choices conspire with the states of the particles while leaving no trace of the conspiracy anywhere else, and that some of what happens is not caused, the second is simpler by a very large margin, and this account accepts hard randomness on that ground alone, before the structural argument. Carried by *The Basis of Physics*, Essay 6, section IV.

Hard randomness is an outcome that no prior specification fixes, however complete, a prior specification being a full account of everything that came before the outcome. Carried by *Measurement; The Steps from Comparison to Physics*, chapter 14, section I, "The Residual the Theorem Guarantees"; and by *Causality Without Determinism*, Glossary.

The Incommensuration Theorem, exactly: "Symmetry and continuity cannot both be applied, simultaneously and fundamentally, to any event or comparison; and neither can asymmetry and discontinuity". Symmetry is being the same under every change of place or setting; continuity is having no gaps, so that a small change of setting gives a small change in what is found. It is a structural fact about the nature of knowing, and it holds wherever anything is compared. Carried by *Physics Is Not Math*, chapter 2, section VI, "The Theorem"; by *Side by Side*, Volume One, "What Beauty Cannot Decide", section V; and by *Causality Without Determinism*, chapter 1, "Two Concepts, Three Differences", section VII, "The Incommensuration Theorem".

Step one: determinism asks for symmetry perfected (one law carrying every state into the next, the same in every place and at every time) and continuity perfected (the law fixing every state at every point, with no gap anywhere); that continuity is Chapter Two's, held without exception: where the setting is the same, what is found is the same, the setting being the setting of a comparison, as Chapter Two named it, the places, the mo-

ment and the conditions in which the comparison is made, as distinct from the setting of an experiment's dial; so at no place and no moment does the law leave the state unfixed; so determinism is unreachable as a matter of structure, as distinct from false as a matter of fact. Carried by *The Basis of Physics*, Essay 9, section II; by *Measurement; The Steps from Comparison to Physics*, chapter 14, section II, "Determinism Is Impossible"; and by *Side by Side*, Volume One, "What Beauty Cannot Decide", section V ("That the state be specified without gap at every point is sameness of content within sameness of context, which is continuity, and determinism asks for it perfected too"). The player piano is this book's picture.

Step two: a position that needs a forbidden pairing does not become possible by needing the same pairing over more of the world; whatever cannot be had for the particles cannot be had for the particles, the apparatus and the experimenter together; so superdeterminism is excluded, for the reason that excludes determinism, which is a reason about comparison and not about quantum mechanics. Carried by *The Basis of Physics*, Essay 9, section II; and by *Measurement; The Steps from Comparison to Physics*, chapter 14, section II.

Step three: there is no partial determinism, and so no partial superdeterminism; a scale, here a level of size such as that of particles or that of dials, is completely fixed only if the smaller things it is made of are completely fixed too, and the dials and the experimenters are made of particles, so one outcome among the particles that nothing fixed leaves the dials unfixed too, at once: a failure of determinism among the particles is a failure of determinism at every larger scale; small differences growing, as a double pendulum's swings do, show how such an outcome can reach the settings; so a determinism that held only nearly at the scale of particles is no determinism at the scale of the experimenters either. Carried by *Causality Without Determinism*, chapter 3, "The Free Will Theorem", section VI, "The Catastrophic Theorem of Determinism" ("a scale cannot be completely specified while the scales that compose it, or that it composes, are not: the microscopic composes the mesoscopic"; "The definition already makes the failure immediate at every scale"; "Amplification shows the

same failure in the world, at the scale where the experimenters choose their settings"; "So a determinism that held only approximately at the scale of particles is no determinism at the scale of the experimenters either"). The ground of the step is the definition, how the small makes up the large; the growth of small differences shows the same failure at work. The section's whole sentence, "So one failure anywhere is a failure at every scale", with its second direction, is the claim of Chapter Eight, and its entry stands there.

Every real event, on this account, holds three things together: causation, the pattern that repeats; change, the happening itself; and choice, what is new in an event, not contained in what came before; the three are distinct, they never come apart, and none of them can do the work of another. Carried by *The Basis of Physics*, Essay 9, section III ("These three are distinct, inseparable, and non-interchangeable"). One round of a Bell test (the law of how often each answer comes, the click, this round's answer) is this book's picture of the three.

Because symmetry and continuity cannot both be total, something is always left over that the pattern does not fix, and this account names it choice; the word names, at every scale, the part of an event that no pattern fixes, described from inside, from the position of the process that part came from; described from outside, from the position of law, the same part is hard randomness; seen from inside by the one from whom it comes, that part is what a person knows as choosing; superdeterminism says the leftover is empty, and the theorem says it cannot be empty. Carried by *The Basis of Physics*, Essay 9, section III ("There is therefore always a residual: a domain in which the outcome is not fixed by the structural pattern. The framework names that residual choice"); and, for choice seen from inside, by *Causality Without Determinism*, chapter 5, and its Glossary.

Whatever selects a setting draws on what the pattern leaves unfixed, in the same way the particle does, whether the dial is turned by a person, by a machine that generates random numbers or by the light of a star. Car-

ried by *The Basis of Physics*, Essay 9, section III ("it is excluded whether the setting was chosen by a person, a photon, or a star"; the machines are the quantum random number generators named in the same section).

The leftover is not ignorance: what we do not yet know is a complete description that is there to be had and that we do not yet have; a world is what comparisons are of, so a description with nothing left over describes no comparison and so no world, and a description with every state fixed without gap and every law holding without exception is a description in which nothing happens. Carried by *The Basis of Physics*, Essay 9, section IV, "Why the Residual Is Not Ignorance" ("and a world is what comparisons are of"; "a description in which the residual is closed is a description in which nothing happens").

Quantum mechanics is not the final word, and this account stands with Hossenfelder on that, for its own reason: "Beneath quantum mechanics lies the act of comparison (as distinct from a deterministic mechanism)". Carried by *Side by Side*, Volume One, "What Beauty Cannot Decide", section VII, "Measurement and Discreteness"; and by *The Basis of Physics*, Essay 9, section VI, "The Circularity, and a Different Dissolution".

Hossenfelder's own standard bears on superdeterminism: her critique of beauty rests on the demand that physics answer to evidence; every experiment presupposes that its settings are independent of what it measures, and that independence is what makes a result evidence about the thing measured; superdeterminism, as a thesis about all events, removes that condition everywhere, so no observation could count as evidence for it, or for anything else, the results of the tests proposed for superdeterminism included; the structure of comparison guarantees a world in which the settings are independent of what is measured, and so it guarantees that an experiment can teach us about the thing it measures. Carried by *Causality Without Determinism*, chapter 3, section VIII, "Why Superdeterminism Is Excluded"; and by *Side by Side*, Volume One, "What Beauty Cannot Decide", section V ("Superdeterminism, taken as a thesis about every event, removes the condition under which anything counts as evidence, its own proposed tests included"). Hossenfelder and Palmer's an-

swer to this charge (their paper, section 4, "Common Objections to Superdeterminism", subsections "The Conspiracy Argument" and "The Tobacco Company Syndrome") concerns how much a given theory can explain, which a concrete model must show, and how far a habit formed on classical systems carries; the ground stated here concerns what makes any result evidence about the thing measured, in a world where the thesis holds of every event; the two are said of different things.

The whole argument is set out in *The Basis of Physics*, Essay 9, "The Structural Impossibility of Superdeterminism"; the step about partial determinism is set out in *Causality Without Determinism*, chapter 3, "The Free Will Theorem".

Chapter Eight: Has Physics Ruled Out Free Will?

Laplace's intelligence of 1814 is told by *Causality Without Determinism*, chapter 1, section II, "Determinism Defined", and by *What Cannot Be*, chapter 5; the standard definition of determinism (John Earman, *A Primer on Determinism*, 1986) is stated in *What Cannot Be*, chapter 5, section "What Determinism Claims".

The laws of physics are reliable, experiments repeat, and the future is very largely fixed by the past; a dropped cup falls every time. Carried by *What Cannot Be*, chapter 5, "Is Everything Already Fixed?", sections "What the Conclusion Rests On" and "The Demon and the Piano Roll". The scope, as that chapter states it: within any limited range a description can be very symmetric and very continuous, and the whole success of physics lives there; the theorem concerns the limit, and determinism is a claim about the limit.

For a large batch of radioactive atoms the rate of breaking apart is among the best-measured regularities in physics, and the moment at which one single atom breaks apart is predicted by nothing. Carried by *Causality Without Determinism*, chapter 1, "Two Concepts, Three Differ-

ences", section I, "A Click That Was Caused"; and by *What Cannot Be*, chapter 8, "A Click No One Could Predict", section "One Atom, One Avalanche, Three Balls".

Soft randomness is unpredictability that comes from a limit of what we know and that better knowledge could shrink, as with a roulette wheel, where the ball's resting place may be settled by details no one measured; it is a statement about our knowledge. Carried by *What Cannot Be*, chapter 8, section "Two Meanings of Random" ("I call this soft randomness: unpredictability that comes from a limit of what we know, and that better knowledge could shrink"), whose instances are a tossed coin, the weather next month, an unworked digit and the top card of a shuffled deck, in each of which "there is, or might be, a fact of the matter that fixes the outcome in advance"; the roulette wheel is an instance of the same kind.

Hard randomness is an outcome that no prior specification fixes, however complete; it is a fact about the world, and the single outcome of a quantum measurement is its plainest instance. Carried by *Causality Without Determinism*, chapter 5, "Computation, Consciousness and Simulation", section III, "The Bound Triple", and its Glossary; by *What Cannot Be*, chapter 8, section "Two Meanings of Random" ("Hard randomness is real, and the single outcome of a quantum measurement is its plainest instance"); and by *Causality Without Determinism*, chapter 3, "The Free Will Theorem", section III, "The Conclusion" ("The indeterminism is ontic, a feature of the world, and not epistemic").

Every comparison leaves a remainder, an outcome that nothing before it fully fixes, and that remainder is hard randomness. Carried by *Causality Without Determinism*, chapter 5, section IV, "Why the Three Come Together", which quotes *Incommensuration; The Theorem and the Three Axioms*, chapter 8, section X.

Both sides of the old quarrel over free will take a fixed world to be at least possible; once a fixed world is shown impossible, the question becomes what choice is in a world that is causal and open. Carried by *Causality Without Determinism*, chapter 1, section XI, "The Distinction in Its Tradition".

Even with complete knowledge of everything before, nobody could predict which single outcome will occur; that knowledge gives the probability of each outcome and nothing more. Carried by *The Last Turtle*, chapter 14, "Free Will and the Compression Argument", section II, "What the Argument Assumes".

"We know that we cannot predict choices; if we could, they would be causes and not choices". Carried by *What Cannot Be*, chapter 8, section "Chance From Outside, Choice From Inside".

The Incommensuration Theorem, exactly: "Symmetry and continuity cannot both be applied, simultaneously and fundamentally, to any event or comparison; and neither can asymmetry and discontinuity". It is a structural fact about the nature of knowing. Symmetry is being the same under every change of place or setting, as one ten-gram piece set against another leaves the beam level in this town or on another continent; continuity is having no gaps, so that a small change of setting gives a small change in what is found, as a settling beam swings through every position between; asymmetry and discontinuity are their opposites. Carried by *Physics Is Not Math*, chapter 2, section VI, "The Theorem"; by *The Last Turtle*, chapter 14, section II; and by *Causality Without Determinism*, chapter 1, section VII, "The Incommensuration Theorem"; the box of weights and the settling beam are this book's pictures, from Chapter Two.

Laplace's all-knowing intelligence needs symmetry made perfect (one law carrying every state into the next, the same everywhere and at every time) and continuity made perfect (every state specified at every point, with no gap anywhere in what the law fixes, at any scale); determinism asks for exactly the pair the theorem's first clause forbids, so no world is purely and completely deterministic. Carried by *Causality Without*

Determinism, chapter 1, section VIII, "Why Determinism Cannot Be Had" ("total specification (continuity) of lawful structure (symmetry) is structurally precluded"); and by *What Cannot Be*, chapter 5, section "Two Perfections at Once".

Pure randomness is forbidden too, and every actual world lies between the clockwork and the noise. Carried by *Causality Without Determinism*, chapter 1, section VIII ("Determinism and pure randomness are the two forbidden rows, and every actual world lies between them").

An equation that carries each state into exactly one next state is deterministic as mathematics, which exists as structure, and not in the findings, which are real; a perfectly exact fence does not make the field inside it exact; what science finds is causal law. Carried by *What Cannot Be*, chapter 5, sections "The Fence and the Field" and "What Remains"; the ground is *An Immanent Metaphysics*, Technical Appendix, section "Causality and Determinism" ("the natural law of science is always causal law, not ever deterministic law").

Science narrows what a device can do to what it is meant to do, which is engineering, and it finds possibilities no one had seen, which is discovery; in both uses what science establishes is causal law, and never the complete specification that determinism would require; heading off a hurricane before it grows, Hossenfelder's example, is engineering in this sense. Carried by *Causality Without Determinism*, chapter 1, section X, "Subjective and Objective Causality" ("It cannot deliver the complete specification that determinism requires"); her example is in *Existential Physics*, chapter 9, "The Limits of Math", and its classification as engineering is this book's application of that section's definition.

Determinism promises everything, and there is no partial determinism, any more than there is a partial guarantee of everything; a scale, a level of size such as that of particles or that of people, is completely fixed only if the smaller scales that make it up are completely fixed too, since the small makes up the large; a failure of determinism also passes from the large to the small: by the free will theorem, if no earlier information

available to the particle fixes the experimenter's setting, nothing that came before fixes the particle's answer; so one failure of determinism anywhere is a failure at every scale. Carried by *Causality Without Determinism*, chapter 3, section VI, "The Catastrophic Theorem of Determinism" ("a scale cannot be completely specified while the scales that compose it, or that it composes, are not: the microscopic composes the mesoscopic, and a free experimenter at the mesoscopic scale entails a free particle at the microscopic"; "So one failure anywhere is a failure at every scale").

In 1961 Edward Lorenz found, with a simple model of the weather, that a number typed in as .506 in place of .506127 changed the whole pattern of two months of simulated weather; in 1963 he published that "slightly differing initial states can evolve into considerably different states". Carried by E. N. Lorenz, "Deterministic Nonperiodic Flow", *Journal of the Atmospheric Sciences* 20 (1963), 130 to 141, whose abstract holds the quoted words.

Followed downward, the magnifying of small differences reaches below the finest difference any interaction can register: below the amount of action that Planck's constant marks, no measurement can tell apart the differences that would fix both where a particle is and how it is moving; every measuring tool is itself an interaction, so no tool that could ever be built reaches below that limit; what cannot be told apart in any way is the same, so two such states are one state; so from anywhere inside the range where measuring works, the outcome is hard random, and the openness rises "the way groundwater rises wherever it finds a path, through every process that amplifies what it cannot resolve". Carried by *What Cannot Be*, chapter 1, "How Does Anyone Find Anything Out?", section "Where Physics Has Edges" ("Below the amount of action that Planck's constant marks, no measurement can tell apart the differences that would fix both members of a pair of conjugate quantities together"); chapter 8, section "An Edge Built Into Measuring" ("because a tool is itself an interaction, and the limit is a limit on interaction"), and section "One Atom, One Avalanche, Three Balls" ("what cannot be told apart in any way is the same", by the principle of identity); and *Causality Without Determinism*, chapter 3,

section VI. The limit is marked by Planck's constant, $h = 6.62607015 \times 10^{-34}$ joule seconds, an exact value in the International System of Units since 2019.

A Geiger counter's click can be the first link of a chain that ends in the course of a rocket or an asteroid, and the first link was a click that nothing beforehand fixed. Carried by *The View from Inside*, chapter 14, "Here, Now, and This", section "A Geiger Counter and the Orbits of Planets".

What happens is not fixed in advance, at the scale of particles and therefore at every scale, by two independent routes: the Incommensuration Theorem; and the free will theorem of Conway and Kochen (2006): if an experimenter's choice of a setting is not fixed by any earlier information available to the particle, the particle's answer is not fixed by anything that came before it; that premise is the statistical independence of Chapter Seven, settings independent of the hidden state of what is measured, which every experiment already assumes, and it uses nothing from the Incommensuration Theorem. Carried by *Causality Without Determinism*, chapter 3, section I, "The Theorem", section II, "The Four Assumptions" ("Fourth, free choice: the experimenter's choice of setting is not a function of prior information available to the particle"; "Free choice of settings is what every experiment presupposes when it treats its settings as independent of what it measures"), section III, "The Conclusion" ("The experimenter's freedom is secured twice"; "And it is secured by the practice of physics itself, since every experiment presupposes that its settings are independent of what it measures"; "The second ground uses nothing from the first, so the free will theorem gives physical confirmation of the impossibility of determinism that is independent of the Incommensuration Theorem"), section VI ("Two independent routes supply the failure"), and its Summary ("Indeterminism is real, at every scale"). That the proof still holds when a computer program picks the settings, so long as the particles have no access to the program, is stated in J. H. Conway and S. Kochen, "The Strong Free Will Theorem", *Notices of the American*

Mathematical Society 56 (2009), 226 to 232, section 5, "Free Will versus Determinism" ("If we dismiss as ridiculous the idea that the particles might be privy to this program, our proof would remain valid").

Hard randomness and choice are one event described from two positions: from the position of law, from outside, the outcome that nothing fixed is hard randomness, something no law specifies, with no pattern and no meaning; from the position of the one engaged, from inside, the same outcome is choice, meaningful to the process from which it came, meaningful here meaning significant to that process and bearing that process's nature. Carried by *Causality Without Determinism*, chapter 5, section V, "Hard Randomness and Choice" ("the undetermined outcome is hard randomness: a gap in the specification, without pattern and without meaning"); and, as a restatement in plain words, by *What Cannot Be*, chapter 7, "Choice, Change and Cause", sections "From Outside, Chance; From Inside, Choice" ("From outside, randomness; from inside, choice: one event, two descriptions, both correct, neither complete") and "Meaning Cannot Be Removed" ("Meaningful, here, means significant to the process an outcome came from").

Write down everything about a person's behavior that can be predicted, as a compression algorithm writes down the regularities of a data stream; however good the algorithm, a residue remains that it cannot compress, indistinguishable from randomness, and that residue is the part the person regards as their choice. Carried by *The Last Turtle*, chapter 14, section III, "The Compression Argument"; and by *What Cannot Be*, chapter 7, section "From Outside, Chance; From Inside, Choice".

The argument against free will assumes that the world is either fully determined or purely random, and neither can be had; choice lives between noise and the playing out of a script. Carried by *The Last Turtle*, chapter 14, section II, "What the Argument Assumes".

A decision is a selection from possibilities already defined, made by cutting away the others; a choice may realize a possibility that was open but not in the set; so each time you choose you are a place where the fu-

ture is selected, from what was open and sometimes from what was on no list; and choice is real, in the fixed sense of the word: it is given in each act of comparison, here and now, with the future still open. Carried by *Causality Without Determinism*, chapter 6, "Choice, Creation, and the Soul", section I, "Two Ways to Spend an Evening", and section III, "Decision, Choice and Creation" ("A choice may realize a possibility that was open but not in the set"); the gloss of real is *Home in the World*'s ("To be real is to be given in an actual act of comparison: here, now, with the future still open").

This account's word is choice, the part of an event that physics records as hard randomness, seen from inside; this account leaves aside the will beyond law and chance that Hossenfelder rejects, neither defending it nor assuming it; every experiment finds the same numbers under her description and under this account's: the quantum chance of the established laws, as she describes them (*Existential Physics*, chapter 6, "A Quagmire of Evasion": "The currently established laws of nature are deterministic with a random element from quantum mechanics"), is this account's hard randomness. Carried by *Measurement; The Steps from Comparison to Physics*, chapter 14, "The Consequences of the Theorem", section I, "The Residual the Theorem Guarantees" ("The single outcome of a quantum measurement is its plainest instance in physics"), which *Causality Without Determinism*, chapter 5, section V, "Hard Randomness and Choice", quotes; by *Side by Side*, Volume One, "What Beauty Cannot Decide", section VI, "Choice, Randomness and the Word "Free""; and Appendix I, section V, "Where No Measurement Decides", subsection "Choice and the word "free"" ("What one account calls randomness and the other calls the residual of choice gives the same statistics in every experiment").

The room for choice is found at every scale, because no deterministic description, at any scale, can be complete. Carried by *Side by Side*, Volume Two, "The Open Future", section IV, "Causation from Above and from Below".

Two claims, each with its own scope: in practice, exact calculation from the laws of particles succeeds only for the simplest systems, such as the hydrogen atom, and already gives out at chemistry, the first step up, where every method used for the chemistry of anything larger approximates, which shows how early calculation stops on the way up; in principle, no description, however refined, contains everything that it describes, and the room for choice rests on this limit in principle. Carried by *The Last Turtle*, chapter 27, "The Size of Chemistry", section IV, "The Failure of Reduction, Stated Exactly" ("The hydrogen atom is solved exactly"; "In practice, exact derivation is never possible except for the simplest systems"; "In principle, no description, however refined, contains everything that it describes").

Most behavior is predictable, and the part which is choice cannot be predicted in principle, because a choice that could be predicted would be a cause; to everyone else, that part looks exactly like randomness. Carried by *An Immanent Metaphysics*, chapter 5, "The Practice of Being", section "Self of Choice", aphorism 1.66-2 ("Choices must appear, at some level of abstraction, to be fundamentally unpredictable to all others"); and by *What Cannot Be*, chapter 8, section "Chance From Outside, Choice From Inside" ("We know that we cannot predict choices; if we could, they would be causes and not choices").

Choice has three parts, a range of what is open, the selection, and the consequence, and a choice without its consequence is not yet a choice; "Because the world is causal, what is chosen goes on to have effects; because it is not determined, the one who chose could have chosen otherwise". Carried by *Causality Without Determinism*, chapter 6, section III, and section VIII, "Questions".

Cause and choice are present together in what a person does, in a proportion that changes from act to act: a habit is a choice made so often that it runs almost wholly as cause, a turning point in a life is a run of causes bent almost wholly by choice, and the life of a person is the movement of the proportion of cause to choice in their acts; "Choice and causality are conjugate: each can be held more fully only as the other is held less fully,

and neither comes before the other". Carried by *Causality Without Determinism*, chapter 1, "Two Concepts, Three Differences", section VI, "Where Causality Lives", for the quoted sentence (the same words stand in *What Cannot Be*, chapter 5); and chapter 6, section IV, "The Conjugacy of Choice and Causality" ("A habit is a choice made so often that it runs almost wholly as causality: the hand reaches for the light switch").

Meaning is present wherever comparison occurs, and it cannot be removed: every line drawn to mark where meaning stops is itself drawn by a comparison, made from where someone or something stands, and such a comparison is significant to the one making it, which is meaning in the sense of the entry above; to declare that nothing matters, that nothing has meaning, is to weigh things for their worth, which is an act of comparison; so the declaration itself has meaning, in that sense. Carried by *What Cannot Be*, chapter 7, section "Meaning Cannot Be Removed" ("Meaningful, here, means significant to the process an outcome came from"; "meaning is present wherever comparison occurs, and it cannot be removed").

Every act of comparison has a part that nothing before it fixes, and a beam balanced to within a hair shows that part plainly. Carried by *Causality Without Determinism*, chapter 5, section IV; the beam balanced to a hair is this book's picture.

Chapter Nine: Are You Only a Bag of Atoms?

"Chemistry is made of nothing but electrons, nuclei, and light; that is not in question". Carried by *The Last Turtle*, chapter 27, "The Size of Chemistry", section IV, "The Failure of Reduction, Stated Exactly".

The list of the kinds of particle is short and closed, and still the matter those kinds make is not simple: matter of many different structures needs only a few kinds, combined in many ways; this is a point about matter, and it stands beside Hossenfelder's point about theories (that the theory of smaller things need not be simpler); it is not the same claim. Carried by

The Last Turtle, chapter 27, section I, "The Wrong Level" ("Richness of structure does not need many kinds; it needs a few kinds, combined in many ways"); her caution is in *Lost in Math*, chapter 10, "Lost in Math".

The small drug-like molecules that the rules of chemistry allow have been estimated at about a one followed by sixty zeros, and only a sliver of them has ever been made. Carried by *The Last Turtle*, chapter 27, section II, "Chemistry, the First Exemplar". Exact value: about 10^{60} (Bohacek, McMartin and Guida, 1996).

In 1929 Paul Dirac wrote that the laws needed for the whole of chemistry were completely known, and that the difficulty is only that applying them exactly leads to equations much too complicated to be soluble. Carried by P. A. M. Dirac, "Quantum Mechanics of Many-Electron Systems", *Proceedings of the Royal Society of London A* 123 (1929), 714 to 733; and by *The Last Turtle*, chapter 27, section IV.

The hydrogen atom is solved exactly and helium is computed to extraordinary precision, while every method in use for the chemistry of actual molecules approximates, one by leaving out the correlation of the electrons, another by carrying a term that is chosen and not derived; exact derivation is never possible except for the simplest systems. Carried by *The Last Turtle*, chapter 27, section IV, which names the Hartree-Fock method and density functional theory.

"In principle, no description, however refined, contains everything that it describes". Carried by *The Last Turtle*, chapter 27, section IV; the same ground is restated in *Physics Is Not Math*, chapter 11, "Why the Order Surprises", section V, "What a Simulation Shows", where a description and what it describes take the two characters, one each, so that the description reaches what it describes as closely as one wishes without containing it, as a map redrawn at any fineness stays a map.

Reductionism, in *The Last Turtle*'s sense, "explains every whole wholly by its parts and by their earlier states", and "That explanation leaves choice out of the account". Carried by *The Last Turtle*, chapter 27, section

VII, "What Reductionism Leaves Out", with the definition in its Glossary ("the claim that a description at a lower level exhausts the thing at a higher level").

This account holds, as firmly as Hossenfelder does, that a thing is made of its parts and of nothing else, and it excludes reductionism in *The Last Turtle*'s sense, the claim that a description of the parts contains everything the thing is; choice, which Chapter Eight explained, is what that explanation leaves out; in the living cell the description falls behind the thing: "In a cell, differences too small to record grow into differences that decide what happens, so no finite description of it stays adequate for long"; Hossenfelder's definition of reductionism, that the behavior of a whole can be deduced from its parts, asks that a description of the parts leave out nothing the whole does; a person's choice is something the whole person does, and an explanation by the parts and their earlier states leaves it out, so here this account parts from her definition. Carried by *The Last Turtle*, chapter 27, section IV, "The Failure of Reduction, Stated Exactly", section V, "Complicated and Complex", and section VII, "What Reductionism Leaves Out" ("That explanation leaves choice out of the account"); her definition and her result are in *Existential Physics*, chapter 4, "More Is More" (reductionism, "according to which the behavior of an object can be deduced from ("reduced to", as the philosophers would say) the properties, behavior, and interactions of the object's constituents"; "if you know what the small things do, then you can tell what the large things do").

The arrow of time (an order that runs one way, without a break), hard randomness (an outcome that no prior specification fixes, however complete) and the subjective (the side from which experience happens, the stance of the one to whom things happen) are three features bound together: where any one is present, so are the other two, and where any one is missing, all three are missing; every interpretation of quantum theory keeps the three together or drops all three at once. Carried by *What Cannot Be*, chapter 22, "Why No Computation Is Everything", section "The Bound Triple, Again"; the gloss of hard randomness is *Causality Without*

Determinism's, in its Glossary, which *What Cannot Be* repeats in the same section. The piece of music heard for the first time is this book's picture of the three.

A thing that has the three together has an inside: a side of its own, from which the comparing is done and to which the outcome happens. Carried by *What Comes After the Dark*, chapter 7, "Can a Mind Keep Thinking for Ever?", section "What a Thought Needs".

I identify the three, taken together as one act, as consciousness. Carried by *What Cannot Be*, chapter 22, section "The Bound Triple, Again" ("I identify it directly as consciousness"); and by *Causality Without Determinism*, Glossary.

A computation is a procedure that goes, step by step and by fixed rules, from one state to the next, where each state is a finite string of symbols. Carried by *What Cannot Be*, chapter 21, "Are We Living in a Simulation?", section "A Computer With No Limits".

The Incommensuration Theorem, exactly: "Symmetry and continuity cannot both be applied, simultaneously and fundamentally, to any event or comparison; and neither can asymmetry and discontinuity". Carried by *Physics Is Not Math*, chapter 2, section VI, "The Theorem"; by *The Last Turtle*, chapter 26, "What Can Be Modeled", section V, "The Quantum Computer and the Single Outcome"; and by *Causality Without Determinism*, chapter 1, section VII. Continuity is having no gaps, so that a small change of setting gives a small change in what is found. In the Incommensuration Theorem, 'fundamentally' means held exactly, at the foundation.

A computation holds symmetry exactly, at the foundation of the computation, in that one rule is applied the same way at every step. So, by the Incommensuration Theorem, a computation is discontinuous at the foundation of the computation, and no continuity can be built out of the steps of a computation. A computation is a mosaic in time. The arrow of time is continuity with asymmetry, so a computation lacks the arrow of time. A computation also lacks hard randomness, since each step of a

computation is fixed by the step before. Lacking two of the three features that are bound together, the arrow of time and hard randomness, a computation also lacks the third feature, the subjective. So classical computation, however intricately organized, cannot be what consciousness is, whatever the computation does and whatever laws consciousness arises under. Carried by *Causality Without Determinism*, chapter 5, "Computation, Consciousness and Simulation", section VI, "Why a Computation Cannot Be What Consciousness Is" ("A classical computation is a mosaic in time: one rule applied the same way at every step, which is symmetry perfected"; "A continuity cannot be assembled from such steps"; "And because the three are bound, lacking two it cannot have the third: it lacks the subjective"); and, as a restatement in plain words, by *What Cannot Be*, chapter 22, section of the same title. Classical computation is defined in *Causality Without Determinism*, Glossary, as "a deterministic algorithm on ordinary digital machinery".

This account reaches Roger Penrose's conclusion, that understanding is not computing, on other ground, needing neither Gödel's theorem nor any particular mechanism in the brain. Carried by *Side by Side*, Volume One, "Two Roads to Reality", section VIII, "Mind, Computation and Gödel"; and by *Causality Without Determinism*, chapter 5, section IX, "Questions".

The update on measurement is the change of the shared record of what has been found, and that change is the whole of the update, so the update holds no hidden process. Carried by *The Quantum Passage*, chapter 9, "The Measurement Problem Dissolved", section IV, "Why Collapse Is Not Physical".

Only a physical process making comparisons in the world can have an inside, and living things are processes of that kind; whether a thing has an inside "never depends on which program it runs"; so a program can be built to behave as a person behaves, and the program never supplies consciousness; whether a brain built of chips has an inside is settled by what kind of physical process the chips make, and never by the arrangement they copy or the program they run; this account ties an inside to a physic-

al process making comparisons in the world, of whatever material, and denies an inside to any program, taken as a program. Carried by *What Cannot Be*, chapter 22, section "What Computation Can Do" ("Whatever has it, has it as a physical process making comparisons in the world, with an inside, as living things do, and the program it runs never supplies it"; "The question for any future device is therefore what kind of physical process it is, and not which program it runs"); and by *What Comes After the Dark*, chapter 7, section "What a Thought Needs" ("only a physical process making comparisons in the world can have an inside, as living things do"). This account states two things that hold together: the bearer of consciousness is a physical process making comparisons (*What Cannot Be*, chapter 22); consciousness itself "is not a phenomena or a process" (*An Immanent Metaphysics*, chapter 9, "Evolution", section "Natural Consciousness", aphorism 2.52-5). Hossenfelder's first possibility, that consciousness is computable if it arises from the laws we already know, uses her definition, that a process is computable "if it can be produced by a computer algorithm" (*Existential Physics*, chapter 9, "The Limits of Math"); the entry's result is the different result this account reaches.

Uploading a mind, on this account, is a category error and not a difficult engineering problem, because the three things experience needs are exactly the features computation cannot represent, and no hardware supplies them: "A person is not a very large file". Carried by *What Cannot Be*, chapter 22, section "A Person Is Not a File".

A system that reproduced a person's behavior to any faithfulness "would not be that person, or any person". Carried by *What Cannot Be*, chapter 22, section "A Person Is Not a File".

"Artificial intelligence is possible": computation can "calculate, predict, translate and converse, and do all of it superbly"; intelligence, as competence at a task, is laid out for anyone to check from outside; the fluent reply in a chat window is behavior, and a program produces it; "a program, as a program, has no one in it"; the line this account draws runs between processing and experience, and a program of any intelligence, taken as a pro-

gram, stands on the side of processing. Carried by *What Cannot Be*, chapter 22, sections "A Reply With No One Behind It" ("The fluent reply in the chat window is behavior") and "What Computation Can Do".

A copy made by scanning is a copy of the outside: "Identity, in the sense of a single unitary consciousness, is not something a copy can carry"; the no-cloning theorem of 1982 "gives this a physical correlate", since no single operation can copy every unknown quantum state. Carried by *The Last Turtle*, chapter 26, section IV, "What Cannot Be Copied" (Wootters and Zurek, 1982; Dieks, 1982).

This account counts the other branches of the many-worlds interpretation as structure laid out in the mathematics, never found in any act of comparison. Carried by *Side by Side*, Volume One, "The Wave Function and the One Who Finds", section III, "The Branches".

A whole world fixed completely by one law, branches and all, joins perfect symmetry to perfect continuity, since the same law carries every state into the next and every state is fixed with no gap; the Incommensuration Theorem forbids that pairing, so the many-worlds account, taken as a description of a whole world, is excluded, and its copies of you go with it. Carried by *Physics Is Not Math*, chapter 8, section VII, "Three Grounds"; and by *Side by Side*, Volume One, "Tasks, Runs and Worlds", section V, "The Multiverse". At the scope of an account of knowing, this account states a second claim: a theory that removes all first-person structure is limited, not refuted, in what it can claim (*Incommensuration; The Theorem and the Three Axioms*, chapter 15, section III).

Everything a computation produces can be listed, and the points of a continuum cannot be listed; so reality holds what no computation, which is a listing, can reach. Carried by *What Cannot Be*, chapter 21, sections "What No List Can Hold" and "The Consequence, and the Amplifier", with Cantor's proofs of 1874 (the real numbers cannot be listed) and 1891 (the diagonal argument).

The arena of space and time is continuous, with no least step: the account derives this, and the arena has been found smooth at every scale yet probed. Carried by *What Cannot Be*, chapter 21, section "The Arena Has No Least Step", which cites the gamma-ray burst measurement of 2009 placing any grain of space that would slow light below the Planck scale.

A simulation of space and time can be refined to come as close as one wishes to what space and time are found to be, and no stage of it ever contains them. Carried by *What Cannot Be*, chapter 21, section "The Consequence, and the Amplifier"; and by *The Quantum Bridge*, chapter 7, "The Reach of Simulation", section IV, "The Reach of a Simulation", Proposition 7.1.

Systems in the world are sensitive to how they start, so a simulation cut at a fixed precision parts, given time, from the continuous world on the scale of everyday things. Carried by *What Cannot Be*, chapter 21, section "The Consequence, and the Amplifier".

A simulated world that contains people, each with experience of their own, shares the world's hard randomness, its arrow of time and its subjectivity, and so has no inside of its own and is a region of the one world, as a prison cell is a walled-off room of one world; the hypothesis in the form "that we are real subjects in a world that is not real" is excluded by the structure of comparison, as a matter of principle and therefore of all future practice. Carried by *What Cannot Be*, chapter 21, section "A Simulated World Is a Region of the One World" ("So a simulated world with real subjects shares with the world that runs it its hard randomness, its direction of time and its subjectivity. It has no bound triple of its own"); and by *Causality Without Determinism*, chapter 5, section VIII, "Simulation"; the prison cell is this book's picture.

Bostrom's argument offers three choices (almost no civilization reaches the power to run such simulations, or almost none that reaches it wants to, or we are almost certainly simulated, since simulated observers would far outnumber the others); the third rests on a count that treats each simulation as a separate world with observers of its own, and a simu-

lation is a region of the one world, so the separate worlds the count needs are not there, and the count gives the third choice no ground in the form that matters to us, which *What Cannot Be* states as "that we are real subjects in a world that is not real". Carried by *What Cannot Be*, chapter 21, section "A Simulated World Is a Region of the One World" ("The argument counts simulated observers as if each simulation were a separate world with its own observers"; "A simulation is not a separate world").

A thought is made of comparisons: only a physical process making comparisons in the world can have an inside, and a thinker, of whatever material, thinks as such a process; and 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 every thought needs signals, which is one step of Hossenfelder's size argument, and this account agrees with that step. Carried by *What Comes After the Dark*, chapter 7, section "What a Thought Needs" ("only a physical process making comparisons in the world can have an inside, as living things do"), where the book's own sentence on the thinker ("thinks only as a physical process making comparisons") is said of a thinker of the far future. This account accepts her count as a limit on thinking: neighboring clusters of galaxies have had time to trade only about a thousand signals, so the universe as a whole has had time for very little thought (*Existential Physics*, chapter 8, "Size Matters"); it does not reach her conclusion that the universe is too big to be conscious, and where it parts from her is given below.

Two results of this account bear on Hossenfelder's conclusion that universes inside particles are incompatible with what is known, and both stand with it: the list of the kinds of particle is closed, so no further kind of particle lies hidden inside the known ones; and in the visible universe this account finds one level only, the physical, with no machine beneath it whose causes could be called on, as a program calls on the computer that runs it, so that "all of the information of what happens must come from somewhere within that one level"; so no deeper level lies beneath the particles from which a universe inside one of them could be supplied. Carried by *Side by Side*, Volume One, Appendix B, "The Sealed Record",

section VII, "The Kinds of Particle", Prediction 30 ("No further kind of particle will be found"); and by *What Cannot Be*, chapter 21, section "One Level Only" ("In the visible universe there is one level only, the physical"), where the one level is said of a simulating level beneath the world. No book of this account names universes inside particles; these two passages bear on her conclusion, neither states it, and the last step, from one level to no universe inside a particle, is this book's inference.

This account places consciousness in interaction, and in no property of matter: "Wherever interaction occurs, some form of consciousness is present". Carried by *Side by Side*, Volume Two, "The Measure of an Inside", section V, "Grades of Experience and Choice in Every Degree", quoting *The Immanent Metaphysics and the Modern Engagement*, chapter 7, section V; and by *Causality Without Determinism*, chapter 2, "Non-Polarization; The Chain of Distinctions", section IX, "Consciousness Between the Poles".

Consciousness is a property of interaction whose degree and kind go with the richness and structure of the interaction, with no least size: a thermostat's interaction with temperature is real and simple, and a brain's interaction with a world is real and enormously complex; a photodiode's single undetermined click is choice at its least gathered, and a living person is choice gathered across every channel of perception into one persisting stance, gathered meaning held together by one self that persists. Carried by *Side by Side*, Volume Two, "The Measure of an Inside", section V ("in the richest of them the choices made are held together by one self that persists"), quoting *The Ground of Objection*, entry T3.19. Hossenfelder grades consciousness by the information processed, and sets a least size; this account grades it by the richness of the interaction, and sets none. This account speaks of degrees of consciousness at two scopes, and both statements hold. As the degree of interaction across the boundary of the self, consciousness has a degree, which correlates with the richness and structure of the interaction (*An Immanent Metaphysics*, chapter 9, section "Natural Consciousness", aphorism 2.52-1; *The Ground of Objection*, T3.19).

As something to be measured objectively, consciousness "is not objective and cannot be measured (consciousness does not admit of degrees)" (*An Immanent Metaphysics*, aphorism 2.52-3).

Hossenfelder's collider argument shows that an electron carries no hidden store of inner states that would change how many electrons a collision makes; this account places consciousness in no property of matter, so it looks for no such states, and her collider result and this account both stand. Carried by the interaction entry above (*Side by Side*, Volume Two, "The Measure of an Inside", section V); her argument is in *Existential Physics*, chapter 8, "Are Electrons Conscious?".

The word "panpsychism" is used in three senses, and each statement holds in its sense. In the sense Hossenfelder rejects, an account that begins from small experiences of matter that must somehow be combined, this account "is structurally different from panpsychism", since it begins from interaction (*Side by Side*, Volume Two, "The Measure of an Inside", section V). Her physics-compatible panpsychism, with consciousness in degrees above a least size (*Existential Physics*, chapter 8), shares this account's grades and parts from it on the least size. In the sense of all things as alive and intentional, intentional meaning having a will and a purpose of one's own (the aphorism before it speaks of how far a machine seems "self willed" and "conscious" to any perceiver), "the concept of panpsychism ... is everywhere applicable (scale invariant)", because the degree to which a thing appears conscious, to anyone perceiving it, is never exactly zero (*An Immanent Metaphysics*, chapter 9, "Evolution", section "Pan-Psychism", aphorisms 2.53-1 and 2.53-2).

Consciousness is at work at every scale of being, and one and the same idea of consciousness applies at every level of scale; the being of consciousness, as distinct from the idea of it, "does not have position, scale, or extent", so consciousness is found in things of every size and itself has no size; and everything "from atoms to universes" has non-zero and positive degrees of meaningfulness, purpose and value. Carried by *An Immanent Metaphysics*, chapter 9, section "Natural Consciousness", aphorism 2.52-4

("Consciousness, as a scale invariant, is operant (real) at all scales of being") with its note on scale invariance ("the same concept of consciousness shall be applicable at all levels of scale within all domains"), and section "PanPsychism", aphorism 2.53-3.

A thought and consciousness are told apart: a thing that has an inside is a physical process making comparisons, and its thoughts are made of those comparisons, each of which needs a signal; consciousness itself is not a process: the idea of a process combines only two ideas, existence and interaction, and the idea of consciousness combines only interaction and creation, without the idea of existence, where creation is potentiality, what is never repeated and is fixed by nothing before it; so every thought needs signals, and size limits how much a thing can think, while consciousness is found wherever there is interaction, at every scale, the universe's included, and size does not decide where it is found. Carried by *An Immanent Metaphysics*, chapter 9, section "Natural Consciousness", aphorism 2.52-5 ("Consciousness is not a phenomena or a process. The concept of consciousness refers to a combination of only the concepts of interaction and creation (without the concept/assumption of existence). In contrast, the concept of process refers to a combination of only the concepts of existence and of interaction"); for creation, chapter 4, "Correspondence Metaphysics", section "Theory of Creation", aphorisms 1.73-3 ("Creation is potentiality, rather than actuality"), 1.73-11 ("Creation is not repeatable. Creation has no process, and is not causal") and 1.73-13 ("Creation is not an event, but rather is an aspect of all events"); and *What Comes After the Dark*, chapter 7, section "What a Thought Needs". That the two hold together, as thought and the being of consciousness, is this book's statement of how the two passages fit.

In a study published in *Nature* on 30 April 2025, two rival theories of consciousness each said in advance where and when the brain's activity would track what a person perceived; the brains of 256 people were measured, and each theory came out partly right and partly wrong. Carried by

the Cogitate Consortium, "Adversarial testing of global neuronal workspace and integrated information theories of consciousness", *Nature* (published 30 April 2025).

The brain science of consciousness is genuine, valuable and necessary, as the study of consciousness from outside. Carried by *Side by Side*, Volume Two, Appendix M, "The Registered Predictions Beside Giulio Tononi", section II, "Where the Two Accounts Predict Differently" ("Neuroscience studies the omniscient-modal aspect of consciousness, and that work is genuine, valuable, and necessary", quoting *The Immanent Metaphysics and the Modern Engagement*, chapter 7, section XV), and "The Measure of an Inside", section VII, "The Charge of Pseudoscience, and What a Measurement Can Reach".

Experience itself is held in the act of experiencing, by the one who experiences, and no measurement made from outside takes another person's act of experiencing as its content; so the question of what experience is belongs to metaphysics, the study of what must be so for anything at all to be known; only a metaphysical account of consciousness is possible: "Perception cannot perceive perception". Carried by *Side by Side*, Volume Two, "The Measure of an Inside", section VII; and by *An Immanent Metaphysics*, chapter 9, section "Natural Consciousness", aphorism 2.52-2; the gloss of metaphysics is the Preface's, from *Home in the World*, Prelude, "Two Crews, One Tunnel", section "The Crew from Knowing".

Chapter Ten:
Does the Past Still Exist, and Why Does Time Run One Way?

Every comparison has a content, what the verdict of the comparison is about, and a context, the respect in which the two things compared are two; in physics, content is the matter, and context is the arena of space and time in which the matter is found. Carried by *Physics Is Not Math*, Appendix C, "Glossary", entries "Content" and "Context"; and by *Side by Side*, Volume One, "Terms of the Collection", entry "Content and context".

An entropy is a count: the number of states of a system that the comparisons available from some context cannot tell apart; the count is made relative to that context, and the box around a gas, the region of space in which the gas is found and from which every measurement on it is made, is the context relative to which its states are counted. Carried by *The Compactification*, chapter 3, "The Past Hypothesis at the Turn", section V, "Every Count Has a Context"; and by *Side by Side*, Volume Two, "Janus and the Turn", section II, "Where the Collection Stands With Him", subsection "Entropy needs a context". For the specialist: the count of a black hole is the Bekenstein–Hawking entropy $S = k_B c^3 A/(4G\hbar)$, where k_B is Boltzmann's constant, c the speed of light, A the area of the horizon, G Newton's constant and $\hbar$ the reduced Planck constant, read in *The Compactification*, chapter 3, section V, equation 3.1, as a count relative to the outside.

This account grounds the count in the context of the comparison, and the one who compares may be a thermometer as well as a person. Carried by *Why Time Travel Is Not a Concept*, chapter 1, "The Question", Key Concepts ("Comparer: Whatever makes a comparison: an instrument, a detector, an interaction. Not a mind").

The universe has no box: a count for the whole universe needs a context for the whole, and the universe has none outside itself. Carried by *Side by Side*, Volume Two, "Janus and the Turn", section II, subsection "Entropy needs a context".

Inside the history we live in, entropy grows, as the second law says; a final state of greatest disorder lasting forever, the old "heat death", has nothing to be counted against. Carried by *What Comes After the Dark*, chapter 8, "Is the Long Emptying the End?", section "The Third Ground: Every Count Has a Context".

Information in the first sense is the form of the matter, what the matter is and which of its alternatives it has taken, carried wherever the matter goes; information in the second sense is a count of states relative to a context, which is an entropy. Carried by *What Comes After the Dark*, chapter 9,

"What Crosses Over, and What Stays Behind?", section "Two Things Called Information" ("In the first sense, information is the form of the content: what the matter is, and which alternatives it has taken"), and its Glossary; the letter in the post office is this book's picture.

Information in the first sense is never destroyed, black holes included: what falls into a black hole is kept, out of reach of everyone who stays outside, and the matter does not cease, and its form goes wherever the matter goes; Hossenfelder reaches the same result from the law that runs backward, and this account from the matter that does not cease, on separate ground. Carried by *What Comes After the Dark*, chapter 9, section "What Crosses" ("the content does not cease at the end, and so a new context forms around it"; "and the form of the content, information in the first sense, is carried with it"); by *The Gravitational Passage*, chapter 18, "The Interior Passage", section XIII, "Predictions", entry "No information paradox"; and by *The Unquantized Arena*, chapter 17, "Black-Hole Information and the Page Curve", opening summary.

A description of the world written from outside, in the third person, holds every moment alike, and so it has no "now" in it; the present is singled out only from inside. Carried by *Home in the World*, chapter 4, "The Circle and the Floor", section "Two Kinds of Perfect Knowing" ("No third-person account of the world has a 'now' or a 'here' in it; from that vantage every moment and every place is like every other. Only from inside does now have its particular weight").

To exist is to stand as structure: timeless, the same in every instance, able to be held in view as a whole; to be real is to be given in an actual act of comparison, here, now, with the future still open; the recipe exists, and the baking is real. Carried by *Home in the World*, chapter 7, "The Open Future", section "A Recipe and the Cooking", and "For the Specialist", section "Exists and Real; Causation and Determinism".

Relativity describes space and time together as one four-dimensional pattern; on this account the dimension of time in that pattern exists, every moment of it with the same standing as every other, and the events that

exist along it are the events that have already happened; those events are structure, the past laid out with every event in its place; last Thursday is still there, as a place in the pattern; its findings were real when they were made, and what remains of them now is their records. Carried by *The Basis of Physics*, Essay 11, section VI, "Time as Process, and Not Only as Dimension" ("Geometric time is the dimension, and it exists; event time is the process"; "A dimension is an omniscient notion: a line along which every point has the same standing as every other"); and by *Why Time Travel Is Not a Concept*, chapter 1, section III, "What Exists and What Is Real".

Geometric time, the dimension of time laid out as structure, exists, and the events laid out along it reach as far as the present; event time, given in acts, is real; each does its own work, and neither is an illusion laid over the other. Carried by *Why Time Travel Is Not a Concept*, chapter 1, section III, and its Key Concepts; and by *Measurement; The Steps from Comparison to Physics*, chapter 12, "Time", section II and section VIII, "Questions".

"The block universe takes geometric time for the whole, and drops event time". Carried by *The Basis of Physics*, Essay 11, "The Structural Arrow of Time", section VI, "Time as Process, and Not Only as Dimension".

A fully fixed world would need laws that are perfectly the same everywhere, which is symmetry, and no gap anywhere in what those laws fix, which is continuity, both perfect at once; the Incommensuration Theorem, a structural fact about the nature of knowing, states: "Symmetry and continuity cannot both be applied, simultaneously and fundamentally, to any event or comparison; and neither can asymmetry and discontinuity"; so "the future does not exist in the sense the past does": the events of the future are not yet part of what exists. Carried by *The Basis of Physics*, Essay 11, section VI ("If determinism is precluded, the future does not exist in the sense the past does"); and by *Measurement; The Steps from Comparison to Physics*, chapter 12, section IV; the theorem's source is given under Chapter Two above.

Two events too far apart for light to join have no fixed order: a lamp flashing in the middle of a moving railway car reaches both end walls at one moment for the rider, the back wall first for someone beside the track, and the front wall first for a faster train overtaking; a signal between two such events would, for some traveler, arrive before it was sent; the order of acts in every comparison runs one way, so no signal joins two such events, and each traveler's own findings come in one order that runs forward. Carried by *What Cannot Be*, chapter 12, "The Shape of What Can Reach What", section "A Signal That Would Arrive Before It Was Sent", and the railway car before it. Kept apart, "exists" and "is real" give a past that exists as structure, a present that is real, and a future that is not already there; Hossenfelder's step from "happen at the same time for someone" to "exists now" uses the one word for both (*Existential Physics*, chapter 1).

George Ellis reached the same open future from inside physics, in his evolving block universe of 2006, in which the future boundary of the block keeps advancing because what will happen is not yet decided; he reached it by way of quantum chance and the one-way step of measurement, and this account reaches it from the structure of comparison. Carried by *Side by Side*, Volume Two, "The Open Future", section II, "The Evolving Block Universe" ("The future does not yet exist, because what will happen is not yet decided"; "Ellis reached the open future from physics, by way of quantum indeterminism and the irreversibility of measurement"; "The collection reaches the open future from the structure of comparison, which every measurement Ellis relies on already has").

Lawful reversal asks for a symmetry, that reversing time leave the laws the same, and the laws are the same with time reversed to an extraordinary degree; that symmetry of the laws guarantees lawful reversal and does not guarantee faithful reversal; faithful reversal asks for symmetry and continuity, both perfected, together, which is the pair the Incommensuration Theorem forbids; so no process, at any scale, can be run back faithfully. Carried by *The Basis of Physics*, Essay 11, Abstract, section III, "Lawful Reversal and Faithful Reversal", section VII, "Consistency with Physical Law" ("The laws exhibit time-reversal symmetry to an ex-

traordinary degree, and the argument does not say otherwise. It says the symmetry cannot be perfect"), and section VIII, "Summary"; and, as a restatement in plain words, by *What Cannot Be*, chapter 13, "Why Time Has a Direction", sections "Two Ways to Run Backward" and "What We Now Know".

Because no process, at any scale, can be run back faithfully, time has a direction in every single interaction, and the direction of time needs no crowd of particles, no entropy and no special beginning. Carried by *The Basis of Physics*, Essay 11, Abstract, and section IV, "Why This Arrow Is Non-Entropic".

The past cannot be rebuilt from the present by running the laws backward, because the present is never given completely enough to run back from. Carried by *The Basis of Physics*, Essay 11, section IV.

The spin echo, found by Erwin Hahn in 1950, undoes the falling out of step only in part, and it undoes no finding: the finding that the signal had faded was made before the pulse and its record stays, and the returning signal is a new finding. Carried by *What Cannot Be*, chapter 13, section "What Can Be Run Backward, and What Cannot"; and by *Why Time Travel Is Not a Concept*, chapter 5, "The Record Is Not Undone", section IV, "Spin Echoes and Loschmidt".

The decays of neutral kaons break the symmetry called CP, which swaps every particle for its antiparticle (a particle like it in every respect except that each of its charges is opposite) while reflecting space as in a mirror; by a general theorem of particle physics (the CPT theorem), that break means the laws are not perfectly the same with time reversed; the time asymmetry has since been seen directly; the Incommensuration Theorem says why the sameness stops short of perfect: the sameness of the laws with time reversed is a symmetry in exactly the theorem's sense, the same laws across a change of setting, here from one direction of time to the other; made perfect, that sameness would hold "for every process, at every scale, in every context, without exception", which is reversal "not merely lawful but faithful": it retraces exactly the states the original

passed through, so it needs the state described with no gap at any point or scale, which is continuity; so perfect sameness of the laws with time reversed asks for symmetry and continuity together, both perfect, the first of the two pairs the theorem excludes; the theorem's words "simultaneously and fundamentally" are the reason the laws can still come so close to perfect sameness: within any finite domain, symmetry and continuity "co-occur to finite degree", and what they cannot do is "both be perfected at once", a finite domain being any bounded range of processes, scales and contexts, short of the whole reach that perfect sameness would need; so the laws are the same with time reversed to an extraordinary degree, and never perfectly; I identify these findings as a place where the impossibility of perfecting the symmetry of time has become visible to instruments. Carried by *The Basis of Physics*, Essay 11, section II, "Symmetry, Continuity, and the Theorem" ("The qualifier is part of the theorem and is never dropped. Within any finite domain, symmetry and continuity co-occur to finite degree. What they cannot do is both be perfected at once"), section III, "Lawful Reversal and Faithful Reversal" ("Time-reversal symmetry is a symmetry in exactly the sense just defined"; "It would require that the reversal hold for every process, at every scale, in every context, without exception"; "Faithful reversal requires a state with no gaps, no ambiguities, no residue left to its own devices"; "Full specification of that kind is precisely continuity in the sense the theorem uses"; "So perfect time-reversal, reversal that is not merely lawful but faithful, requires two things at once: the symmetry of the laws under reversal, and the continuity of the state specification"), and section VII, "Consistency with Physical Law" ("the reason is the qualifier in the theorem"; "It says the symmetry cannot be perfect"; "By the CPT theorem, CP violation entails T violation"; "a place where the impossibility of perfecting temporal symmetry has become visible to instruments"); and by *What Cannot Be*, chapter 13, section "What Physics Already Shows". The scope of the identification, in the same section: "The argument says that some asymmetry must exist. It does not say how large, in which interaction, or through what mechanism". The measurements: J. H. Christenson, J. W. Cronin, V. L. Fitch and R.

Turlay, *Physical Review Letters* 13 (1964), 138 to 140; the CPLEAR Collaboration, *Physics Letters B* 444 (1998), 43 to 51; the BaBar Collaboration, *Physical Review Letters* 109 (2012), 211801.

Every record ever found, by any instrument, is a record of the past; no instrument holds a finding before the act that makes it; I identify the one-way order of every act of comparison, from what could be found, to the act, to the record, with the direction of time. Carried by *Measurement; The Steps from Comparison to Physics*, chapter 12, section I, "One Direction, from the Single Stance", and section III, "The Three Times as One Triple" (the identification P19: "I identify the one-way order of findings, the order of Axiom II, with the direction of time"); and by *Home in the World*, chapter 7, section "Records That Are Never Un-laid".

Making a record is itself a change that cannot be undone, and it raises the entropy of the instrument that holds it, so each act of recording joins the two arrows in one event; the growth of disorder is how the one-way order of acts shows itself in things made of very many parts. Carried by *Measurement; The Steps from Comparison to Physics*, chapter 12, section VII, "The Two Arrows"; by *What Cannot Be*, chapter 13, section "An Arrow Beneath the Arrow of Heat"; and by *The Basis of Physics*, Essay 11, section IV.

"The Past Hypothesis is not the source of the arrow". Carried by *What Cannot Be*, chapter 13, section "An Arrow Beneath the Arrow of Heat".

As a statement about how our history began, the Past Hypothesis has two halves that stand differently: the high entropy of the matter is simply what is observed, and the low entropy of gravity has a reason in this account. Carried by *The Compactification*, chapter 3, section VIII, "The Magnitudes", subsection "Where the Past Hypothesis stands"; and by *Side by Side*, Volume Two, "Janus and the Turn". This account treats the low entropy of the beginning at two scopes, and both statements hold. At the scope of the structural arrow of time, the argument does not say why the starting condition was what it was, since the direction of time never depended on it (*What Cannot Be*, chapter 13, section "An Arrow Beneath the Arrow of Heat"; *The Basis of Physics*, Essay 11, section IV). At the scope of

the beginning itself, the low gravitational entropy has a reason: the reset of the count at the turn (*The Compactification*, chapter 3, section VIII; *The Gravitational Passage*, chapter 18, section VIII). For the specialist: Penrose's improbability figure for the beginning, one part in $10^{10^{123}}$, is held in the same section, subsection "The improbability estimate", to presuppose "a count that no comparison makes".

The history of the universe comes in epochs: an epoch is one whole span of the universe's history, from one turn to the next, and ours began at the Big Bang; the turn is the boundary between two epochs, where the interiors of all the black holes of the ending epoch end together, as one end, and the next epoch begins, and no comparison reaches across it. Carried by *What Comes After the Dark*, chapter 9, section "What Crosses" ("So no comparison tells one interior's form from another's, and by the principle they are not two"); and by *Side by Side*, Volume One, "Two Roads to Reality", section V, "The Beginning and the Cycle of the Universe", subsection "The turn and Penrose's crossover" ("The collection identifies the ends of all black-hole interiors by the principle that "a difference that no comparison can register is no difference"").

Every count of an epoch's entropy, the count for gravity included, is made against that epoch's outside world as its context, the space and time outside its black holes, in which its matter is found; by the turn that outside world has emptied; no signal from the end of a black hole's interior ever reaches the outside world, so that end lies at no moment of the outside world's time; so at the turn nothing of the old outside world is there to count against. Carried by *What Comes After the Dark*, chapter 8, "Is the Long Emptying the End?", section "The Third Ground: Every Count Has a Context" ("The end of an interior lies at no moment of the outside world's time, so nothing of the outside world is there to count against"; "The count for the matter is a count of the same kind, made against the same outside world, which ends"), and chapter 10, "Could Anyone Escape?", section "No Other Sky Along Any Path" ("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"); and by *The Gravitational Passage*, chapter 18, section VIII, "One Process, Two Sides". The census of a newly founded country, which starts its own count, is this book's picture.

The new epoch's geometry has no past of its own to be lumpy with, so it begins even, up to small departures from evenness; its low entropy "is the count that a new context starts with". Carried by *What Comes After the Dark*, chapter 8, section "The Third Ground: Every Count Has a Context"; by *The Gravitational Passage*, chapter 18, section VIII; and by *The Compactification*, chapter 3, section VIII, subsection "The improbability estimate".

Penrose's eons and this account's epochs are both whole histories, each beginning where the one before it ends; Penrose joins two eons where nothing with mass is left in the old one, and this account joins two epochs at the turn; both reset the count of entropy at each new start: Penrose resets it by having black holes destroy information, and this account resets it by the ending of the context, and keeps the information. Carried by *Side by Side*, Volume One, "Two Roads to Reality", section V, "The Beginning and the Cycle of the Universe", subsection "The turn and Penrose's crossover" ("the end of one epoch becomes the beginning of the next, and there is no first"; "For Penrose, the remote future holds only massless radiation; nothing with rest mass is left to make a clock"; "Fourth, both reset the count of entropy by removing what the count needs").

Two grounds answer the Boltzmann-brain worry, which needs a universe that sits forever in a fully mixed calm: a featureless world would be perfectly symmetric and perfectly continuous at once, which no comparison ever finds; and a final state of greatest disorder has no context against which to be counted; so in this account no such calm is ever reached. Carried by *What Comes After the Dark*, chapter 8, section "The Second Ground: A Featureless Emptiness Is Never Found", quoting *The View from Inside*, and section "The Third Ground: Every Count Has a Context".

The Matter We Know, Volume Two, counts every arrangement with the same energy equally, on a ground that holds "whether or not" the system's motion passes through every such arrangement in time, which is the ergodic hypothesis; so Hossenfelder's conclusion that at least one fundamental theory cannot be ergodic costs this account's counting of states nothing. Carried by *The Matter We Know*, Volume Two, chapter 2, "The Counting of Ways", section II, "Every Microstate Counts Alike" ("The equal counting holds over the whole set of microstates with the given energy, whether or not the motion joins every pair of them"), and Key Concepts, entry "Ergodic hypothesis".

The present is where every measurement is made: "comparison is made only in the present, and the present is not one point on a line but the site of the interaction itself"; so Hossenfelder's sentence that the Now does not exist objectively is true in this account, with "exist" in its exact sense of standing as structure, and the Now is real, given in the act of comparison. Carried by *The Basis of Physics*, Essay 11, section VI.

"The present moment is the place where many possible futures converge into the one thing that actually happens"; physics describes what is left afterward extremely well, and the happening itself is given only in the act. Carried by *Incommensuration; The Theorem and the Three Axioms*, chapter 9, "Each Axiom Derived Again", section II, "Axiom II: The Cycle of Precedence", subsection "Time and the Reversal of Perspective".

Treating "exists" and "is real" as one word is what makes the present look like an illusion. Carried by *The Last Turtle*, chapter 7, "Real, Existent, Objective", section VIII, "Kant's Target".

Time runs one way in every single interaction, because no process can ever be run back exactly. Carried by *The Basis of Physics*, Essay 11, section VIII, "Summary".

Chapter Eleven: How Did the Universe Begin, and How Will It End?

The horizon seen from a beach is the edge of what can be seen, and not the edge of the sea; the beginning of our history is an edge of that kind. Carried by *At the Edge of Reality*, chapter 2, section "What This Means for You".

The past is known only by the impression it makes on the present; from those impressions one history of the universe is rebuilt, and traced backward that history runs toward a limit, which it takes for its beginning: "The Big Bang is that beginning, as our history finds it". Carried by *At the Edge of Reality*, chapter 2, "What Came Before the Big Bang?", section "The Answer of This Book". *At the Edge of Reality* is the plain-words form of *The Gravitational Passage*.

This account calls the limit the turn: the boundary between two epochs, where the interiors of all the black holes of the ending epoch end together, as one end, and the next epoch begins, and no comparison reaches across it; an epoch is one whole span of the universe's history, from one turn to the next, and ours began at the Big Bang. Carried by *What Comes After the Dark*, chapter 8, "Is the Long Emptying the End?", section "One End, and the Turn", and chapter 9, section "What Crosses"; the argument for the one end is given below.

I identify the Big Bang with the turn: the Big Bang is the turn as our history, traced back from inside our epoch, finds it; so the Big Bang is the beginning of our epoch, and not the beginning of the universe. Carried by *What Comes After the Dark*, chapter 8, section "One End, and the Turn" ("I identify the restoring of the outside world with the Big Bang of the new epoch"; "The Big Bang is the turn as it appears in that pieced-together history"), and chapter 11, "Has This Happened Before?" ("Chapter 8 identified the Big Bang of our own history with the turn, as our history, traced back from inside our epoch, finds it"); and by *At the Edge of Reality*, chapter 2, section "The Answer of This Book" ("The Big Bang is that beginning, as our history finds it").

No comparison is made across the turn, because nothing on either side has a moment at the turn itself: each side's history comes ever nearer to it and never reaches it; "So no comparison registers the turn as an event, and it cannot be known as one"; Hossenfelder reaches the same point from the data, and this account reaches it from the structure of comparison. Carried by *At the Edge of Reality*, chapter 17, "Why the Big Bang Looks Like a Beginning", section "No Comparison Across the Turn"; and by *What Comes After the Dark*, chapter 8, section "One End, and the Turn".

Inflation, proposed by Alan Guth in 1981, was brought in to answer three puzzles: why regions of the sky that no signal could ever have joined share one temperature, why space is flat on the largest scales, and why none of the monopoles is found that theories uniting the forces predict, made when one larger force splits into the three; the account answers all three without inflation, "from the turn and from the structure of the forces, so it needs no inflation"; and since I identify the first ripples with the form of the content carried through the turn, it excludes a long inflation, and a shorter one it neither requires nor excludes. Carried by *What the Beginning Left Behind*, chapter 13, "No Inflation Needed", opening ("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"), and sections "A Patch of Dough the Size of a City" and "A Long Inflation Is Excluded" ("In Chapter 11 I identified the first ripples with the form of the content carried through the turn"; "So, on that identification, the account excludes a long inflation"). Exact value: the sky is alike in every direction to about one part in a hundred thousand.

No monopoles were made, because in this account no single larger force ever split into the three forces of the particles, so nothing breaks in the way that makes monopoles. Carried by *What the Beginning Left Behind*, chapter 13, section "No Monopoles, No Strings, No Walls" ("In this account the forces were never one larger force, so nothing breaks in the way that makes monopoles, and the monopole problem does not arise").

The account has no inflaton at all; the reason, at its scope: the six held dimensions provide no such field, since their only fields, the two moduli that set their size and shape, are far too heavy to drive a slow-roll inflation. Carried by *What the Beginning Left Behind*, chapter 13, opening ("This account has no inflaton"), and section "Nothing for Inflation to Work With" ("The material: the six held dimensions provide no such field"; "So neither modulus can drive slow-roll inflation"); and by *The Gravitational Companion*, "Comparisons at Single Steps", section IX, "Inflation". Exact values: the two moduli weigh about 2.25 and 3.09 Planck masses (computed at first order in *The Gravitational Passage*), and slow-roll inflation would need a field far lighter than the rate of expansion it drives.

The favored models of inflation give the same kind of ripple as this account (one in which matter and light of every kind are uneven together, in step) and the same flat space; those models also give a slight tilt (the first ripples a little stronger on large sizes than on small, an index below one), and this account does not fix the tilt or its sign and takes them from measurement; so the measured kind of ripple and the measured flatness fit this account, which has no inflaton, and those models alike, and they are no evidence that there is an inflaton field. Carried by *The Compactification*, chapter 6, "The Primordial Departures", section IX, "Comparison with Observation", Table 6.1 ("None of them is yet a test that distinguishes this account from the standard picture with inflation: the inflationary models now favored also give an index below one, adiabatic departures, and a flat space"); the gloss of adiabatic is *What the Beginning Left Behind*'s ("every component of matter and radiation departs from uniformity together"). For the tilt, the same table gives this account's entry as "not fixed; sign of the tilt not fixed", where "not fixed" means "that the account does not fix the quantity and takes its value from measurement". The step after "so" is this book's inference from the quoted sentence: features that an account with no inflaton gives equally are no evidence for an inflaton. Exact value: the measured tilt of the ripples, the spectral index, is 0.9649 ± 0.0042.

The interiors of all the black holes are like funnels, each separate along its whole length; at their ends no comparison made in our epoch can tell one end from another, since no signal comes back out of any of them, and the new epoch carries no mark of which interior any part of it came from; this account holds that two things that no comparison, at any time, can ever tell apart are one thing; so the ends of all the interiors are one end, joined by being impossible to tell apart, and not by being pulled together; that one end is the turn, approached from one side by the collapse and from the other by the history of the new epoch, and reached from neither. Carried by *What Comes After the Dark*, chapter 8, section "One End, and the Turn" ("They are joined at their ends by being indistinguishable, and not by being pulled together"), and chapter 2 ("This physics holds that a difference no comparison can ever register is no difference"); and chapter 4, "Could Empty Space Change Its Nature?", section "Where the Hold Ends".

The whole sky of the new epoch comes from that one end, and that is why it is alike in every direction. Carried by *What the Beginning Left Behind*, chapter 13, section "The Sameness and the Flatness, Answered From the Turn" ("Regions of the sky that no signal within this epoch's history has connected are alike because they come from one domain").

I identify what lies on the other side of the turn with the collapse of the interiors of the black holes of the epoch before ours; so the question "what came before the Big Bang?" has that answer. Carried by *At the Edge of Reality*, chapter 2, section "The Answer of This Book" ("I identify what lies on the other side of the limit with the collapse of the interiors of the black holes of the epoch before ours").

The word 'before' names the order of a cycle, one epoch and then the next, and no clock measures a time across the turn. The cycle has no first performance. Carried by *At the Edge of Reality*, chapter 2, and chapter 20, "The Cycle Without a First Turn", section "A Creation Story With No First Moment"; the picture of the play performed from one script is carried by *What the Beginning Left Behind*, chapter 21, "What the Beginning Left Behind", section "A Play Performed from One Script".

The account starts from the present act of measurement and rebuilds the one history that the present requires. Carried by *What the Beginning Left Behind*, chapter 8, "The One Edge That Sets the Vacuum", section "Fixed Once"; and by *At the Edge of Reality*, chapter 17, section "How a History Is Made".

In Einstein's equations the bending of space as a whole is set once, at the start of an epoch, and the equations do not choose it; the start of our epoch carries over no length from the epoch before, since a length that nothing in our epoch could ever be compared with is no length of our epoch at all; the only length the start holds is the Planck length, at which gravity and the physics of the very small meet on equal terms, and a space bent on so small a length would close up at once or fly apart before anything could gather; such an epoch makes no stars and no black holes, so it gives rise to no epoch after it and is not the kind of epoch this cycle makes; so the start of an epoch in the cycle sets no bending at all, and space is flat. Carried by *What Comes After the Dark*, chapter 2, "Will It All Fall Back?", section "The First Way: Space Is Flat" ("So a length from before the beginning, which nothing in our epoch could ever be compared with, is no length of our epoch at all"; "An epoch that made no black holes could give rise to no epoch after it, so it is not the kind of epoch that this cycle makes").

Space is measured flat: one part in a thousand, give or take two, which is zero within the measurement. Carried by *What Comes After the Dark*, Appendix B, "What the Coming Measurements Will Measure", section "The Flatness of Space". Exact value: the curvature share $\Omega_k = 0.001 \pm 0.002$ (Planck satellite combined with the spacing of galaxies; Planck Collaboration, 2020).

The beginning left five things, and four of them are already in our measurements: a faint pattern in the oldest light; one settled state of empty space, the same in every epoch, whose energy is measured as the energy of empty space; the dark matter, made as our epoch formed from the turn; and the small excess of matter over antimatter (matter made of antiparticles; a particle's antiparticle is like it in every respect except that

each of its charges is opposite); the fifth, a faint hum of gravitational waves made just after the turn, as the six small dimensions settled into their held size and shape, is gathered with the coming measurements in Appendix A. Carried by *What the Beginning Left Behind*, chapter 21, opening ("In brief, the beginning left five things: one form, one vacuum, the dark matter, a faint hum and the matter we are made of"); and, for the hum, chapter 16, "The Hum of the Settling", section "Summary" ("The waves come from the settling, when the energy of the motion of the six goes into breathing vibrations of their volume").

In April 1992 the team of the Cosmic Background Explorer announced ripples in the first light of about one part in a hundred thousand. Carried by *What Comes After the Dark*, chapter 12, "What Comes After the Dark?", section "What Crosses" (announcement of 23 April 1992).

Everything the black holes of the epoch before ours took in differed from place to place; at the turn no comparison tells one interior from another, so those differences pass into the new epoch as one pattern, averaged together and not erased, and the new epoch registers them only as faint departures from evenness; I identify the faint differences in the oldest light with that averaged pattern. Carried by *What the Beginning Left Behind*, chapter 13, section "The Sameness and the Flatness, Answered From the Turn" ("The form of the content passes the turn as one form"; "So the new context registers the form only as small departures from uniformity, averaged and not erased"), and chapter 21, section "What the First Light Records"; and by *At the Edge of Reality*, chapter 19, "The Faint Pattern in the Sky", section "The Departures" ("I identify the departures with the form of the content carried from one side of the turn to the other").

Two numbers of the first ripples, their strength and their slight tilt from large sizes to small, the account takes from measurement. Carried by *What the Beginning Left Behind*, chapter 21, section "What the First Light Records". Exact values, measured: a strength of about two parts in a billion, and a spectral index of 0.9649.

The long emptying of the sky will happen, and the emptying is not the end. Carried by *What Comes After the Dark*, Preface, "The Question of the Far Future", section "The Answer, in Brief" ("The answer of this book is that the long emptying of the sky is real, and that it is not the end"), where "real" is that book's own word.

The sky beyond our own small family of galaxies empties out of reach in a hundred billion to a trillion years; black holes glow themselves slowly away, and for a hole of the Sun's mass that takes a number of years sixty-seven digits long; the emptying comes first, by an enormous margin. Carried by *What Comes After the Dark*, chapter 1, sections "Clumping and Departing" and "The Slow Glow of a Black Hole". Exact value: about 2×10^{66} years for a black hole of one solar mass (Page, 1976).

The account adds four forecasts of its own: the galaxies of our epoch never fall back together, everything bound stays bound, empty space keeps its nature, and the matter lasts. How fast space expands is given as a rate, the share by which every great distance grows in a given time, and the rate is set by a sum of three parts, one for the matter, one for the bending of space and one for the cosmological constant; the part for the matter is never negative; space is flat, so the part for bending is zero, and more matter only makes the sum larger and never bends space closed; the part for the constant is positive, as the two teams of 1998 found; as space grows the matter thins and its part shrinks, which is gravity holding the expansion back, while the part for the constant stays the same; so the sum never falls to zero, and gravity never stops the expansion. Carried by *What Comes After the Dark*, chapter 2, section "The First Way: Space Is Flat" ("The density part is never negative"; "Gravity holds the expansion back, and it never stops it"; "In the far future the matter thins, and the expansion rate settles toward the rate the constant alone sets"), and "A Ball Thrown Upward" ("Our epoch does not fall back"). Exact form: in Friedmann's equation for a flat universe holding matter and the constant, $H^2 = (8\pi G_N/3)\rho_m + \Lambda/3$ (in units where the speed of light is 1), where H is the rate of expansion and ρ_m the density of matter; both terms are positive, so H never falls to zero.

The dark energy is exactly the cosmological constant: one constant, with no dark energy field behind it. Carried by *What Comes After the Dark*, chapter 1, section "Faster, Not Slower"; and by *The Gravitational Passage*, chapter 13, "Λ as a Prediction; Information Cost at the Horizon", section V, "The Equation of State" ("There is no dynamical field, no quintessence and no evolving scalar, driving the acceleration"). Exact form: the equation of state is $w = -1$ exactly.

The value of the constant is no free number: I identify the constant with the share of the energy of empty space that a measurement made inside empty space takes in, and with that identification the structure of the account sets its value, together with the measured strength of gravity and the measured size of the particle horizon; the value so set agrees with the measured value to within about two percent. Carried by *What Comes After the Dark*, chapter 2, section "The First Way: Space Is Flat" ("I identify the cosmological constant with the part of the energy of empty space that a measurement made from inside the universe can take in"); and by *What the Beginning Left Behind*, chapter 21, section "What the Six Left Fixed" ("That value of the energy of empty space follows from the structure once the identifications of Chapter 8 are taken, with the measured size of our particle horizon"), and chapter 8. Exact values: 2.56 against a measured 2.52, in units of 10^{-47} GeV^4, a difference of 1.6 percent; matter share 31.1 percent against a measured 31.5 percent; the formula is given under Chapter Four above.

A theorem about Einstein's equations makes the constant one number at every place and every time of our epoch. Carried by *What Comes After the Dark*, chapter 2, section "The Second Way: One Number for Our Whole Epoch"; and by *The Gravitational Passage*, chapter 13, section VI, "The Comparison That Fixes Λ". Exact form: in $G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G_N T_{\mu\nu}$, where $G_{\mu\nu}$ is Einstein's tensor, $g_{\mu\nu}$ the metric and $T_{\mu\nu}$ the stress-energy of the content, the divergence of $G_{\mu\nu}$ vanishes by the contracted Bianchi identity, the divergence of $g_{\mu\nu}$ vanishes, and $T_{\mu\nu}$ is conserved; so the divergence of the left side is the gradient of Λ, and the equations set it to zero.

A "Big Rip" needs dark energy whose pressure is more negative than minus its energy density, an equation of state below minus one (Caldwell, Kamionkowski and Weinberg, 2003); the constant does not meet that condition, and nothing bound is ever torn apart by it. Carried by *What Comes After the Dark*, chapter 3, "Will the Expansion Tear Us Apart?", section "One Number Through Our Whole Epoch"; and its "For the Specialist", chapter 3, which gives the rip to a dark energy "whose equation of state lies below minus one", and the gloss: "The equation of state w is the ratio of a component's pressure to its energy density". Exact form: a rip needs an equation of state $w < -1$; the constant has $w = -1$.

This account's forecast of the far future rests on two of its own statements: a kind of particle has the same properties wherever and whenever it is found, at every place and every time of our epoch; and the same law sets the cosmological constant in every epoch. The first statement rests on the six small dimensions: their shape sets which kinds of particle there are, and they are held at one size and in one shape; the second rests on what comes back at each turn: the law, the structure of the world that this account derives, holds again in every epoch. Carried by *What Comes After the Dark*, chapter 3, section "Binding Lives Where the Matter Is" ("In this physics a kind of particle has the same properties wherever and whenever it is found. For us that means at every place and every time of our epoch"; "The forms that matter can take stay fixed for as long as what holds them lasts, and Chapter 4 says what holds them"), and chapter 2, section "The Second Way: One Number for Our Whole Epoch" ("In every epoch the same law sets the constant"); for the first ground, chapter 4, "Could Empty Space Change Its Nature?", section "The Six Small Dimensions" ("So the shape of the six sets which kinds of particle there are, and how those kinds can join into atoms and bodies"; "While the shape of the six is held, the forms of matter, the atoms, stars and bodies of our epoch, stay fixed"); for the second ground, chapter 9, "What Crosses Over, and What Stays Behind?", section "The First Faint Pattern of the Next Sky" ("What returns is the law, the structure of the world that this physics derives: the same law holds again on the far side, and it is not carried across"). No

book of this account discusses Hume or induction; the two statements are what the forecast rests on, at their own scope, and they are not offered as an answer to the problem of induction.

A false vacuum is a settled state of empty space that holds for now and is not the lowest state empty space could have; Sidney Coleman showed in 1977 how such a state could give way everywhere through one growing bubble; every such decay needs a second, lower valley. Carried by *What Comes After the Dark*, chapter 4, section "Bubbles in a Superheated Liquid".

Besides the three directions of space and the one of time, every point of space carries the six small dimensions, curled up far smaller than an atom, as a garden hose seen from far away hides a second direction that curls around it; I identify the same six with the space of all the states a particle of matter can be in, as a chessboard is the set of all the squares on which a piece can stand, so their shape fixes what kinds of particle there can be; the six can change in only two ways, in their size and in their shape, and they are held at one size and in one shape; so they have one settled state and no second, lower valley, and a bubble has nowhere to lead. Carried by *What Comes After the Dark*, chapter 4, sections "The Six Small Dimensions" (the garden hose and the chessboard are that book's pictures: "Read in another way, the same six are the space of all the states that a particle of matter can be in"), with the identification behind it made in *The Gravitational Passage*, Appendix C, "A Parallel Derivation of the Dimensions of Context", section VIII, "Concordances", where the six dimensions of the internal space and the six dimensions of possibility are "one set" ("I identify the two sixes as one set"), and "Coleman's Question, Answered for the Six", and chapter 2 ("That hidden geometry can change in only two ways, in its size and in its shape, and it is held at one size and in one shape").

For the Higgs field this account states a different strength: the field's energy, in the curve this account derives at the energies where the field is measured, has its lowest place at the present state, as the round trough at the bottom of a wine bottle is the lowest place of the glass, with the glass rising beyond it on every side; so the account's forecast for the Higgs field

is that, in the curve the account derives, the field rests now at its lowest place; the account does not follow the field's strength out to very high energies, and the standard calculation, which does, finds the present state lasting far beyond the age of the universe. Carried by *What Comes After the Dark*, chapter 4, section "The Higgs Field" ("A curve made of those two parts has one lowest place, the trough of the present vacuum"; "This physics gives the field's energy a floor, and, in the two-part curve it derives, that floor is the present state. It does not follow the field's strength out to very high energies. The standard calculation, which does, finds the present state long-lived, far beyond the age of the universe"); the standard calculation is that of Buttazzo and colleagues, 2013; "floor" is that book's word for the lowest place. Calculations of that kind give the estimate Hossenfelder reports for vacuum decay, and she calls such estimates meaningless, because they carry the field across energies that no experiment has reached (*Existential Physics*, chapter 2, "In the End": "In my opinion, though, this and similar estimates are meaningless").

The three forces of the particles stand side by side, each force with carriers of its own, and no single larger force splits into the three forces. A proton is made of three quarks, and the proton is the lightest particle made of three quarks. No carrier of any force turns a quark into the electron or into one of the electron's relatives, so the proton keeps its three quarks. The proton, keeping its three quarks, has nothing lighter to become, and so the proton lasts. Carried by *What Comes After the Dark*, chapter 5, "What Becomes of the Stars and Their Ashes?", section "Does the Proton Last?" ("Each force is carried by particles of its own, and each carrier belongs to one symmetry only"; "The proton is the lightest particle made of three quarks, as measured, so it has nothing lighter to become while keeping its count"; "The proton lasts"). The book and the cup are this book's picture. Exact value, measured: Super-Kamiokande (2020) sets the proton's lifetime for the decay into a positron and a pion above 2.4×10^{34} years.

William Thomson's paper of 19 April 1852 to the Royal Society of Edinburgh and Rudolf Clausius's second law gave the old fear of a final heat death. Carried by *What Comes After the Dark*, chapter 8, section "Edinburgh, 1852: The Old Fear".

Three grounds, each standing on its own, show that the emptying cannot come to rest in a heat death. First, content and context: the content of a comparison is what its verdict is about, and its context is the respect in which the two things compared are two (a thermometer comparing this morning's warmth with this evening's finds a temperature, the content, and the two times of day are the context); in physics the content is the matter and light of the world, and the context is the arena of space and time in which they are found, together with the setting of possibility, the range of states in which they could be found; every content has its context; the matter that falls into the black holes does not cease to be, so the content is still there; at the end of the emptying the large outside world, the arena of space and time in which the matter was found, is gone; so a context must form again, and it forms from the geometry of all ten dimensions as a new large world (*What Comes After the Dark*, chapter 8, section "The First Ground: No Content Without a Context": "The content is still there, and no large world is left to be its context"; "So a context must form again"; "So the new context forms from the ten-dimensional geometry"; and chapter 4, section "The Six Small Dimensions": "The six are part of the context of every outcome, so they cannot shrink to nothing"). Second, a featureless emptiness, the same everywhere and with no break anywhere, would be perfectly symmetric and perfectly continuous at once, symmetry being the same under every change of place or setting and continuity having no gaps; the Incommensuration Theorem, a structural fact about the nature of knowing, makes that the one thing no comparison ever finds; so the emptying cannot come to rest in a featureless emptiness (section "The Second Ground: A Featureless Emptiness Is Never Found": "So the emptying cannot come to rest in such a world"). Third, an entropy is a count of the states of a thing that the comparisons available from some context cannot tell apart, and so always a count made against a con-

text; the largest count toward which an epoch's entropy tends is a count made against that epoch's own outside world, the large arena of space and time outside its black holes, in which its matter is found, and when that world has emptied, the count has nothing left to be counted against, and the next epoch begins its own count against its own context (section "The Third Ground: Every Count Has a Context": "So an entropy is always a count made against a context"; "and the next epoch begins its own count against its own context"). "The emptying ends in a turn, not in a final dark" (section "What This Means for You"); from the turn the next epoch begins, under the same law. The census of a new country is this book's picture.

A new epoch begins in one way only: at the turn, from the ends of all the black hole interiors of an epoch together, and never from one region of space or from one black hole. Carried by *What the Beginning Left Behind*, chapter 21, section "A Cycle with No First Turn".

The baby universe of the plans that Michio Kaku describes in *Parallel Worlds* begins as a false vacuum; in this account the six small dimensions have one settled state, with no second one beyond it, so a made bubble has no other world to open into ("This physics has one vacuum, with no second held state beyond it, so a made bubble has no other world to open into"); and this account has no inflaton to drive its growth. Carried by *What Comes After the Dark*, chapter 10, "Could Anyone Escape?", section "The Plan, Step by Step", and chapter 4, "Could Empty Space Change Its Nature?", section "Coleman's Question, Answered for the Six" ("So the six have one vacuum, and no second one for a bubble to lead to"); and by *What the Beginning Left Behind*, chapter 13, section "Nothing for Inflation to Work With".

Space is the pattern of which events a signal can join, so any region a path from here could reach, by any machine, is by that fact part of our own world; and no path runs from any place in our epoch to any place in the next; so no laboratory can make a second universe: whatever a machine here makes or reaches is a region of our own world. Carried by *What Comes After the Dark*, chapter 10, section "No Other Sky Along Any

Path" ("In this physics, space is the pattern of which events a signal can join. So any region that a path from here can reach, through a wormhole, a warp drive or anything else, is by that fact a part of our own pattern: a part of our world"; "No path runs from any place in our epoch to any place in the next"). The country where the only way to travel is by road is this book's picture.

The forecast of the end, built from what the weighings of our own epoch show together with the structure of comparison, gives one constant, one settled state of the six small dimensions, a Higgs field resting at the lowest place of the curve the account derives, a proton that lasts, and a context that forms again. Carried by the entries above: *What Comes After the Dark*, chapters 2 to 5 and 8.

Chapter Twelve:
What Is the Dark Matter, If Every Search Comes Back Empty?

The outer parts of the Andromeda galaxy turn about as fast as its inner parts, so that the galaxy's mass keeps growing far from its center; Fritz Zwicky had met the same surplus in 1933, in the speeds of the galaxies of the Coma cluster, a swarm of more than a thousand galaxies. Carried by *The Weight of Possibility*, chapter 1, "The Question and Its Ground", section I, "What Is Observed" (Rubin and Ford, 1970; Zwicky, 1933). Exact value, from the paper of Rubin and Ford: the outermost point lies at 24 kiloparsecs from the center, which is about 78,000 light-years. Catalogs list over a thousand identified members of the Coma cluster.

In the colliding clusters called the Bullet Cluster, the weight lies with the galaxies, which have sailed on through, and not with the glowing gas, although the gas holds most of the ordinary matter; the dark matter passes through itself and through ordinary matter without any collision that anyone has measured. Carried by *What the Beginning Left Behind*, chapter 18, "Matter Made of Possibility", opening; and by *The Weight of*

Possibility, chapter 1, section I. Exact value: the same collision bounds the scattering of the dark matter on itself below about one square centimeter per gram (Markevitch and others, 2004).

The pattern of warm and cool spots in the oldest light weighs the ordinary matter and the dark matter separately; by weight there is about five and four tenths times as much dark matter as ordinary matter, and that ratio is the same everywhere the oldest light can measure it. Carried by *The Weight of the Unseen*, chapter 1, question 1.5; and by *What the Beginning Left Behind*, chapter 18, section "What Is Seen". Exact values, measured: 5.364 ± 0.065 from the Planck satellite alone (Aghanim and others, 2020), and 5.370 ± 0.048 from the South Pole Telescope, Planck and the Atacama Cosmology Telescope together (*The Weight of Possibility*, chapter 5, "The Measurements", section I, "The Ratio").

The measured expansion of the universe since the oldest light was released requires any decay of the dark matter into something unseen to take longer than about a hundred and sixty billion years. Carried by *What the Beginning Left Behind*, chapter 18, section "What Is Seen" ("and the measurements of the expansion require any such decay to take longer than about a hundred and sixty billion years"; Poulin, Serpico and Lesgourgues, 2016).

Ordinary matter alone would have made no galaxy at all: departures of three parts in a hundred thousand, grown one thousand and ninety times, reach about three parts in a hundred, and a region draws together into a galaxy only when its excess of density reaches about one, that is, about twice the average density. Carried by *What the Beginning Left Behind*, chapter 18, section "What Is Seen"; and by *The Weight of Possibility*, chapter 1, section I. Exact form: $3 \times 10^{-5} \times 1{,}090 \approx 3 \times 10^{-2}$, where 3×10^{-5} is the departure of the matter from evenness when the oldest light was released (the departure of its temperature is about 10^{-5}) and 1,090 the growth since then.

Nobody concludes from phonons, the vibrations of a crystal's lattice, that the crystal is made of phonons. Carried by *What the Beginning Left Behind*, chapter 18, section "A Vibration of the Held Space".

The world has six small dimensions besides the three of space and the one of time, and they keep the same size and the same shape at every place, as a crystal keeps its lattice. Carried by *The Weight of Possibility*, chapter 1, section III, "What This Book Takes from the Passage, and What It Does Not", and section IV, "The Identification". Exact form: the six have the shape $\mathbb{C}P^2 \times S^2$, held at a radius of $\sqrt{6}$ Planck lengths (the $\mathbb{C}P^2$ part) and of one Planck length (the S^2 part); the Planck length, the smallest length built from the constants of gravity, quantum theory and light, is about 1.6×10^{-35} meters, about a hundred billion billion times smaller than a proton (*The Weight of the Unseen*, chapter 2, question 2.3).

Each possible state of a system with two alternatives is one point of a globe; the six are a space of possibility in the plain mathematical sense. Carried by *The Weight of the Unseen*, chapter 2, question 2.3; and by *The Gravitational Passage*, Appendix C, "A Parallel Derivation of the Dimensions of Context", section VIII, "Concordances" ("$\mathbb{C}P^2$ is the space of possibilities of a system with three alternatives, and S^2, which is $\mathbb{C}P^1$, is that of a system with two").

Set beside the large dimensions, the six are part of what the large world holds; set beside what could be found in them, the six are the range of possibilities in which a finding lies, and two possible findings are two by lying at two places in that range, so the six are a context, the setting of possibility; so every finding is placed in all three measures of context: space, time and possibility. Carried by *What the Beginning Left Behind*, chapter 18, section "A Vibration of the Held Space" ("The six can be set beside two different things. Set beside the large dimensions, the six belong to what the large world holds. Set beside what could be found in them, the six are the range in which it is found, and so they are a context"); by *The Weight of Possibility*, chapter 1, section III, which names the two comparisons and takes the second ("This book uses the second comparison");

and by *The Last Turtle*, "The Three Boundaries of Knowing", section VII, "How the Constants Join the Measures" ("The measures of context are space, time and possibility").

I identify the dark matter with a ringing of the setting itself: a lasting vibration of these six small dimensions, taken as the setting of possibility, a vibration of context; the account names one such vibration a gyration, as a crystal's unit of ringing is named a phonon. Carried by *What the Beginning Left Behind*, chapter 18, section "A Vibration of the Held Space" ("I identify the dark matter as a conserved excitation of the six held internal dimensions"); and by *The Weight of Possibility*, "A Note to the Reader" and chapter 1, section IV, "The Identification" ("This statement is an identification, and this section gives its argument"). Theories with extra dimensions have long studied heavy vibrations of this kind, and they call each one a particle; physically, a gyration is a vibration of that kind; in this account a particle is a thing found in the arena, and a gyration is a ringing of the setting, so a gyration is not matter of any kind on the list of particles (same section: "In the language of physics, a gyration is a heavy vibration of the geometry of the six, of a kind long studied in theories with extra dimensions, which call such a vibration a particle"; "the dark matter is a vibration of context"). This account reads the six at two scopes, and both statements hold. Taken as a space of states with no size, on which the kinds of particle are read, the six carry the kinds, and the dark matter's gravitational effects belong to the context, as gravity does, and not to that space (*The Alphabet of Particles*, "Names Without an Entry", entry N3, "Dark-Matter Particle"). Taken as held at their size, the six carry the gyrations that are the dark matter (*The Weight of Possibility*, chapter 1, section III); *What the Beginning Left Behind*, chapter 18, names these as the same six "read two ways".

A gyration has energy, so it has weight, and it pulls as all energy pulls; light and every detector built to catch a particle register things found in the arena, which light can bounce from and which can strike a detector, and a gyration is a ringing of the setting, and never a thing found in the arena, so neither light nor any such detector registers it. Carried by *What*

the Beginning Left Behind, chapter 18, section "A Vibration of the Held Space"; and by *The Weight of Possibility*, chapter 1, section III ("the dark matter is an excitation of possibility as the context of what could be found").

On that identification, the dark matter acts on the world through its weight alone, and every search for it through any other way of acting finds nothing, at any sensitivity. Carried by *The Weight of Possibility*, chapter 5, section VII, "The Searches" ("The dark matter is registered through its weight alone: on the identification of Chapter 1, Section IV, every search for it through any interaction but gravity finds nothing, at any sensitivity"). Other accounts of a dark matter that acts only through gravity make the same prediction for these searches, among them the particles of Feng, Rajaraman and Takayama (2003), and so do neutral relics of the Planck mass; so a lasting silence of the detectors separates this account from particles of weak interaction, and not from those accounts (same section: "So a lasting null result separates this account from particles of weak interaction, not from those accounts").

A gyration weighs about a Planck mass, the mass at which gravity and the quantum act on equal terms: some twenty-two millionths of a gram, about ten billion billion times the mass of a proton. Carried by *What the Beginning Left Behind*, chapter 18, section "How Heavy, How Many, How Cold". Exact values: the Planck mass is about 2.2×10^{-5} grams, and the gyration's mass lies between 0.6 and $\sqrt{2}$ Planck masses (same section; *The Weight of Possibility*, chapter 4, "Why the Dark Persists, and Its Gyrations", section V).

Near the Sun there is about one gyration in every few tens of thousands of cubic kilometers. Carried by *What the Beginning Left Behind*, chapter 18, section "How Heavy, How Many, How Cold". Exact value: about one gyration for every 1.5 to 3.4×10^{18} baryons (*The Weight of Possibility*, chapter 4, section VI, "The Number of the Gyrations").

Gyrations are made only as a new epoch forms from the turn, the boundary between two epochs, where the interiors of all the black holes of the ending epoch end together, as one end, and the next epoch begins (an epoch being one whole span of the universe's history, from one turn to the next, ours beginning at the Big Bang); as a new epoch forms from the turn, and only then, the six small dimensions and the large ones form again together. Carried by *What the Beginning Left Behind*, chapter 18, section "A Vibration of the Held Space" ("the turn is the one place where the dark matter is made"); the glosses of epoch and turn are those of Chapter Ten.

Once made, a gyration keeps its energy, because each of its three ways out is closed: it cannot become an ordinary thing, since a vibration of the six and an actual thing are two different sorts of thing and the six form again only as a new epoch forms from the turn; it cannot hand its energy to ripples of space, since under the swap of opposite points of the small globe, which leaves the laws of the six unchanged because those laws contain only the shape of the globe and the swap leaves that shape as it was, the gyration comes out upside down and the ripples come out unchanged; every link between the six and space is left unchanged by the swap, and such a link can pass the energy of a single upside-down vibration only to another upside-down vibration; and the gyration is the lightest vibration that comes out upside down, so none is lighter for it to hand its energy to; and it cannot leak its mass away as a black hole does, since it is a vibration at the scale of the Planck length and the Planck mass, leaking would carry it into a lighter level of the same kind, and a vibration at the Planck scale has no lower level of its kind; the next scale at which leaking could act at all lies some thirty powers of ten away. Carried by *What the Beginning Left Behind*, chapter 18, section "Three Ways Out, All Closed" ("The laws of the six contain their geometry alone, with no sense of handedness for the small space, so the swap leaves the laws unchanged"; "An odd vibration could fall only to a lighter odd vibration, and the lightest odd level has none below it"; "A vibration at the Planck scale has no lower level of its kind to leak into. The next scale at which evaporation

could act lies some thirty powers of ten away"); and by *The Weight of Possibility*, chapter 1, section IV, and chapter 4. Exact form: the swap is the antipodal map of S^2, the sphere of the two-way choice; the gyration is odd under it, and the gravitational waves of the large dimensions, uniform over the six, are even, so a conserved parity forbids the decay.

Every finding is placed in space, in time and in possibility; each of the three measures of context has no gaps; a measure of context with its plain shape everywhere, the shape it has when nothing bends it, would make sameness and smoothness both perfect at once, which the Incommensuration Theorem forbids; so each departs from its plain shape; the three come together, so none can stay unbent while another is bent; none can stand in for another, so the bending of one cannot serve as the bending of another; and they are three, so the bendings are three, each made by a thing of its own: gravitation bends space, around matter; the cosmological constant bends time, the same at every place and every moment, and from each moment to the next it widens the distance between every pair of distant places; and the dark matter bends possibility; so a world whose setting of possibility is smooth must carry the dark matter, as it must carry gravitation and a cosmological constant. Carried by *What the Beginning Left Behind*, chapter 18, section "A Vibration of the Held Space" ("Every finding is placed in space, in time and in possibility, and none of these settings can keep its plain shape, the shape it has when nothing bends it"; "the three go together, none can do another's work, and they are three"); and by *The Weight of Possibility*, chapter 1, section V, and chapter 2, "Three Distortions of Context", section I, "Why Context Must Distort" ("the three contexts are inseparable, so none can be undistorted while another is distorted; they are non-interchangeable, so no column's distortion can stand in for another's; and they are distinct, so the distortions are three"). The theorem, exactly: "Symmetry and continuity cannot both be applied, simultaneously and fundamentally, to any event or comparison; and neither can asymmetry and discontinuity". The floor that dips is this book's picture of a bent setting.

There is no species of dark matter among the kinds of particle, and no axion: a label of a force is a charge by which that force acts on a particle, and the one slot on the list that a particle of dark matter touching ordinary matter through gravity alone would need, matter with no label of any force, is filled in each generation by the neutrino's right-handed state, the part of each neutrino that lets it carry its small mass, which carries no label of any force and plays no part in dark matter; a second occupant would be told from it by nothing, and two things that nothing tells apart are one thing; the structure that fixes the kinds has no slot for a field with no labels at all, which an axion would need; and the strong force's own angle is already zero. Carried by *The Alphabet of Particles*, "Names Without an Entry", entry N3, "Dark-Matter Particle", subsection "What the Structure Says", and entry N8, "Axion"; and, as a restatement in plain words, by *Why These Numbers*, chapter 2, "What There Is, and Why It Is Built So", section "What Has No Place Among the Kinds". This route, from what the list of particles is, and the route of *The Weight of Possibility*, from what the dark matter is, reach the silence of the detectors from different books on different ground, and neither leans on the other: the route from the kinds rests on the closed list alone (*The Branches of the Kinds*, chapter 4, "The Carriers", section III, "What Is Not a Particle").

Hossenfelder's two rules describe how a proposed particle is kept alive: a reason it has not yet been seen, and an argument that it is just about to be discovered; this account proposes no new kind of particle, since the gyration is a vibration of the setting and the list of kinds stays closed; the reason it gives for the empty detectors is the kind of thing the dark matter is, and that reason holds at every sensitivity; so the account's answer to her second rule is the weighing, the one kind of comparison that registers the dark matter. Carried by *The Weight of the Unseen*, Appendix, question A.10 ("No detector will ever catch the dark matter by any means other than its weight"); her two rules are in *Lost in Math*, chapter 9; the coming searches are gathered in Appendix A.

The Gravitational Passage derives Einstein's equations of gravity, and a theorem of David Lovelock (1971) fixes their form; Lovelock's conditions are three: four dimensions; an equation built only from the measure of distance in space and time (the metric) and its first two rates of change; and agreement with the conservation of energy and momentum, the rule that energy and momentum, the quantity of motion, can move from place to place and are never made or lost, in any small region over any short time; under those conditions the equation has Einstein's form, with the cosmological constant included: "Within the theorem's conditions there is no other equation". Carried by *The Gravitational Passage*, chapter 12, "The Einstein Field Equations", section VII, "Uniqueness: Lovelock's Theorem" ("the most general symmetric, divergence-free tensor built from the metric and its first and second derivatives"), where the conservation is the condition that the tensor be divergence-free, a condition that holds at each point of space and time; and, for the plain statement, by *What Comes After the Dark*, chapter 2, "Will It All Fall Back?", section "The Second Way: One Number for Our Whole Epoch" ("they are moved from place to place and never made or lost"). Exact form: in four dimensions, the only divergence-free symmetric tensor built from the metric $g_{\mu\nu}$ and its first and second derivatives is a $G_{\mu\nu} + b\ g_{\mu\nu}$, with a and b constant, which gives $G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G_N T_{\mu\nu}$.

Those equations hold two constants, Newton's constant and the cosmological constant, and no constant of acceleration; so the account keeps the law of gravity exactly as general relativity gives it, from the laboratory to the largest structures, and down to the smallest scale at which space can be described as smooth. Carried by *The Weight of Possibility*, chapter 5, section V, "Small Scales"; and by *The Weight of the Unseen*, chapter 1, question 1.7.

Galaxies keep to regularities, such as the Tully-Fisher relation; Mordehai Milgrom proposed in 1983 one rule for faint pulls, below an acceleration of about one ten-billionth of a meter per second gained every second, and predicted, before the measurements, that faint and spread-out galaxies would depart from Newton's law throughout, which they do; Stacy

McGaugh and his colleagues measured the Tully-Fisher relation with the mass of all the stars and gas of a galaxy in place of its brightness, and found that it holds with little scatter across galaxies of very different size; in 153 disc galaxies the pull found from the rotation at each distance from the center is one and the same function of the pull the visible matter alone would give; these are among the most exact regularities in astronomy, and this account takes them as they were measured. Carried by *Side by Side*, Volume Two, "The Law and the History", section I, "What the Galaxies Show" ("The first is the baryonic Tully–Fisher relation: the mass of the stars and gas of a galaxy goes as the fourth power of its flat rotation speed, with little scatter, across galaxies of very different size (McGaugh, Schombert, Bothun and de Blok 2000)"; "These are among the most exact regularities in astronomy"); her report of the regularities is *Lost in Math*, chapter 9, "Sitting Around Hoping", which does not speak of their exactness. Exact form: the baryonic Tully-Fisher relation is $M_b \propto V_f^4$, where M_b is the mass of stars and gas and V_f the flat rotation speed. Exact values, measured: 2,693 points in 153 galaxies, with a scatter of about 0.13 dex (0.13 in the logarithm to base ten), and an acceleration scale of 1.2×10^{-10} meters per second per second (*The Weight of Possibility*, chapter 5, section V).

Milgrom's rule and this account agree on what the galaxies show, and they part on whether what the galaxies show is a law or a history. Carried by *Side by Side*, Volume Two, "The Law and the History", Abstract.

The relation is a record of how galaxies formed under general relativity with a cold component that acts only through gravity, cold meaning slow, with no motion from heat that could matter: the gas of ordinary matter shines as it falls inward, loses energy, sinks and breaks up into stars, while the dark matter gives off nothing and stays spread out; simulations of galaxy formation with such a component reproduce the relation and its small scatter; and in clusters of galaxies the same pattern departs from Newton's law at an acceleration about seventeen times the galactic one: a pattern set by formation departs from Newton's law at a different acceleration in each kind of structure, while a law with one constant of ac-

celeration sets one such acceleration for all of them, and the clusters show the first. Carried by *The Weight of Possibility*, chapter 5, section V; by *Side by Side*, Volume Two, "The Law and the History", section VI, "The Tightness of the Relation"; and, for "cold", by *What the Beginning Left Behind*, chapter 18, section "How Heavy, How Many, How Cold" ("slow, with no motion from heat that could matter"). Exact value, measured: in clusters the acceleration at which the pattern departs from Newton's law is $(2.02 \pm 0.11) \times 10^{-9}$ meters per second per second (Tian and others, 2020 and 2024).

Changing the law of gravity as Milgrom's rule does still leaves clusters of galaxies short of mass, and without dark matter it predicts a third peak in the pattern of the oldest light lower than the one measured. Carried by *The Weight of Possibility*, chapter 5, section V; and by *Side by Side*, Volume Two, "The Law and the History", section V, "Where the Two Accounts Part"; a peak is glossed in *The Weight of the Unseen*, chapter 1, question 1.5.

Pairs of stars in wide orbits test Milgrom's rule against this account directly, because no galaxy formed around them: a law of gravity acts on such pairs, and a history of galaxy formation does not; the account predicts that two stars in a wide orbit, at accelerations below Milgrom's scale, move by Newton's law, since the field equations hold no constant of acceleration; in 2024 Indranil Banik and his colleagues found, from the Gaia satellite's survey of such pairs, that Newton's law describes them far better than Milgrom's rule does. Carried by *Side by Side*, Volume Two, "The Law and the History", section VI ("a law with a constant of acceleration acts on two stars orbiting each other at low acceleration, far from any galaxy's history, and a regularity of formation does not"), section VII, "What the Measurements Say" ("The account predicts that two stars in a wide orbit, at accelerations below Milgrom's scale, move by Newton's law, since the field equations hold no constant of acceleration"), and "Time Is Real", section IX, subsection "Galaxies at low acceleration". Exact value, measured: Newtonian dynamics preferred over the modified dynamics at 19 standard deviations (Banik and colleagues, 2024). Kyu-Hyun Chae has reported an anomaly in samples of binaries he selected (Chae, 2024); in 2026 Serat Saad and Yuan-Sen Ting reanalyzed the 36 binaries of a later

sample of Chae and his colleagues, which had given a strengthening of gravity of about 1.6 times Newton's, and, modeling the orbit of each pair in three dimensions, found a factor of 1.00 (+0.24/−0.19) on Newtonian gravity, consistent with Newton's law; with the separation of each pair estimated as Chae and his colleagues estimated it, Saad and Ting recover the anomaly (same section VII).

Hossenfelder sets the particle proposal and the modified-gravity proposal side by side and looks for an answer between them; this account gives the dark matter a place of its own, beside the new particle, the changed law and the mixtures of the two: a ringing of the setting of possibility, under Einstein's law unchanged. Carried by *Side by Side*, Volume Two, "Where the Dark Sector Lives", section III, "What the Collection Shares", subsection "The dark sector belongs to the context".

The dark matter belongs, as gravity does, to the setting in which every measurement is made. Carried by *Why These Numbers*, chapter 2, section "What Has No Place Among the Kinds" ("so it belongs to context, as gravity does"); and by *The Alphabet of Particles*, entry N3.

Chapter Thirteen:
Is Gravity's Meeting with the Quantum the One Real Problem?

The clocks on navigation satellites run a little fast in the weaker gravity of the satellites' orbits. The system that a phone uses to find where the phone is corrects every one of the satellite clocks for running fast. Carried by *Two Theories, One World*, chapter 1, "Two Theories That Never Fail", section "The Theory of the Arena". Exact value: the net gain is about 38 millionths of a second each day. *Two Theories, One World* and *The Unquantized Arena* are one argument in two forms.

The magnetism of a single electron is computed by quantum theory and matches measurement to about one part in a trillion. Carried by *Two Theories, One World*, chapter 1, section "The Theory of What Is Found".

"The difficulty appears only where both theories must speak about the same thing": a mass in a superposition of two places, a black hole, and a scale far below anything yet measured. Carried by *Two Theories, One World*, chapter 1, section "Where the Two Seem to Collide".

An object's gravitational size and its quantum size are equal at about twenty-two millionths of a gram; that meeting point is the Planck scale. Carried by *Two Theories, One World*, chapter 1, section "Where the Two Seem to Collide"; chapter 2, "Ninety Years of Trying", section "The Assumption They Share"; and chapter 11, "What Quantizing Does, and Why the Arena Cannot Take It", section "Exactly What Is Excluded". Exact values: the Planck mass is about 2.2×10^{-5} grams, and the Planck length about 1.6×10^{-35} meters, "a decimal point, thirty-four zeros, and then the digits 16".

Hossenfelder names the same place: the standard model and general relativity, combined, "lead to internal contradictions that, above the Planck energy, can't describe any observation" (*Lost in Math*, chapter 8, "Just a Humble Physicist"); and *The Basis of Physics*, stating the problem as physics has it, names three places where the two theories meet: "And where their ranges are forced to overlap, at the Planck scale, at the singularities of black holes, at the earliest moments of the cosmos, they contradict one another". Two of the essay's three places, the Planck scale and the black hole, are among the three of *Two Theories, One World*; the essay's third place is the earliest moments of the universe; so both books place the difficulty wherever gravity and the quantum must describe the same thing. Carried by *The Basis of Physics*, Essay 12, "Cross-Modal Reach: Why General Relativity and Quantum Mechanics Cannot Be Unified", section I, "The Problem as Physics Has It". In that section the essay states the problem as physics already holds it; it is not a second route to the three places.

"Every step of the calculation keeps the geometry classical": in Hawking's calculation of 1974, quantum fields are laid on the classical geometry of a collapsing star, and at no step is space or time quantized. Carried by *Two Theories, One World*, chapter 25, "Where Does the Information Go?", section "The Radiation Hawking Found". For the specialist: a black hole of

stellar mass has a Hawking temperature T_H of about 6×10^{-8} kelvin, nearly eight orders of magnitude below the microwave background (*The Gravitational Passage*, chapter 18, "The Interior Passage", section X, "The Hawking Question").

A question about the world, turned into a question of mathematics, can yield only further questions of mathematics while the question about the world stays where it was; the remedy is to ask the question about the world again. Carried by *Physics Is Not Math*, chapter 15, "The Descent", section III, "The Descent", and section VI, "The Outcome Table" ("the work stops, and the physics question is asked again: what is this work for?"). For the meeting of gravity and the quantum, the question asked again is what kind of thing space and time are.

The content of a comparison is what its verdict is about, at the balance how heavy the apple is; the context is the respect in which the two things compared are two, at the balance the two places they occupy, left pan and right pan, with the floor and the room that hold those places, at the moment of the weighing, and the setting names that whole context: the two places, the floor, the room and the moment of the weighing; in physics the content is the matter that measurements find, and the context is the arena of space and time in which they find it, together with the setting of possibility, the range of states in which it could be found; content and context always come together, and they are never the same thing. Carried by *Two Theories, One World*, Key Terms, entries "Content" and "Context"; chapter 24, "Joined, Not Merged", section "What the Theorem Permits"; and chapter 12, "One Geometry for Each Alternative", section "The Reason From the Ground"; the moment as part of the context is *Measurement; The Steps from Comparison to Physics*, chapter 1, section I ("The context is the respect in which they are two: two pans, two places, one moment"). The pans' two places, the floor and the room are this book's picture of the context, and the beam, which carries the comparison, is part of the setting.

Space and time together are the arena, in which quantum matter is found and every measurement is made, as Chapter Three named it; general relativity is the theory of the arena's shape, and that shape is what we feel as gravity. Carried by *Two Theories, One World*, chapter 1, section "The Theory of the Arena".

I identify quantum theory as the description of the content of physics, what every measurement finds, and general relativity as the description of its context, the arena where it is found. Carried by *Two Theories, One World*, "The Argument in Brief", section "The Answer in a Page".

Any setting of measurement bears four marks, found before gravity is named, and gravity carries all four, while no force of particle physics carries even one: the setting takes part in everything found in it; it reaches every region, so nothing can shield it (the metal walls of a lift keep out the signal of a phone, and no box keeps out gravity), since a region with no context is no region at all; one mass, since what ties a body to the setting and what resists any change in the body's motion through the setting both measure how much the body takes part in the setting, and I identify the two as one quantity, which is the equivalence principle in its weak form; and no charge that comes in steps: an electric charge comes only in whole multiples of one smallest step, an exact label that a body carries, the same for every particle of a kind, and the setting is smooth, and smoothness gives a body no such stepped label, since what gravity pulls on is a body's whole energy, which takes any value; by that match I identify gravity as the arena, the shape of the floor and not one more thing standing on it. Carried by *Two Theories, One World*, chapter 9, "Four Marks of the Arena": "So an arena takes part in every content of its domain, without exception"; "and a region with no context is no region at all"; "There is no gravitational Faraday cage, and the two accounts say why"; "The other is its inertia, which is how strongly it resists a change in its motion"; "I identify the two as one quantity, the body's participation in its context"; "Each label is exact, the same for every particle of a kind, and countable"; "This is the equivalence principle. In its weak form it says that gravitational mass and inertial mass are equal"; section "The Identification": "I identify grav-

ity as the arena of physics, the context of every physical measurement, by that match". The mat on the floor, the lift and the phone, and the hot brick are the pictures of the chapter; the hot brick and gravity acting on antimatter are in the same chapter of *Two Theories, One World*.

When a description of content is quantized, its context stays in place to receive the new description, as the arena stayed when light was quantized; when the context itself is to be quantized, nothing stays in place. Carried by *Two Theories, One World*, chapter 11, section "Why the Arena Admits No Mode Exchange".

The Incommensuration Theorem, exactly: "Symmetry and continuity cannot both be applied, simultaneously and fundamentally, to any event or comparison; and neither can asymmetry and discontinuity". It is a structural fact about the nature of knowing. Carried by *Physics Is Not Math*, Preface and chapter 2, section VI, "The Theorem"; and by *Causality Without Determinism*, chapter 1, section VII.

Perfected, a comparison has one of two characters, and no third; the arena has one, smooth and different from place to place, and the things found in it have the other, exactly repeating and in countable steps; to quantize the arena is to ask it to take on the character of what is found in it while it stays the arena; each of the four features, two of the arena and two of what is found, answers one of two questions, whether it is the same from place to place or different, and whether it is smooth or in steps; the arena answers "different" and "smooth", and what is found answers "the same" and "in steps"; staying the arena, it keeps its own answer to one question and takes the answer of what is found to the other question, since continuity with discontinuity, or asymmetry with symmetry, is a contradiction: keeping its smoothness and taking on exact sameness, it would carry continuity with symmetry; keeping its unevenness and taking on steps, it would carry asymmetry with discontinuity; either way the quantized arena carries a pairing that the theorem excludes. Carried by *Two Theories, One World*, chapter 11, "What Quantizing Does, and Why the Arena Cannot Take It", section "Why the Arena Admits No Mode Exchange" ("it would carry asymmetry with discontinuity. Those are the

two pairings that the Incommensuration Theorem forbids"); "The Argument in Brief", section "The Answer in a Page"; and chapter 24, section "What the Theorem Forbids"; and, for the contradictions, by *Physics Is Not Math*, chapter 2, section IV, "Three Tests" ("Six of them fail as plain repetitions or contradictions"). Exact strength, as *Two Theories, One World* states it: "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" (chapter 11). The poured-stone floor and the box of weights are this book's pictures.

The arena is smooth all the way down, with no smallest length, area or stretch of time of its own; to ask it for steps is to apply a concept where the concept does not belong, a category error. Carried by *Two Theories, One World*, "The Argument in Brief", section "The Answer in a Page", and chapter 1. The same argument in technical form is *The Unquantized Arena*, chapter 6, "The Category Error" (named in *Two Theories, One World*, "The Argument in Brief", section "The Technical Form").

A mass in a superposition of two places has two shapes of space, one in each alternative: "The answer I give is the first two, each in its own alternative"; neither alternative carries the other's shape, and no alternative carries a blend. Carried by *Two Theories, One World*, chapter 12, section "Two Places, Two Shapes".

Each alternative of the matter is something a measurement could find, so each is a content, and every content has its context; contexts join into one only where what they hold is found together; the alternatives exclude each other, so each alternative has a context of its own; I identify the geometry with that context: each alternative of the matter has its own smooth geometry, shaped by that alternative alone; "This answer quantizes nothing". Carried by *Two Theories, One World*, chapter 12, section "The Reason From the Ground" ("The reason comes from the inseparability of content and context. Where there is content, there is context"; "Contexts join into one only where what they hold is found together"), where an architect's

two drawings for two possible sites are each right about their own shadow, and their average is right about nothing; the trampoline photographs are this book's picture.

In its chapter on Einstein's equations, which it gives, from the product geometry, at curvatures far below the Planck curvature and with the value of Newton's constant taken from measurement, *The Gravitational Passage* makes the same identification from the same principle as *Two Theories, One World*, that where there is content there is context: the equations hold in each alternative, each alternative has its own smooth geometry, and "A geometry for each alternative quantizes nothing". Carried by *The Gravitational Passage*, chapter 12, "The Einstein Field Equations", section VI, "One Geometry for Each Alternative" ("I identify the geometry with the context of each alternative of the matter: where there is content there is context, so each alternative of a content has its own context, and so its own classical geometry"), with the scope of the equations in the same chapter ("Given the product geometry and the reduction with its moduli held, the four-dimensional gravitational equations, at curvatures far below the Planck curvature", are $G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G_N T_{\mu\nu}$ "and no others"). The two books share one ground here, so this is one route in two books, not two independent routes. For the specialist who asks whether a geometry for each alternative is only a semiclassical approximation to a quantum geometry, the same section answers: "The framework contains no quantum theory of the geometry; a geometry for each alternative is not an approximation to one".

In 1981 Don Page and C. D. Geilker hung a torsion balance, as Cavendish did in 1798, let a Geiger counter choose the positions of its masses, and found that the bar turned on every run the way the actual position required: the gravity followed the outcome, not the average; they titled their paper "Indirect Evidence for Quantum Gravity". Carried by *Two Theories, One World*, chapter 12, section "The Experiment of Page and Geilker".

The two theories are joined side by side, quantum theory for what is found and general relativity for where it is found, and never merged; the unity the theorem permits is a common source: both descriptions arise

from the same act of comparison and apply to the same world, each perfected in one of the two characters a comparison allows; the theorem forbids only a merger, one description in which the directions of space and time themselves carry both characters together. Carried by *Two Theories, One World*, chapter 24, sections "Two Kinds of Unity" ("Two descriptions have a common source when both arise from the same act and apply to the same world, each perfected in one of the two characters a comparison allows") and "One World, One Account, Two Descriptions", and section "What the Theorem Forbids" ("It forbids only one kind of unity: a single description in which the directions of space and time themselves carry both characters together").

The puzzle of black-hole information rests on a premise: that geometry and matter form one quantum state, to which quantum theory is applied as a whole system. Carried by *Two Theories, One World*, chapter 25, sections "The Puzzle" and "The Premise Underneath".

Quantum theory guarantees that the matter's state, laid out on its geometry, goes forward without loss: the fields inside and outside together stay pure at every stage the calculation describes, and the outgoing radiation is mixed because it is entangled with the field inside and is only part of the whole, as a coded message is only part without its key. Carried by *Two Theories, One World*, chapter 25, section "The Premise Underneath".

"Information is not destroyed in a black hole": neither description destroys it, and while the hole stands, the horizon hides what fell in from everything outside and destroys none of it. Carried by *Two Theories, One World*, chapter 25, opening and section "Information Is Not Destroyed".

For a hole far lighter than any star, light enough to evaporate completely while the world around it remains, the firewall argument is the question to answer: it says that a glow that in the end carries out everything that fell in, ordinary physics outside the hole, and a smooth horizon cannot all hold together; against it, *Two Theories, One World* keeps the smooth horizon, ordinary physics outside and the equivalence principle, and gives up only the assumption that what lies just inside the hori-

zon is independent of the glow that has already left; the computations of 2019 count the inside region together with the early glow. Carried by *Two Theories, One World*, chapter 25, section "Small Holes and the Page Curve" ("Take first a hole far lighter than any star, light enough to evaporate completely while an outside world remains around it"; "The account keeps the smooth horizon and ordinary physics outside, and gives up only the assumption that the partners inside the horizon are independent of the early radiation"); and by *The Unquantized Arena*, chapter 17, "Black-Hole Information and the Page Curve", section VIII, "Questions" ("The step the argument needs, and the account does not grant, is that independence"). The computations of the Page curve are those of G. Penington (2019) and of A. Almheiri, N. Engelhardt, D. Marolf and H. Maxfield (2019). Hossenfelder's own note that the firewall proof "relies on an unnecessary hidden assumption that can be dropped" is in *Lost in Math*, Notes to chapter 8, note 13.

For a hole formed from a star, *Two Theories, One World* says exactly two things: the information that fell in is not destroyed, and while the hole stands no one outside can reach it; it asserts neither that the information returns to the world outside nor that it is lost to that world, because its argument needs neither. Carried by *Two Theories, One World*, chapter 25, section "Holes Formed From Stars" ("The information that fell in is not destroyed. While the hole stands, the information is not accessible from outside"; "The account asserts neither that this information returns to the outside world nor that it is lost to the outside world. The thesis needs neither assertion"); by *The Unquantized Arena*, chapter 17, section VII; and by *Side by Side*, Volume One, Appendix B, section IX, "What the Books Do Not Predict".

The Gravitational Passage follows what falls into a black hole through the interior, to its end: the interiors of all the black holes of an epoch end together at the turn (epoch and turn as glossed under Chapter Ten), and what fell in is carried with the matter to that end and comes out in the beginning of the next epoch as its small departures from perfect evenness, the faint pattern from which that epoch's galaxies grow; the information

"is lost to every observer who remains outside the horizon, and it is not destroyed". Carried by *The Gravitational Passage*, chapter 18, "The Interior Passage", section XII, "The Cycle", and section XIII, "Predictions", entry "No information paradox"; and, as a restatement in plain words, by *At the Edge of Reality*, chapter 18, "A Clean Slate", section "Information Is Not Destroyed". *The Gravitational Passage* states the passage under a condition ("If the black hole interior connects to a cosmological origin"). I state the passage as that book's account. The sealed record of *Side by Side*, Volume One, Appendix B, section IX, states the passage without condition: on the account of *The Gravitational Passage*, the information is not destroyed, and the information re-emerges in the initial conditions of the next epoch.

What passes the turn is the form of what fell in, which alternatives it took; an entropy reckoned from outside the hole is a count, the number of states of a system that the comparisons available from some context cannot tell apart, and it belongs to the outside world that made it, and ends with that world, at the turn. Carried by *The Gravitational Passage*, chapter 18, section XIII; by *At the Edge of Reality*, chapter 18; and, for the gloss of entropy, by *The Compactification*, chapter 3, section V, as given under Chapter Ten.

Two routes, from two books on different ground, arrive at one statement, that nothing is destroyed: *Two Theories, One World* removes the premise that geometry and matter form one quantum state, and finds that each theory carries the information forward (its ground is its chapters 11 and 12); *The Gravitational Passage* rejects a different premise, that the information must come back to the world outside the hole, and follows what fell in through the interior to the next epoch (its ground is the interior passage and the cycle of its chapter 18). Carried by *Two Theories, One World*, chapter 25, section "The Premise Underneath" ("The premise is this: geometry and matter form one quantum state"); and by *The Gravitational Passage*, chapter 18 ("The information paradox rests on the premise that information must be recoverable in the original exterior, and

this account rejects that premise"). *The Unquantized Arena* is counted with *Two Theories, One World*, and *At the Edge of Reality* with *The Gravitational Passage*, as restatements of each.

This account establishes that the arena of space and time, which holds two of the three measures of the context of every measurement, cannot be quantized; each of its results in Chapter Thirteen needs only the two theories exactly as they stand. Carried by *Two Theories, One World*, "The Argument in Brief", section "The Answer in a Page" ("The arena cannot be quantized"); the claim rests on my identification of gravity as the arena, given above (chapter 9, section "The Identification"); the three measures of the context are named by *The Last Turtle*, "The Three Boundaries of Knowing", section VII, "How the Constants Join the Measures" ("The measures of context are space, time and possibility").

From the same theorem, general relativity is continuity with asymmetry, and quantum theory is symmetry with discontinuity; "The failure to unify them is not a problem awaiting a solution. It is a structural exclusion"; the unity that can be had is already in hand: two descriptions of one world, "each capturing what the other must leave out". Carried by *The Basis of Physics*, Essay 12, section X, "Summary" ("General Relativity is continuity with asymmetry. Quantum Mechanics is symmetry with discontinuity"). The conclusion that the failure to unify general relativity and quantum theory is a structural exclusion rests on the Incommensuration Theorem, the same theorem on which *Two Theories, One World* rests. The conclusion is therefore not a route separate from *Two Theories, One World*.

The measurements made so far agree: the waveform of the first gravitational wave detected, in 2015, matched general relativity; MICROSCOPE found titanium and platinum to fall alike to within a few parts in a million billion (2022); LHAASO timed light of very different energies from the burst of 9 October 2022 and found no delay that depends on energy (2024), so the simplest pictures of a grainy space and time are excluded; and every body falls alike, as a floor shared by everything requires. Car-

ried by *Two Theories, One World*, chapter 1, and chapter 27, "What the World Will Show", sections "Every Material Will Fall Alike" and "Space and Time Will Stay Smooth"; and by *Side by Side*, Volume One, Appendix B, section III, "The Arena and Gravitation", Prediction 3, "Gravitation is not quantized", and Prediction 4, "Free fall is universal and nothing shields gravity". Exact values, measured: the Eötvös parameter of MICROSCOPE, $[-1.5 \pm 2.3 \text{ (statistical)} \pm 1.5 \text{ (systematic)}] \times 10^{-15}$, where the Eötvös parameter is the fractional difference in the free fall of two materials (Touboul and others, 2022); LHAASO places the energy scale of a first-order energy-dependent delay above ten times the Planck energy.

Chapter Fourteen: Whom Can We Trust When Scientists Agree?

William Thomson reckoned the age of the Earth from the heat flowing out of it; his figures carried the authority of exact physics, and they prevailed, and many geologists came to accept a limit set by the physicists. Carried by *Physics Is Not Math*, chapter 14, "When the Mathematics Overruled the World", section I, "A Stone from the Fire", section II, "The Record in the Rocks", and section III, "The Premise That Was Not the World's". Exact values: in 1862, between 20 million and 400 million years; by 1897, more than 20 and less than 40 million years, and probably much nearer 20; Arthur Holmes in 1911, about 1,600 million years; Clair Patterson in 1956, about 4,550 million years; the measured age today, about 4,540 million years.

The age of the Earth was settled by measurement, after John Perry's questions about the calculation's starting points had shown where to look: Perry took each starting point and asked whether the Earth is like that, and the disagreement with the record of the rocks said that some starting point was not the world's. Carried by *Physics Is Not Math*, chapter 14, section VI, "The Physics Question Stays in Charge".

There are three ways in which anything can be held to be validated, and no others: measurement, agreement and proof; "Of the three, only the first and the third validate truth. Agreement among people validates

nothing by itself"; at most, agreement is circumstantial evidence, standing in for a measurement where no measurement can be made. Carried by *Physics Is Not Math*, chapter 19, "A Right Method of Evaluation", section IV, "Three Ways of Validation"; circumstantial evidence, facts that point to a conclusion without showing it directly, as a footprint in the garden matches the soles of a man's boots, is glossed in chapter 12, section III, "A Court Weighs Many Strands". The weighing, the miller's sum and the queue at the stall are this book's pictures of the three.

Every comparison has three roles: the act itself, the comparing as it happens, here and now; what is laid out, a result, a record, a sum or a map, anything that can be held in view as a whole and shared; and the stance, the standpoint from which the act is made together with the range of what could be found from it; held in a stance are commitments that its holders carry without stating or checking them. Carried by *Physics Is Not Math*, chapter 3, "Truth Has a Frame", section IX, "A Role Depends on the Frame" ("One is the act itself: the comparing as it happens, here and now"; "One is what is laid out as structure: the result, the record, the map, what can be held in view as a whole and shared"; "And one is the stance from which the act proceeds, together with the range of what could be found from it"); chapter 9, section III ("A claim is implied when it is held without being stated: the commitment that a practice carries and never says"). That book names the three roles the immanent, the omniscient and the transcendent; I use the plain names only.

These three roles are Chapter Three's three positions, taken more widely: the weighing itself is the act; the thing compared gives what is laid out once the weighing's result is written down; the thing it is compared against is the standard from which the thing compared is read; and *Comparison; The Necessary Basis* calls a standard a stance, as a length is read from a rod, and widens the position of the thing compared against into the third role, the standpoint from which any act of comparison is made. Carried by *Comparison; The Necessary Basis*, chapter 5, "Three Roles", section I, "Three Roles in Every Comparison" ("One position is the act of comparing"; "One position is the thing compared"; "One posi-

tion is the thing compared against"; "The thing compared against is the standard, and a standard is the stance from which the other thing is read"; "Generalized, the position of the thing compared against is the stance"; the third role is "the stance and the possibility from which an act proceeds"). The parcel and the kilogram weight on the stall are this book's picture.

There are three roles because there is the one act and exactly two ways in which an act of comparison can be held perfectly, continuous and asymmetric or symmetric and discontinuous; each of the two ways goes to one of the two roles besides the act: what is laid out is held perfectly in the symmetric and discontinuous way, the same for everyone and in separate, countable marks; the stance is held perfectly in the continuous and asymmetric way, one unbroken engagement from where it stands; and the act is the one act from which the other two are made, what is laid out being the act set down and the stance having been formed by the acts before it; so there is the one act, and one role for each of the two ways, three roles in all, and there is no fourth; the three are distinct, inseparable and not interchangeable, which is the relation the third axiom of the Immanent Metaphysics states. Carried by *Physics Is Not Math*, chapter 3, section IX ("There are three because, as Chapter 2 found, there is the one act and there are exactly two ways in which it can be perfected; the one and the two together make three"); chapter 10, "Order and Role", section IV, "Distinct, Inseparable, Non-Interchangeable" ("The three are distinct: no one of them collapses into another. They are inseparable: none stands without the other two. And they are non-interchangeable: putting one in another's place gives a different and wrong result"), and section V, "First Among the Three, and Two Peers", which pairs the kinds with the roles in the frame *Incommensuration* calls the focus of the two laws, where content is held to symmetry and context to continuity ("symmetry carries the omniscient character and continuity the transcendent"; "the structure is the act laid out, and the stance from which an act proceeds was itself formed by the acts before it"), and adds that "a role and a character answer two different questions"; and chapter 19, section IV. The pairing of each way with its

role is stated without that frame in *The Last Turtle*, "Comparison, Its Four Compounds, and the Incommensuration Theorem", section VIII, "The Two Characters: The Objective and the Subjective" ("Symmetry with discontinuity is the character of the omniscient: exact, repeating, in discrete steps"; "Continuity with asymmetry is the character of the transcendent: smooth, connected, never exactly repeating"), and "The Three Modalities and the Three Axioms", section II, "Their Characters, and the Three Persons" ("The first-person stance, the position from which an act proceeds, is transcendent in character: continuity with asymmetry"); in both books the omniscient names what is laid out and the transcendent names the stance.

The three ways of validation are those three roles, read as ways of validating: a measurement is the act, made here and now, in the first person; a proof is what is laid out, held in view as a whole, in the third person, the same for anyone who checks it; agreement belongs to the stance, carried by many people as a shared commitment, in the second person, without any one of them checking it; since a comparison has three roles and no fourth, there are three ways of validation and no fourth, and since no role can do another's work, agreement cannot do the work of a weighing or of a proof. Carried by *Physics Is Not Math*, chapter 19, section IV ("Agreement is implied: it is held in the stance of a practice, as a commitment that its holders carry without any of them checking it, and so it is transcendent"), where measurement is "performed" and proof "surveyed".

The agreement of experts trained in one tradition is "not independent confirmation", since "a shared training can carry a shared error into every one of their judgments at once". Carried by *Physics Is Not Math*, chapter 18, "Evaluating the Evaluator", section VI, "The Power of the Critic".

Treating objectivity as reality (the convergent as the immediate) is the error of consensus: "taking agreement to be encounter", an encounter being one actual meeting with the thing itself. Carried by *Comparison; The Necessary Basis*, chapter 12, "Domains and What Is Real", section VI,

"Realism, Idealism, and the Errors of Extrema", subsection "The Three Tests" ("Treating objectivity as reality (the convergent as the immediate) is the error of consensus: taking agreement to be encounter").

An argument has merit when its claims follow from its starting points, and it is true of the world when it has merit and its starting points are also true of the world; Thomson's calculation had merit, and "That connection holds today exactly as it held in 1862", while its starting points were not true of the world. Carried by *Physics Is Not Math*, chapter 17, "Relevance, Merit and Truth", section IV, "Merit Before Truth", and chapter 14, section IV, "Merit Without Truth".

The evidence of the rocks and of life was a cable: many strands, each rough, from independent sources, which agreed on the need for far more time; the mistake "was to let one exact route stand above the whole inquiry, as if its exactness made it the whole cable, and to weigh the other strands by how exact they were in place of what they showed". Carried by *Physics Is Not Math*, chapter 14, section IV, "Merit Without Truth"; the picture of the cable is in chapter 12, "Chains and Cables", section I, "A Chain and a Cable". That book states the mistake without naming who made the mistake, and I name Thomson and those who accepted his limit, from the story told in this chapter.

On 1 November 2026 every prediction made by the books of this account was gathered into one record, forty-two in all, each stated with the book and chapter that argue it, the measurements already reported, and, where the books name one, the coming measurement that decides it; the record is fixed at its date and is not revised; I call it the sealed record: a record of predictions sealed at a date before the measurements that will decide them, with the rule of decision stated in advance; it is printed whole in *Side by Side*, Volume One, as that book's Appendix B. Carried by *Side by Side*, Volume One, Appendix B, "The Sealed Record", which prints "The Registered Predictions of Physics from Comparison; A Dated Record, 1 November 2026", with its Abstract; "Terms of the Collection", entry "Sealed record"; and Part One, Abstract ("the forty-two predictions sealed on 1 November 2026"). The record's DOI is 10.67291/RQQS3025.

The rule of decision says, before any result comes in, what will count as a result, and it was written into the record on the same date as the predictions, so the measure a result must reach was fixed before any result could be seen. Carried by *Side by Side*, Volume One, Appendix B, section II, "The Rule of Decision and the Inputs"; the rule's own words, with the gloss of a standard deviation, are printed in Appendix A.

The record also says, on its date, which measurements bear on this account, so no one can choose afterward, once the data are in, which results to count. Carried by *Side by Side*, Volume One, Appendix B, section IX, "What the Books Do Not Predict" ("A record of predictions is exact only if it also says what is not predicted, so that no later measurement is counted for or against the account where the account makes no claim").

This account keeps Popper's test, which counts a theory as science when some possible observation could show it false, where the test applies: wherever the outcome of a comparison can be objective; in *Physics Is Not Math* an outcome is objective when it comes from an actual comparison, when it can be compared again by another person, at another time, along another route, with every finding consistent with the others, and when it could have come out against what was expected; there falsification, the attempt to show a claim false by setting a predicted outcome against the outcome found, is "a valid and powerful tool". Carried by *Physics Is Not Math*, chapter 19, section III, "Where a Test Applies" ("Where it applies it is a valid and powerful tool"; "The first is intensity: there must be actual interaction with it, more than a report of someone else's"; "The second is consistency: the interactions must close into consistent rings, one person's finding agreeing with another's, a photograph with a memory, today's reading with last year's"; "The third is novelty: it must be able to surprise, to show what no one expected or could have fixed in advance"; "A test is these three rings at work: an actual comparison, repeated and agreed across many, whose outcome could have gone against the expectation"; "So a test applies exactly where the outcome of a comparison can be objective, and nowhere else"), whose three conditions are intensity, consistency and novelty, taken together; Hossenfelder's re-

port that the test is outdated, which Chapter Five quotes, is in *Lost in Math*, chapter 2, "Why Trust a Theorist?". Every claim of this account about what the world will show stands in the sealed record beside the measurement that bears on it, and Appendix A gathers those measurements.

The first rule of judging any claim: name the kind of claim first, then apply its own method, fully, and no other; a proof is checked by following its steps, and a claim about the world is checked by measurement and by independent routes to the same result. Carried by *Physics Is Not Math*, chapter 19, section II, "Three Kinds of Claim".

A report on the people and their situation tells about the people, and is not a check of what they concluded; a conclusion reached under poor conditions may still be right, and one reached by a master of his subject may still be wrong, as Thomson's was. Carried by *Physics Is Not Math*, chapter 18, section III, "Five Errors and How to Look for Them" ("A fact about a method is never a finding about its subject"), and chapter 20, "Two Answers to a Proof", section III, "The Twelve Patterns", Pattern 2, "The Social Substitute" ("Social consensus is evidence for social claims").

A review of anyone's work serves its reader when "it hands over its methods along with its findings, since findings without their methods leave the reader nothing to do but defer"; to defer is to take someone's word because of who they are, and a finding handed over with its method asks to be checked. Carried by *Physics Is Not Math*, chapter 19, section VIII, "Three Roles in a Cycle".

Several kinds of thing lie outside the reach of any test, among them the act of comparing itself ("An act cannot be falsified"), a claim of logical form, a claim that a conclusion follows from its starting points, as in a proof, and a description of what a thing is; "their lying outside is a fact about the range of the test, not about their truth". Carried by *Physics Is Not Math*, chapter 19, section III, which also names what is real, what exists

and what is subjective; and section II, "Three Kinds of Claim" ("A claim of logical form is established by its structure: whether its conclusion follows from its premises. A proof is the plain case").

A claim about the world could be otherwise, so which way the world is must be found by looking. Carried by *Physics Is Not Math*, chapter 19, section II.

A claim that no measurement can reach is still decided, by the argument that fits its kind: a claim of logical form by following its steps, and a description of what a thing is by two checks, the steps of its derivation followed and each of its definitions checked against the way its word is used; since every measurement already presupposes the structure such a claim concerns, no measured result counts for or against it. Carried by *Side by Side*, Volume One, Appendix I, section V, "Where No Measurement Decides" ("Every measurement already presupposes the structure such a claim concerns"; "each is decided by the argument that fits it"); and by *Physics Is Not Math*, chapter 19, section III.

Some such claims are settled outright, as superdeterminism is excluded by argument. Carried by *Side by Side*, Volume One, Appendix I, section V ("The collection's claim is of logical form, and the sealed record states it as an exclusion"), and Appendix B, Prediction 28, "No world is perfectly deterministic, and no process is perfectly reversible".

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". Here symmetry means the same under every change of place or setting, and continuity means with no gaps, so that a small change of setting gives a small change in what is found; asymmetry and discontinuity are their opposites. Carried by *Physics Is Not Math*, chapter 2, section VI, "The Theorem"; and by *Side by Side*, Volume One, Appendix I, section V.

Every measurement ever made is an act of comparison, and so an instance of the theorem; the theorem is proved from nothing but what the parts of a comparison mean; "No measurement, no proof and no agreement has ever gone against it, in any subject, and none can, since each would be an act of comparison and so an instance of the theorem before it began"; so the theorem carries no "as far as we currently know", and no further finding can revise it, because every further finding is one more instance of it. Carried by *Physics Is Not Math*, chapter 19, section V, "The Most Fully Confirmed Truth".

A claim gathered from the cases seen so far is stated together with the cases it covers, while a claim that holds in every act of checking it needs no such phrase, since every check uses it; I take Hossenfelder's "as far as we currently know" to say exactly the first. Carried by *Physics Is Not Math*, chapter 18, section V, "The Register Taken for the Result"; the step from that section to her phrase is mine, stated in the first person in the chapter.

The not yet known is what a weighing will reach, as a parcel still on the miller's cart; the unknowable is what the structure of comparison does not reach, so that it cannot be known "even in principle, by any observer, at any time, by any method"; and the framework of *The Basis of Physics* does not enter the unknowable: it marks its boundary ("The framework does not enter the unknowable. It marks its boundary"). Carried by *The Basis of Physics*, Essay 14, "The Three Horizons", section I, "The Unknown and the Unknowable", and Essay 17, "What Physics Cannot Reach", section VII, "The Unknowable, and Where the Boundary Lies" ("It can say: here is where knowledge ends and the unknowable begins"); the parcel on the cart is this book's picture.

Closing: What the Balance Shows

Each pixel of a photograph is the result of a comparison, the light from one small patch of sky set against the camera's scale of brightness, made by an instrument that is itself a small piece of the world; so the photograph is a weighing made from inside the world, which is the way every

finding of physics is made: I identify every finding of physics with an act of comparison made from inside the world. Carried by *Physics Is Not Math*, chapter 1, section V, "A Premise Used by Every Attempt to Deny It" ("I identify every finding of physics with an act of comparison made from inside the world"); and by *Home in the World*, Prelude, "Two Crews, One Tunnel", section "The Crew from Knowing" ("To know anything at all is to have compared").

Hossenfelder's critique of beauty is this account's ally. Carried by *Side by Side*, Volume One, "What Beauty Cannot Decide", section IX, "Summary" ("Her critique of beauty is the collection's ally").

A property of a mathematical description (its symmetry, its economy, the absence of large unexplained ratios in it) belongs to the description, and is no evidence about the world it describes; beauty, naturalness and simplicity, in the sense the field has given them, are properties of a mathematical description, so they are no evidence about the world either; on this point this account and Hossenfelder arrive at one place by separate roads. Carried by *Side by Side*, Volume One, "What Beauty Cannot Decide", Abstract ("a property of a mathematical rendering cannot decide what is true of the world it renders"), and section II, "Where She Is Right: Beauty Is No Evidence" ("But a property of a mathematical rendering (its symmetry, its economy, the absence of large unexplained ratios in it) is a property of the rendering"; "The world is under no obligation to the instrument").

Elegance counts in one sense that anyone can check: many results from few premises, and independent routes arriving at one structure. Carried by *Physics Is Not Math*, chapter 19, section VII, "Merit Has Many Measures"; and by *Side by Side*, Volume One, "What Beauty Cannot Decide", section II.

The number stamped on a weight is the record of an earlier weighing, and any arithmetic done with such numbers comes after the weighings that made them. Carried by the Chapter Two entries above (*Home in the World*, chapter 4, section "Six Parts of Every Comparison"; *Physics Is Not Math*, chapter 9, section II).

The order of depth is metaphysics, physics, computation, mathematics, each standing after the one before, because every proof is checked by a run, every run is a physical process, and every finding of physics is a comparison made from inside the world; mathematics is the finest instrument there is for what is laid out as structure, and it keeps every power it has. Carried by *Side by Side*, Volume One, "What Beauty Cannot Decide", section II; and by *Physics Is Not Math*, chapter 5, "What Depth Means", sections V, "The Order of the Four", and VII, "Summary".

The world that comparisons find is not a mathematical structure, and so physics is not mathematics. Carried by *Side by Side*, Volume Two, "The Structure and the Act", section III, "The Step at Which They Part".

The Incommensuration Theorem: "Symmetry and continuity cannot both be applied, simultaneously and fundamentally, to any event or comparison; and neither can asymmetry and discontinuity". Symmetry means the same under every change of place or setting, and continuity means with no gaps, so that a small change of setting gives a small change in what is found; asymmetry and discontinuity are their opposites; the box of weights and the settling beam of Chapter Two show all four. It is a structural fact about the nature of knowing, and it holds wherever anything is compared. Carried by *Physics Is Not Math*, chapter 2, section VI, "The Theorem", and Appendix C, "Glossary"; and by *Causality Without Determinism*, chapter 1, section VII, "The Incommensuration Theorem".

At every mass where a new kind of particle had been expected, the collider's beam stayed level, and a level beam is a result too; the list of the kinds of particle is closed by the structure of comparison, and there is no supersymmetric partner, at any energy. Carried by *Side by Side*, Volume One, "What Beauty Cannot Decide", section II, citing *The Kinds of Particle*,

chapter 6, section IV; by *The Story of the Particles*, Level 9, "The Composites and the Boundary", section IV, "What the Zoo Does Not Contain"; and by *Non-Commutative Geometry and the Immanent Metaphysics*, chapter 19, "The Particle Content", section IV, Propositions 19.7(iii) and 19.8, which together exclude a partner at any mass (given under Chapter Three above).

The standard model's three forces were never one force: no single larger force splits into them. Carried by *The Particular Evidence*, Case 12, "The Heavy Messengers", section V, "The Confession" ("They were never one force"), with the sense given under Chapter Three above: the mixing of the weak and electromagnetic carriers stands, and it makes no larger force.

The proton is stable: it does not decay; no route to decay exists in the structure. Carried by *The Branches of the Kinds*, chapter 2, "The Stable Proton", section II, "Baryon Number" ("The proton is stable: no route to decay exists in the structure"); and by *What Comes After the Dark*, chapter 5, "What Becomes of the Stars and Their Ashes?", section "What This Means for You" ("The proton does not decay, because no carrier joins color to the weak charge"). *The Branches of the Kinds* states the matter in two forms, and both hold. As a statement of the structure, the proton is stable: no route to decay exists (chapter 2, section II). As a statement of conditional stability, the proton is stable if it is the lightest whole of baryon number one; the condition is a statement of the structure, and whether it is met is measured (chapter 2, Key Concepts, entry "Conditional stability"), and measurement shows it is met.

A value that lands is a number that agrees with measurement before anyone knows why; this account holds such a value as a question, "why does it land?", and as evidence of a reason not yet known. Carried by *Physics Is Not Math*, chapter 13, "A Value That Lands", section II, "Why Does It Land?", and section IV; and by *Side by Side*, Volume One, "What Beauty Cannot Decide", section III, "What the Collection Puts in Place of Beauty" ("It holds something further: that the agreement is "evidence of a reason not yet known"").

Every pure number of the standard model has a stated standing, a statement of where the number comes from: set by the structure; set by the structure once a stated step is taken; measured; or reached by the account and found by measurement, with the reason it lands still a question. Carried by *Why These Numbers*, chapter 1, section "Four Ways a Number Can Stand" (four in plain words); and by *The Spectral Chain*, chapter 1, section V, "The Six Standings" ("A measured agreement is a value the account reaches that measurement finds, and it carries the question of why it lands"), which divides the same ground into six.

The strong force has an angle of its own that could have let it treat a process differently from that process's mirror image with matter swapped for antimatter, the symmetry called CP; in this account the strong force's own angle is zero, set by the structure. Carried by *The Branches of the Kinds*, chapter 3, "The Discrete Symmetries", Chapter Overview ("The strong force preserves CP: its own angle is zero").

The cosmological constant is one constant: one number at every place and every time of our epoch, with no dark energy field behind it; I identify its value with the share of the energy of empty space that a measurement made inside empty space takes in, and by that identification its value is set by the structure together with the measured strength of gravity and the measured particle horizon, the distance from which light has had time to reach us. Carried by *What the Beginning Left Behind*, chapter 8, "The One Edge That Sets the Vacuum", section "Three Tiles Out of All the Tiles" ("The share itself, three parts out of the count, is an identification: mine, made in the three steps above"; "So I assign the particle horizon the count of Bekenstein and Hawking, by an identification"), and "Before We Begin", section "How the Book Speaks of a Number"; and by *What Comes After the Dark*, chapter 2, "Will It All Fall Back?", section "The Second Way: One Number for Our Whole Epoch" ("In this physics the dark energy is not a field"), and chapter 3, "Will the Expansion Tear Us Apart?" ("Within our epoch, the cosmological constant is the same at every place and every time"; "In this physics the dark energy is the cosmological constant, one number, fixed once and the same at every time of our epoch").

Exact values: 2.56 against a measured 2.52, in units of 10^{-47} GeV^4; matter fraction 0.311 against a measured 0.315 ± 0.007; the formula is given under Chapter Four above.

Only what can be set on a pan of this world can be weighed, and a universe that can never be set beside ours gives no result. Carried by the Chapter Five entries above (*Side by Side*, Volume Two, "The Structure and the Act", section VI).

Every point of space carries the six small dimensions, curled up far too small to see. The six small dimensions have one settled state, so empty space has one settled state, one vacuum. The landscape of other settled states that string theory allows is not there in this account. The other universes of the landscape, and the universes of eternal inflation, in which new universes bud off without end from an expanding background, are not real. In this account no structure contains the other universes of the landscape or the universes of eternal inflation. Carried by *What Comes After the Dark*, Preface, "The Question of the Far Future", section "The Answer, in Brief" ("Empty space carries a small hidden geometry, and that geometry has no other shape to change into"), and chapter 4, section "Coleman's Question, Answered for the Six" ("So the six have one vacuum, and no second one for a bubble to lead to"); by *The Compactification*, chapter 1, "The Re-Forming of the Internal Space", section XI, "Conclusion", and chapter 2, "One Vacuum", for the one vacuum and no landscape; and, for the universes of eternal inflation, by *Side by Side*, Volume Two, "The Structure and the Act", 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").

Any interaction that lays down a record is a finding, and no conscious observer is needed. Carried by *Why the Quantum Is the Way It Is*, chapter 17, "Why a Measurement Has an Outcome", section "Every Comparison Has a Cut", and chapter 18, "The Interpretations, Each Missing a Role", section "QBism" ("In this book a comparer is any interaction").

What is updated on measurement is the shared record, and the update is no physical process. Carried by *The Quantum Passage*, chapter 9, "The Measurement Problem Dissolved", section IV, "Why Collapse Is Not Physical"; and by *Side by Side*, Volume One, "What Beauty Cannot Decide", section IX.

Every act of comparison leaves something that no law fixes, so the experimenter's choice and the particle's answer were never written together in advance, and the structure of comparison excludes superdeterminism; a world in which it held would have no evidence in it, its own included; this account credits the exact statement of statistical independence that Hossenfelder and Palmer give, and the tests of it that they propose. Carried by *Side by Side*, Volume One, "What Beauty Cannot Decide", section IV, "Superdeterminism at Full Strength" ("Hossenfelder and Palmer identify the assumption of statistical independence exactly, and they propose tests of it", quoting *The Unquantized Arena*, chapter 13, section VII), section V, and section IX.

The future is very largely fixed by the past, as Hossenfelder says, and no world is fixed completely, at any scale. Carried by *What Cannot Be*, chapter 5, "Is Everything Already Fixed?", section "What the Conclusion Rests On"; by *Side by Side*, Volume One, Appendix I, section V, "Where No Measurement Decides", subsection "Superdeterminism" ("no world is purely and completely deterministic"); and by *Causality Without Determinism*, chapter 1, section VIII, "Why Determinism Cannot Be Had".

Hard randomness is an outcome that no prior specification fixes, however complete, and hard randomness, seen from inside by the one from whom it comes, is choice; choice is a fact about the world, beside cause, at every scale. Carried by *Causality Without Determinism*, chapter 5, "Computation, Consciousness and Simulation", section III, "The Bound Triple", and section V, "Hard Randomness and Choice" ("hard randomness and choice are one event described from two positions").

A description of the balance, however complete, is not a weighing; a person is made of nothing but particles and is also an act of comparison happening from inside, running one way in time, with outcomes that nothing fixed in advance; no description of the particles a person is made of, however complete, is the whole of that person, and a copy, an upload or a program can carry the pattern of the parts and not the act. Carried by *The Last Turtle*, chapter 27, "The Size of Chemistry", section IV, "The Failure of Reduction, Stated Exactly" ("The claim of reductionism, though, is that the description exhausts the thing, and that claim fails even in the most classical case").

A person is not a file, and a computation is not what consciousness is. Carried by *What Cannot Be*, chapter 22, "Why No Computation Is Everything", section "A Person Is Not a File"; and by *Causality Without Determinism*, chapter 5, opening ("Consciousness is three things bound together and taken as one act (the arrow of time, hard randomness, and the subjective), and the Incommensuration Theorem shows that a process made of one rule repeated cannot compose them").

Every act of comparison runs one way, from what could be found, to the act, to the record, and I identify that one-way order with the direction of time; no process can be run backward faithfully, with every detail returned as it was, so time has a direction in every single interaction, before any count of disorder is made. Carried by *What the Beginning Left Behind*, chapter "Two Arrows of Time", section "The Direction in Which Comparison Proceeds" ("I identify the one-way order of findings, the order of Axiom II, with the direction of time"); and by *The Basis of Physics*, Essay 11, "The Structural Arrow of Time", section III, "Lawful Reversal and Faithful Reversal" ("Lawful reversal is not faithful reversal"), and section VIII, "Summary".

The past exists: the past stands as structure, timeless, the same in every instance, able to be held in view as a whole. The present is real: the present is given in an actual act of comparison, here, now, with the future still open. The future is not yet there. Carried by *The Basis of Physics*, Essay

11, section VI, "Time as Process, and Not Only as Dimension"; the glosses are those of *Home in the World*, "For the Specialist", section "Exists and Real; Causation and Determinism".

Every measurement of the early universe is a weighing made now, of what the beginning left; no comparison registers the first moment as an event, because no comparison reaches across it; this account answers every puzzle that inflation was brought in to solve, and so it needs no inflation; an epoch is one whole span of the universe's history, from one turn to the next, ours beginning at the Big Bang, and the turn is the boundary between two epochs, where the interiors of all the black holes of the ending epoch end together, as one end, and the next epoch begins; I identify what came before the Big Bang with the collapse inside the black holes of the epoch before ours. Carried by *What the Beginning Left Behind*, "Before We Begin", section "Where the Story Stands", chapter 13, "No Inflation Needed" ("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"), and chapter 7, "A Clean Slate, Counted", section "Every Count Has a Context" ("The collapse inside the black holes and the beginning of the new epoch are one process"); and by *At the Edge of Reality*, chapter 2, section "The Answer of This Book" ("I identify what lies on the other side of the limit with the collapse of the interiors of the black holes of the epoch before ours"), and chapter 16, "The Turn", section "What Comes After the End".

The galaxies of our epoch never fall back together, and nothing bound is ever torn apart; the six small dimensions that every point of space carries have no other settled state to drop into; for the Higgs field, the other settled feature of empty space and the field that gives many particles their masses, the present state is the lowest point in the curve this account derives for the field's energy at the energies where the field is measured, and the standard calculation, which follows the field to far higher energies, finds the present state lasting far beyond the age of the universe; the proton lasts; and the long emptying of the sky ends in a turn, and the next epoch begins. Carried by *What Comes After the Dark*, chapter 2, "Will It All

Fall Back?", section "A Ball Thrown Upward" ("Our epoch does not fall back") and section "The Second Way: One Number for Our Whole Epoch" ("So the hidden geometry has one held state, and no lower state of its own for a bubble to open into") and section "What This Means for You" ("Empty space has no second state to drop into"); chapter 3, "Will the Expansion Tear Us Apart?", section "What This Means for You" ("so nothing bound is ever torn apart by the expansion"); chapter 4, section "The Higgs Field"; chapter 5, section "What This Means for You" ("The proton does not decay"); and the Preface, section "The Answer, in Brief". The six's one settled state and the Higgs field's lowest point are stated each at its own strength, as under Chapter Eleven above; "floor" and "hidden geometry" are *What Comes After the Dark*'s words.

A weighing can show a pull that comes from no thing set in a pan; every comparison has a content, what the verdict of the comparison is about, and a context, the respect in which the two things compared are two; at the balance the content is how heavy the thing in the pan is, and the context is the two places the things weighed occupy, left pan and right pan, together with the floor and the room that hold those places, at the moment of the weighing; in physics the content is matter, and the context is the arena of space and time in which matter is found, and the setting of possibility, the range of states in which it could be found; I identify the dark matter with a ringing of the setting itself: a lasting vibration of the six small dimensions, taken as the setting of possibility, and so a vibration of context; it shows in the result only as extra pull, it is never a thing set in a pan, and it is not matter of any kind on the list of particles; it acts on the matter we know through gravity alone, so every search for it through any other interaction comes back empty. Carried by *Measurement; The Steps from Comparison to Physics*, chapter 1, section I, for the moment in the context ("The context is the respect in which they are two: two pans, two places, one moment"); by *The Weight of Possibility*, chapter 1, section III ("the dark matter is an excitation of possibility as the context of what could be found"), section IV, "The Identification" ("This statement is an

identification, and this section gives its argument"; "in role it is a vibration of context"), "A Note to the Reader", and chapter 4, "Why the Dark Persists, and Its Gyrations", section II, "No Exit into Content".

Einstein's law of gravity stays as he wrote it, unmodified. Carried by *The Weight of Possibility*, chapter 5, "The Measurements", section V, "Small Scales" ("The field equations hold Newton's constant and the cosmological constant, and no constant of acceleration"); and by *Side by Side*, Volume Two, "The Law and the History".

Space and time together form the arena of physics, which holds two of the three measures of the context of every measurement, the third being possibility; I identify gravity as the arena: the shape of the arena is what we feel as gravity, and gravity is not one more thing found in it; the arena cannot be quantized: the Incommensuration Theorem excludes its taking on the smallest steps that quantum physics gives to matter; the two great theories are joined side by side and never merged; when matter is in two places at once, the answer I give is one smooth geometry for each alternative of the matter, shaped by that alternative alone; and information is not destroyed in a black hole. Carried by *Two Theories, One World*, chapter 9, "Four Marks of the Arena", section "The Identification" ("I identify gravity as the arena of physics, the context of every physical measurement, by that match"); chapter 12, "One Geometry for Each Alternative", section "Two Places, Two Shapes" ("The answer I give is the first two, each in its own alternative"; "Each alternative of the matter carries its own smooth geometry"); "The Argument in Brief", sections "The Answer in a Page" ("The arena cannot be quantized") and "How the Book Is Set Out", with "The Question" for the arena as the context of every measurement; chapter 11, "What Quantizing Does, and Why the Arena Cannot Take It" ("Those are the two pairings that the Incommensuration Theorem forbids"); and chapter 25, "Where Does the Information Go?", section "Information Is Not Destroyed"; and by *The View from Inside*, chapter 6, "Symmetry and Continuity Cannot Both Be Perfected", section "The Two Theories of Physics"; the three measures of the context, of which the arena

holds space and time, are named by *The Last Turtle*, "The Three Boundaries of Knowing", section VII, "How the Constants Join the Measures" ("The measures of context are space, time and possibility").

A claim about the world is settled by measurement, and a claim of logic by proof; agreement among people, however wide, is a fact about the people, and it validates nothing by itself. Carried by *Physics Is Not Math*, chapter 19, "A Right Method of Evaluation", section IV, "Three Ways of Validation" ("Agreement among people validates nothing by itself").

The step against bias is to write a prediction down and seal it before the weighing, with the rule that will decide it stated in advance; this account has taken that step in the sealed record, forty-two predictions sealed before the measurements that will decide them, which Appendix A gathers. Carried by *Side by Side*, Volume One, "Twenty-Four Models, One Record", Appendix B, "The Sealed Record", and "Terms of the Collection", entries "Sealed record" and "Rule of decision"; the rule's own words are printed in Appendix A.

Some claims reach past every instrument, and each is decided by the argument that fits its kind; the Incommensuration Theorem is decided in that way, by its proof; every measurement already uses the structure the theorem describes, so no result of any measurement can count for or against it. Carried by *Side by Side*, Volume One, Appendix I, section V, "Where No Measurement Decides" ("Every measurement already presupposes the structure such a claim concerns"; "each is decided by the argument that fits it"); and by *Physics Is Not Math*, chapter 20, "Two Answers to a Proof", section VII, "Summary" ("each kind of claim is judged by the method that fits it").

Every finding of physics is an act of comparison, so the structure of comparison is the ground on which every finding of physics stands, and the Incommensuration Theorem states one fact of that ground exactly. Carried by *Physics Is Not Math*, chapter 1, section V, for the identification of every finding with an act of comparison, and chapter 2, section VI, "The Theorem".

A review serves its reader when the review hands over the methods of the review along with the findings of the review, "since findings without their methods leave the reader nothing to do but defer". I pass on my findings in the same way, and my method is the balance. Carried by *Physics Is Not Math*, chapter 19, section VIII, "Three Roles in a Cycle" ("And the review serves the reader: its purpose is to enable the reader's own judgment, and so it hands over its methods along with its findings, since findings without their methods leave the reader nothing to do but defer"); that book says it of a review, and the step to passing on any finding with its method is this book's own, shown in Chapter Fourteen.

Every measurement is an act of comparison made from inside the world, and the structure of comparison is the ground of physics: every measurement anyone has ever made was made by setting one thing beside another, and finding how they stand. Carried by *Physics Is Not Math*, chapter 1, "What It Is to Compare", sections I and V.

Her Word and This Book's Word

Each row of this glossary sets two words side by side. The left column holds a word that the physicist Sabine Hossenfelder uses, while the right column holds this book's word for the subject that her word names. Her words come from her books *Lost in Math* (2018) and *Existential Physics* (2022), or from a paper of hers that the row names. Each word carries a short explanation of the word, called a 'gloss'. Each gloss is the explanation of the word in the word's chapter, in the chapter's own phrasing. A line in italics below each gloss states the chapter where you first meet the word. When the word is explained or restated in a later chapter, the line names the later chapter too. Where a word of hers has no counterpart in this account (the account of physics that I set beside hers in this book), the right column states what I hold instead. Where she has no word for one of this book's terms, the left column reads "(no word of hers)". The rows follow the alphabetical order of her words. The last rows hold the terms of this book for which she has no word: first 'comparison'; 'content' and 'context', which share one row; 'epoch'; and 'the Incommensuration Theorem'; then the other terms of this book, in alphabetical order.

Her word	This book's word
anthropic principle: in her words, "a constraint on our theories that enforces agreement with observation". *Chapter Five*	In this account, the anthropic principle is a true limit on what we can find, but the anthropic principle explains no constant. Each number of our one world has a reason: a law that fixes the number, or a proof that no law fixes the number. *Chapter Five*
	a claim stated with its cases: a claim gathered from the cases seen so far is stated together with the cases the claim covers.

Her word	This book's word
"as far as we currently know"; **"compatible with all we currently know"**: the preamble that she asks everything she says to carry, "meaning that further scientific progress might lead to revision". *First met in the Preface; glossed in Chapter Fourteen*	*Chapter Fourteen*
ascientific: the word she takes from the physicist Tim Palmer for a belief about which science says nothing either way. An ascientific belief is a belief that science can neither confirm nor rule out, and that is not needed to describe anything we observe. *First met in the Preface; glossed in Chapter Five*	**decided by the argument that fits its kind**: when no measurement can reach a claim, so that no measured result counts for or against the claim, the claim is still decided, by the argument that fits the claim's kind. **a claim of logical form**: a claim that a conclusion follows from certain starting points, as in a proof. A claim of logical form is decided by following the steps from the starting points to the conclusion. *Chapter Fourteen*
beauty, **elegance**, **simplicity**: in her words, beauty is "a combination of all of the above: simplicity, naturalness, and a dose of the unexpected". *First met in the Preface; glossed in Chapter One*	**a property of the description**: when a mathematical description has a property, such as symmetry (being the same under every change of place or setting), economy, or the absence of large unexplained ratios, the property is a property of the description. A property of a description is no evidence about the world the description describes. *First met and stated in Chapter One; the second sentence in the words of Chapter Five*
Big Bang, in her sense: a first moment in time, at which the universe began.	

Her word	This book's word
First met in Chapter One; her sense glossed in Chapter Eleven	**the turn**: the boundary between two epochs (two whole spans of the universe's history), where the black-hole interiors of the ending epoch all end together, as one end. The next epoch begins at the turn. Every comparison is made on one side of the turn or the other, and no comparison is made across the turn. "I identify the Big Bang with the turn. The Big Bang is the turn as our history shows the turn, when we trace our history back from inside our epoch". *The turn first met and glossed in Chapter Ten; the identification of the Big Bang with the turn stated in Chapter Eleven, which describes the turn in full*
blind analysis, Chapter Fourteen's name for the practice she describes: the experimentalists fix the method of analysis before anyone sees which way the data lean. *Chapter Fourteen*	**the sealed record**: a record of predictions that also states the rule of decision in advance, sealed at a date before anyone makes the measurements that will decide the predictions. **the rule of decision**: the rule that says, before any result comes in, what will count as a result. *The sealed record first met in Chapter Three; the sealed record and the rule of decision both explained in Chapter Fourteen*

Her word	This book's word
block universe: the whole of space and all of time taken as one four-dimensional block, with every event in the block, past and future alike. *Chapter Ten*	**geometric time**: time laid out with space as one pattern. Geometric time means two things together: the time measured along each path through space and time, and the order of before and after that the pattern of space and time carries. **event time**: the order in which findings are made, one after another, each finding leaving its record. *The Basis of Physics* is this account's book of essays on what physics rests on. In the words of *The Basis of Physics*, "The block universe takes geometric time for the whole, and drops event time". *Chapter Ten*
collapse; **measurement update**: when one result is found in a measurement, physicists update the wave function (the piece of mathematics that describes a system) so that the result found has odds of one in one. Physicists call the update of the wave function the measurement update, or collapse. *Chapter Six*	**the update of the shared record**: when a measurement is made, the shared record of what has been found changes, and the change of the shared record is the whole of the measurement update. *Chapter Six*
dark energy: the name for whatever drives the speeding up of the expansion of the universe. *Chapter Eleven*	**the cosmological constant, one constant**: in this account, the dark energy is exactly the cosmological constant. The cosmological constant is an energy of empty space itself. The cosmological constant is one constant: one number at every place and every time of our epoch. No dark energy field lies behind the cosmological constant.

Her word	This book's word
	First met in Chapter Four; stated in these words in Chapter Eleven, section "Will It All End in the Dark?"
dark matter: matter that has been seen to do only one thing, which is to pull by its weight. *First met in the Preface; glossed in Chapters Three and Twelve*	**a ringing of the setting itself**; **a vibration of context**: "I identify the dark matter with a ringing of the setting itself: a lasting vibration of the six small dimensions, taken as the setting of what could be found". In the balance's picture, the dark matter shows in the result of a weighing only as extra pull. The dark matter is never a thing set in a pan. The dark matter is not matter of any kind on the list of particles. *First stated in Chapter Three; set out in Chapter Twelve*
determinism: in her words, "The idea that all events in the future can in principle be calculated from any earlier time is called determinism". *First met in Chapter Six; her gloss quoted in Chapter Eight*	**determinism**, the same word: the thesis that when the same law, everywhere, carries forward a complete description of the world at one moment, the description fixes the world at every other moment. *Chapter Seven*
elegance, as physicists use the word: simplicity joined with surprise, the moment when everything falls into place. *Chapter One*	**convergence**: independent routes, resting on different starting points, arriving at one value or one conclusion. *Chapter One*
entropy, in her definition: the count of detailed arrangements of the parts that all give the same overall look. *First met in Chapter Five; her definition given in Chapter Ten*	**a count relative to a context**: in the words of *The Compactification*, this account's book on the six small curled dimensions of space, "An entropy is a count: the number of

Her word	This book's word
	states of a system that the comparisons available from some context cannot tell apart". *Chapter Ten*
fermions: the particles of matter, such as the electron and the quarks inside the proton. No two fermions will share one state. **bosons**: the carriers of force, such as the particle of light. Any number of bosons can share one state. *Chapter Three*	**content**; **context**, at the scale of single particles: Hossenfelder's fermions, the extreme individuals, are content. Her bosons, which share their states freely, are context. *Chapter Three*
fine-tuned: in her words, "a number that seems to require explanation". *First met in Chapter One; her words quoted in Chapter Four*	**a value that lands**: a number that agrees with measurement before anyone knows why. *Chapter Four*
free will: in the reasoning she takes from the philosopher Friedrich Nietzsche, a will that is free should not be caused by anything else. *First met in the Preface; glossed in Chapter Eight*	**choice**: the part of an event that no pattern fixes can be described from inside or from outside. Described from inside, the part that no pattern fixes is what I call choice, in this account, while described from outside, the same part is hard randomness. *First met in Chapter Seven; explained in Chapter Eight*
grand unification: the hope that the three forces of the standard model are pieces of one larger symmetry, so that the three forces would act as one force at some very high energy. *Chapter Three*	**three forces that were never one**: the three forces of the standard model belong to three distinct positions of comparison. So the three forces were never one force, at any energy. No single larger force splits into the three forces. **positions of comparison**: the three positions that every comparison has, namely the thing compared,

Her word	This book's word
	the second thing against which the first thing is compared, and the act of comparing, which joins the two things. **label**: the property of a particle that a force acts on. The label of a force sets which position of comparison the force has. *Chapter Three*
internally consistent: not giving rise to conclusions that contradict each other. **consistent with observation**: not in contradiction with the data. *Chapter Two*	**merit**: when the claims of an argument follow from the argument's premises, the argument has merit. **true**: when an argument has merit and the argument's premises are also true of the world, the argument is true, in the sense used here for arguments. *Chapter Two*
many-worlds interpretation: the interpretation of quantum theory in which every possible outcome of a measurement happens, each outcome in a world of its own. *Chapter Five*	**structure in the mathematics, never found**: the Incommensuration Theorem excludes the many-worlds account, taken as an account of a whole world. The other branches exist as structure in the mathematics of the many-worlds account. No one ever finds the other branches by comparison, so the other branches are not real. *Chapter Five; restated in Chapter Six*
measurement, in her sense: in her words, "any interaction that is sufficiently strong or frequent to destroy the quantum behavior of a system". *Chapter Six*	**a finding**: any comparison that lays down a record. In a finding, an interaction takes place, and afterward some part of the world carries a record of the outcome. *Chapter Six*

Her word	This book's word
multiverse: a whole collection of universes, each universe started in its own way, each with its own settings. **landscape**: the vast range of possible worlds that string theory allows, each world with its own particles and constants. *Chapter Five*	**one world, one settled state**: this account has one world, with one settled state of empty space. **vacuum**: empty space settles into the state with the least energy that empty space can have nearby. Physicists call the settled state of empty space a vacuum. *Chapter Five*
naturalness: the expectation that the pure numbers of a theory (numbers with no units, such as the ratio of one mass to another) be neither very large, nor very small, nor very close to one another. *Preface*	**a stated standing**: in this account, every number carries a statement of where the number comes from, and each statement names one of four sources: the structure of comparison, the structure of comparison with one stated step, measurement, or this account and measurement both. *Chapter Four*
the Now: her name for the present moment. *Chapter Ten*	**the present, real**: in this account, I conclude that the present is real. I also conclude that the present is where all of physics is done. The Now is given in the act of comparison. *Chapter Ten*
past-hypothesis: the hypothesis that the universe began in a state of low entropy, a state that was very unlikely. *Chapter Ten*	**the count that a new context starts with**: every count of an epoch's entropy is made against the epoch's outside world, which is the context of the count. The outside world of an epoch is the space and time outside the epoch's black holes, and everything found in that space and time.

Her word	This book's word
	By the turn, the outside world of the ending epoch has emptied, so at the turn nothing of the old outside world is there to count against. So, in the words of *The Compactification*, the low gravitational entropy of the beginning "is the count that a new context starts with". *Chapter Ten*
physics isn't math: her claim that physics has "the purpose of describing observations of natural phenomena", and her further claim that a claim that the world is math is not science. *First met in the Preface; glossed in Chapter Two*	**the order of depth**: the four fields arranged by what each field presupposes, deepest first: metaphysics, physics, computation, mathematics. *Chapter Two*
Platonism: the view that mathematical objects have a being of their own, apart from anyone who thinks of the objects, and that the world is one of the mathematical objects. *Chapter Two*	**exist**: to stand as structure, which means to be timeless, the same in every instance, and able to be held in view as a whole. **real**: given in an actual act of comparison. A thing that is real is given here, now, with the future still open. *Chapter Two*
quantum gravity: the effort to bring gravity into quantum theory. *Chapter Thirteen*	**two theories, joined and never merged**: in this account, quantum theory is the theory of what is found, while general relativity is the theory of where a thing is found. The two theories are joined side by side. The two theories are never merged into one description. *Chapter Thirteen*

Her word	This book's word
a random element from quantum mechanics: in her words, "occasional quantum events that we cannot influence". *Chapter Eight*	**hard randomness**: when no prior specification fixes an outcome, however complete the specification is, I call the outcome hard randomness, in this account. **soft randomness**: when randomness is a limit of what we know, which better knowledge could shrink, I call the randomness soft randomness, in this account. *Hard randomness first met in Chapter Seven; hard randomness and soft randomness both explained in Chapter Eight*
reductionism: the view, in her words, that "the behavior of an object can be deduced from" the properties, behavior and interactions of its constituents. *Chapter Nine*	**composition, without a total description**: in this account, I hold, as firmly as she does, that a thing is made of its parts and of nothing else. *The Last Turtle* is the book among this account's books that treats reductionism most fully. In this account, I exclude reductionism in the sense of *The Last Turtle*: the claim that a description of the parts contains everything the thing is. *Chapter Nine*
simulation hypothesis: the proposal that our world is a program running on a computer in some other world. *Chapter Nine*	**a region of the one world**: a simulated world with people in it is a walled-off region of the one world, and no second world. *Chapter Nine*
space-time: her word for space and time taken together. In the words of Chapter Thirteen, general relativity "says that	**the arena**: space and time together. The context of every measurement has three measures: space, time and possibility (the range of states

Her word	This book's word
gravity is the shape of space and time, curved by the matter and energy in space and time". *Chapter Thirteen*	in which a thing could be found). The arena holds two of the three measures, space and time. *First met and glossed in Chapter Three; explained in Chapter Thirteen*
statistical independence: the assumption that the settings of the measuring devices are independent of the hidden state of the things measured. She and Tim Palmer give the assumption the name statistical independence in their paper "Rethinking Superdeterminism" (2020). *Chapter Seven*	**statistical independence**, her word, kept unchanged: the assumption that the settings of an experiment are independent of the hidden state of what the experiment measures. *First met in Chapter Seven; restated in the closing chapter*
strong CP problem: the strong force binds quarks into protons and neutrons. The strong force could treat a process differently from the mirror image of the process with matter swapped for antimatter. Physicists write the amount of the difference as an angle. C swaps a particle for its opposite charge, P swaps a particle for its mirror image, and CP does both. *Chapter Four*	**the strong force's own angle, zero by structure**: in this account, the strong force's own angle is zero. The reason the angle is zero is the structure of comparison, so the structure of comparison needs no axion, the new light particle that physicists proposed in 1977 and 1978 to drive the angle to zero. The angle that experiments measure is the strong force's own angle plus the quarks' phase, an angle that the masses of the quarks carry with them. The quarks' phase lands on zero: in this account, I derive the value zero for the phase, and measurement finds zero, so the landing on zero is a measured agreement. *Chapter Four*
superdeterminism: determinism with one clause added. The clause says that the settings the experimenters choose are fixed along with everything else, together with the hidden state of the particles the	**superdeterminism, excluded by the structure of comparison**: superdeterminism is excluded for the same reason that determinism is excluded. Determinism needs per-

Her word	This book's word
experimenters measure. Superdeterminism is her word in her papers, among them "Rethinking Superdeterminism" (2020), written with Tim Palmer. *Chapter Seven*	fect symmetry and perfect continuity at once. The Incommensuration Theorem forbids perfect symmetry and perfect continuity together. The reason for both exclusions is about comparison, and not about quantum mechanics. *Chapter Seven; restated in the closing chapter*
supersymmetry; **superpartners**: in her words, "Supersymmetry postulates that the laws of nature remain the same when bosons are exchanged with fermions". *Chapter Three*	**the closed list of kinds**: the kinds of particle of the standard model, with a right-handed neutrino in each generation, and no other kinds. The particles of matter come in three generations, each generation a heavier copy of the one before. *Chapter Three*
symmetry, as physicists use the word: a set of changes under which the laws stay the same. *Chapter Three*	**symmetry**, the same word: being the same under every change of place or setting, so that what is found stays the same when the setting changes. Chapter Three says that the physicists' word keeps the sense of being the same under every change of place or setting. *First met in Chapter One; explained in Chapter Two*
time-reversible: able to run backward as well as forward. *Chapter Six*	**lawful reversal**: if the laws allow a process, the laws also allow the reverse of the process. **faithful reversal**: the reversed process passes back through exactly the states that the original process passed through. *Chapter Ten*

Her word	This book's word
uploading: scan the brain, run the scan as a program, and the running program is to be you. *Chapter Nine*	**a category error**: a request that treats a thing as being of a kind that the thing is not, like asking what color the number seven is, because a number is not the kind of thing that has a color. In this account, uploading is a category error, and not a hard problem of engineering. *Chapter Nine*
WIMP: short for "weakly interacting massive particle", a new particle with mass that touches ordinary matter only very rarely. *Chapter Twelve*	**gyration**: a ringing of the six small curled dimensions of space, and not an extra thing inside the six small dimensions. A phonon is the smallest step of energy in one way of ringing of a crystal, and a gyration is to the six small dimensions what a phonon is to the crystal. *Chapter Twelve*
(no word of hers)	**comparison**: setting one thing beside another and finding how the two stand. *First met in the Preface; explained in Chapter One*
(no word of hers)	**content**: what the verdict of a comparison is about. **context**: the respect in which the two things compared are two. *Chapter Three*

Her word	This book's word
(no word of hers)	**epoch**: one whole span of the universe's history, from one turn to the next. Our epoch began at the Big Bang. *First met and glossed in Chapter Four; glossed in these words in Chapter Ten; described in full in Chapter Eleven*
(no word of hers)	**the Incommensuration Theorem**: "Symmetry and continuity cannot both be applied, simultaneously and fundamentally, to any event or comparison; and neither can asymmetry and discontinuity". *Continuity* means having no gaps, so that a small change of setting gives a small change in what is found. Asymmetry and discontinuity are the opposites of symmetry and continuity. The Incommensuration Theorem is a structural fact about the nature of knowing. *Chapter Two*
(no word of hers)	**causation**, **change** and **choice**: the three things every real event contains, bound together. The pattern that repeats is causation; the happening itself, the actual passage from one state to the next, is change; what is new in an event, not contained in what came before, is choice. The three are distinct, but they never come apart, and none of the three can do the work of another. *Chapter Seven*
(no word of hers)	

Her word	This book's word
	the different line: a line of research that starts the other way round from string theory and follows three rules: gravity stays the arena, the space and time in which everything happens; no single description is asked to carry both characters; and space and time are never treated as made of quanta. *Chapter Five*
(no word of hers)	**the far regions**: the regions beyond our horizons. Our event horizon is the boundary past which no event, now or at any later time, can ever send us a signal. *Chapter Five*
(no word of hers)	**identification**: a stated step from the structure of comparison to a measured quantity. *Chapter One*
(no word of hers)	**measured agreement**: a value that I reach and that measurement also finds, while the reason for the agreement is still a question; a measured agreement carries the question of why the value agrees with measurement. *Chapter Four*
(no word of hers)	**the partition**: the one line that divides content from context; the Incommensuration Theorem asserts the partition. *Chapter Three*
(no word of hers)	

Her word	This book's word
	the setting: the whole context of a weighing: the two places, the floor, the room and the moment of the weighing. **The setting of possibility**: the range of states in which a thing could be found. *First met in the Preface; the setting of possibility in Chapter Three; set out in Chapter Twelve*
(no word of hers)	**the side from which** and **the side about which**: the second way of dividing a weighing. The side from which the weighing is made is the instrument itself, together with whoever reads the instrument, and the side about which the weighing is made is the things in the pans. *Preface*
(no word of hers)	**six small dimensions**: six dimensions besides the three dimensions of space and the one dimension of time, curled up far too small to see, the same in size and shape at every place; their shape fixes what kinds of particle there can be. *Chapter Four*
(no word of hers)	**the three roles**: the three positions of every comparison taken more widely: 'the act', 'what is laid out' and 'the stance', the place from which another thing is read, as a length is read from a rod. *Chapter Fourteen*
(no word of hers)	**tiles**, **channels** and **the trimmed total**: a tile is one independent way in which what lies inside an edge

Her word	This book's word
	can hold energy or vary, one tile for every four tiny squares a Planck length on a side; the trimmed total is what remains of the total vacuum energy after the charge, a little under nine tenths of the Planck density, and is what the tiles share; empty space reaches a measurement through three channels, one for each kind of thing that a measurement registers. *Chapter Four*
(no word of hers)	**the visitor's mistake**: taking the third-person view of mathematics for the whole of what is, and so taking a property of the description for a property of the world. *Chapter One*

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