A SCIENTIST'S GUIDE TO
LIFE'S BIGGEST QUESTIONS

EXISTENTIAL PHYSICS

SABINE
HOSSENFELDER

VIKING
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PREFACE

Can I ask you something?" a young man inquired after learning that I am a physicist. "About quantum mechanics," he added, shyly. I was all ready to debate the measurement postulate and the pitfalls of multipartite entanglement, but I was not prepared for the question that followed: "A shaman told me that my grandmother is still alive. Because of quantum mechanics. She is just not alive here and now. Is this right?"

As you can tell, I am still thinking about this. The brief answer is, it's not totally wrong. The long answer will follow in chapter 1, but before I get to the quantum mechanics of deceased grandmothers, I want to tell you why I'm writing this book.

During more than a decade in public outreach, I noticed that physicists are really good at answering questions, but really bad at explaining why anyone should care about their answers. In some research areas, a study's purpose reveals itself, eventually, in a marketable product. But in the foundations of physics—where I do most of my research—the primary product is knowledge. And all too often, my colleagues and I present this knowledge in ways so abstract that no one understands why we looked for it in the first place.

Not that this is specific to physics. The disconnect between experts and non-experts is so widespread that the sociologist Steve Fuller claims that academics use incomprehensible terminology to keep insights sparse and thereby more valuable. As the American journalist and Pulitzer Prize winner Nicholas Kristof complained, academics encode "insights into turgid prose" and "as a double protection against public consumption, this gobbledygook is then sometimes hidden in obscure journals."

Case in point: People don't care much whether quantum mechanics is predictable; they want to know whether their own behavior is predictable. They don't care much whether black holes destroy information; they want to know what will happen to the collected information of human civilization. They don't care much whether galactic filaments resemble neuronal networks; they want to know if the universe can think. People are people. Who'd have thought?

Of course, I want to know these things too. But somewhere along my path through academia I learned to avoid asking such questions, not to mention answering them. After all, I'm just a physicist. I'm not competent to speak about consciousness and human behavior and such.

Nevertheless, the young man's question drove home to me that physicists *do* know some things, if not about consciousness itself, then about the physical laws that everything in the universe—including you and I and your grandmother—must respect. Not all ideas about life and death and the origin of human existence are compatible with the foundations of physics. That's knowledge we should not hide in obscure journals using incomprehensible prose.

It's not just that this knowledge is worth sharing; keeping it to ourselves has consequences. If physicists don't step forward and explain what physics says about the human condition, others will jump at the opportunity and abuse our cryptic terminology for the promotion of pseudoscience. It's not a coincidence that quantum entanglement and vacuum energy are go-to explanations of alternative healers, spiritual media, and snake oil sellers. Unless you have a PhD in physics, it's hard to tell our gobbledygook from any other.

However, my aim here is not merely to expose pseudoscience for what it is. I also want to convey that some spiritual ideas are perfectly compatible with modern physics, and others are, indeed, supported by it. And why not? That physics has something to say about our connection to the universe is not so surprising. Science and religion have the same roots, and still today they tackle some of the same questions: Where do we come from? Where do we go to? How much can we know?

When it comes to these questions, physicists have learned a lot in the past century. Their progress makes clear that the limits of science are not fixed; they move as we learn more about the world. Correspondingly, some belief-based explanations that once aided sense-making and gave comfort we now know to be just wrong. The idea, for example, that certain objects are alive because they are endowed with a special substance (Henri Bergson's "élan vital") was entirely compatible with scientific fact two hundred years ago. But it no longer is.

In the foundations of physics today, we deal with the laws of nature that operate on the most fundamental level. Here, too, the knowledge we gained in the past hundred years is now replacing old, belief-based explanations. One of these old explanations is the idea that consciousness requires something more than the interaction of many particles, some kind of magic fairy dust, basically, that endows certain objects with special properties. Like the élan vital, this is an outdated and useless idea that explains nothing. I will get to this in chapter 4, and in chapter 6 I'll discuss the consequences this has for the existence of free will. Another idea ready for retirement is the belief that our universe is especially suited to the presence of life, the focus of chapter 7.

However, demarcating the current limits of science doesn't only destroy illusions; it also helps us recognize which beliefs are still compatible with scientific fact. Such beliefs should maybe not be called *un*scientific but rather *a*scientific, as Tim Palmer (whom we'll meet later) aptly remarked: science says nothing about them. One such belief is the origin of our universe. Not only can we not currently explain it, but also it is questionable whether we will ever be able to explain it. It may be one of the ways that science is fundamentally limited. At least that's what I currently believe. The idea that the universe itself is conscious, I have found to my own surprise, is difficult to rule out entirely (chapter 8). And the jury is still out on whether or not human behavior is predictable (chapter 9).

In brief, this is a book about the big questions that modern physics raises, from the question whether the present moment differs from the past, to the idea that each elementary particle may contain a universe, to the worry that the laws of nature determine our decisions. I cannot, of course, offer final answers. But I want to tell you how much scientists currently know, and also where science crosses over into mere speculation.

I will mostly stick with established theories of nature that are backed up by evidence. 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. In some cases, the answer to a question depends on properties of natural laws that we do not yet fully understand, like quantum measurements or the nature of space-time singularities. If so, I will point out how future research could help answer the question. Because I don't want you to hear just my own opinion, I have added a few interviews. And at the end of the book, you'll find a brief glossary with definitions of the most important technical terms. Terms in the glossary are marked bold when they first appear in the text hereafter.

Existential Physics is for those who have not forgotten to ask the big questions and are not afraid of the answers.

A WARNING

I want you to know what you are getting yourself into, so let me put my cards on the table up front. I am both agnostic and a heathen. I have never been part of an organized religion and never felt the desire to join one. Still, I am not opposed to religious belief. Science has limits, and yet humanity has always sought meaning beyond those limits. Some do it by studying holy scripture, some meditate, some dig philosophy, some smoke funny things. That's all fine with me, really. Provided that—and here's the crux—your search for meaning respects scientific fact.

If your belief conflicts with empirically confirmed knowledge, then you are not seeking meaning; you are delusional. Maybe you'd rather hold on to your delusions. Trust me; I am sympathetic to that—but then this book is not for you. In the coming chapters, we will talk about free will, afterlife, and the ultimate search for meaning. It won't always be easy. I myself have struggled with some of the consequences of what I know to be well-confirmed natural laws, and I suspect some of you will find it equally difficult.

You may think I exaggerate to make dry physics sound more exciting. Look, we all know I want this book to sell, so why pretend otherwise? But the main reason I issue this warning is that I am sincerely worried that this book may negatively affect some readers' mental health. Occasionally someone contacts me, writing that they came across one of my essays, and now they don't know how to go on with their life. They seem genuinely disturbed. What sense does life make without free will? What's the point of human existence if it's just a random fluke? How can you not freak out knowing that the universe might blink out any moment?

Indeed, some scientific facts are hard to stomach and, worse, there's no psychologist who'll be able to help. I know this because I've tried. But hang on. If you think it through, science gives more than it takes. In the end, I hope you will find comfort in knowing that you do not need to silence rational thought to make space for hope, belief, and faith.

EXISTENTIAL PHYSICS

Chapter 1

DOES THE PAST STILL EXIST?

Now and Never

Time is money. It's also running out. Unless, possibly, it's on your side. Time flies. Time is up. We talk about time . . . all the time. And yet time has remained one of the most difficult-to-grasp properties of nature.

It didn't help that Albert Einstein made it personal. Before Einstein, everybody's time passed at the same rate. Post-Einstein, we know that the passage of time depends on how much we move around. And while the numerical value we assign to each moment—say 2:14 p.m.—is a matter of convention and measurement accuracy, in pre-Einstein days, we believed that *your* now was the same as *my* now; it was a universal now, a cosmic ticking of an invisible clock that marked the present moment as special. Since Einstein, *now* is merely a convenient word that we use to describe our experience. The present moment is no longer of fundamental significance because, according to Einstein, the past and the future are as real as the present.

This doesn't match with my experience and probably doesn't match with yours either. But human experience is not a good guide to the fundamental laws of nature. Our perception of time is shaped by circadian rhythms and our brain's ability to store and access memories. This ability is arguably good for many things, but to disentangle the physics of time from our perception of it, it is better to look at simple systems, like swinging pendulums, orbiting planets, or light that reaches us from distant stars. It is from observations on such simple systems that we can reliably infer the physical nature of time without getting bogged down by the often inaccurate interpretation that our senses add to the physics.

A hundred years' worth of observation have confirmed that time has the properties Einstein conjectured at the beginning of the twentieth century. According to Einstein, time is a dimension, and it joins with the three dimensions of space to one common entity: a four-dimensional space-time. The idea of combining space and time to space-time goes back to the mathematician Hermann Minkowski, but Einstein was the one to fully grasp the physical consequences, which he summarized in his theory of special relativity.

The word *relativity* in *special relativity* means there is no absolute rest; you can merely be at rest relative to something. For example, you are now probably at rest relative to this book; it's moving neither away from nor toward you. But if you throw it into a corner, there are two ways of describing the situation: the book moves at some velocity relative to you and the rest of planet Earth, or you and the rest of the planet move relative to the book. According to Einstein, both are equivalent ways to describe the physics and should give the same prediction—that's what the word *relativity* stands for. The *special* just says that this theory doesn't include gravity. Gravity was included only later, in Einstein's theory of **general relativity**.

The idea that we should be able to describe physical phenomena the same way regardless of how we move in Einstein's four-dimensional space-time sounds rather innocuous, but it has a host of counterintuitive consequences that have entirely changed our conception of time.

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In our usual three-dimensional space, we can assign coordinates to any location using three numbers. We could, for example, use the distance to your front door in the directions east-west, north-south, and up-down. If time is a dimension, we just add a fourth coordinate, let's say the time that has passed at your front door since 7:00 a.m. We then call the complete coordinates an *event*. For example, the space-time event at 3 meters east, 12 meters north, 3 meters up, and 10 hours might be your balcony at 5:00 p.m.

This choice of coordinates is arbitrary. There are many different ways to put coordinate labels on space-time, and Einstein said these labels shouldn't matter. The time that actually passes for an object can't depend on what coordinates we chose. And he showed that this invariant, internal time—*proper time,* as physicists call it—is the length of a curve in space-time.

Suppose you go on a road trip from Los Angeles to Toronto. What matters to you is not the straight-line coordinate distance between these points, about 2,200 miles, but the distance on highways and streets, which is more like 2,500 miles. It's similar in space-time. What matters is the length of the trip, not the coordinate distance. But there's an important difference: in space-time, the longer the curve between two events, the *less* time passes on it.

How do you make a curve between two space-time events longer? By changing your velocity. The more you accelerate, the slower your proper time will pass. This effect is called *time dilation*. And, yes, in principle, this means if you run in a circle, you'll age more slowly. But it's a tiny effect, and I can't recommend it as an antiaging strategy. By the way, this is also why time passes more slowly near a black hole than far away from one. That's because, according to Einstein's principle of equivalence, a strong gravitational field has the same effect as a fast acceleration.

What does this mean? Imagine I have two identical clocks; I hand you one, and then you go your way and I go mine. In pre-Einstein days, we'd have thought that whenever we met again, these clocks would show exactly the same time—this is what it means for time to be a universal parameter. But post-Einstein, we know this isn't right. How much time passes on your clock depends on how much and how fast you move.

How do we know this is correct? Well, we can measure it. It would lead us too far off topic to go into detail about which observations have confirmed Einstein's theories, but I will leave you recommendations for further reading in the endnotes. To move on, let me just sum it up by saying that the hypothesis that the passage of time depends on how you move is supported by a large and solid body of evidence.

I have been speaking of clocks for illustration, but the fact that acceleration slows time down has nothing in particular to do with the devices we call clocks; it happens for any object. Whether it's combustion cycles, nuclear decay, sand running through an hourglass, or heartbeats, each process has its own individual passage of time. But the differences between individual times are normally minuscule, which is why we don't notice them in everyday life. They become noticeable, however, when we keep track of time very precisely, which we do, for example, in satellites that are part of the global positioning system (GPS).

The GPS, which your phone's navigation system most likely uses, allows a receiver—like your phone—to calculate its position from signals of several satellites that orbit Earth. Because time is not universal, time on these satellites passes subtly differently compared with how it passes on Earth, both because of the satellites' motion relative to the surface of Earth and because of the weaker gravitational field that the satellites experience in their orbits. The software on your phone needs to take this into account to correctly infer its location, because the different passage of time on the satellites oh-so-slightly distorts the signals. It's a small effect, all right, but it's not philosophy; it's physically real.

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The fact that the passage of time isn't universal is pretty mind-bending already, but there's more. Because the speed of light is very fast but finite, it takes time for light to reach us, so, strictly speaking, we always see things as they looked a little bit earlier. Again, though, we don't normally notice this in everyday life. Light travels so fast that it doesn't matter on the short distances we see on Earth. For example, if you look up and watch the clouds, you actually see the clouds the way they looked a millionth of a second ago. That doesn't really make a big difference, does it? We see the Sun as it looked eight minutes ago, but because the Sun doesn't normally change all that much in a few minutes, light's travel time doesn't make a big difference. If you look at the North Star, you see it as it looked 434 years ago. But, yeah, you may say, so what?

It is tempting to attribute this time lag between the moment something happens and our observation of it as a limitation of perception, but it has far-reaching consequences. Once again, the issue is that the passage of time is not universal. If you ask what happened "at the same time" elsewhere—for example, just exactly what you were doing when the Sun emitted the light you see now—there is no meaningful answer to the question.

This problem is known as the *relativity of simultaneity,* and it was well illustrated by Einstein himself. To see how this comes about, it helps to make a few drawings of space-time. It's hard to draw four dimensions, so I hope you will excuse me if I use only one dimension of space and one dimension of time. An object that doesn't move relative to the chosen coordinate system is described by a vertical straight line in this diagram (figure 1). These coordinates are also referred to as the *rest frame* of the object. An object moving at constant velocity makes a straight line tilted at an angle. By convention, physicists use a 45-degree angle for the speed of light. The speed of light is the same for all observers, and because it can't be exceeded, physical objects have to move on lines tilted less than 45 degrees.

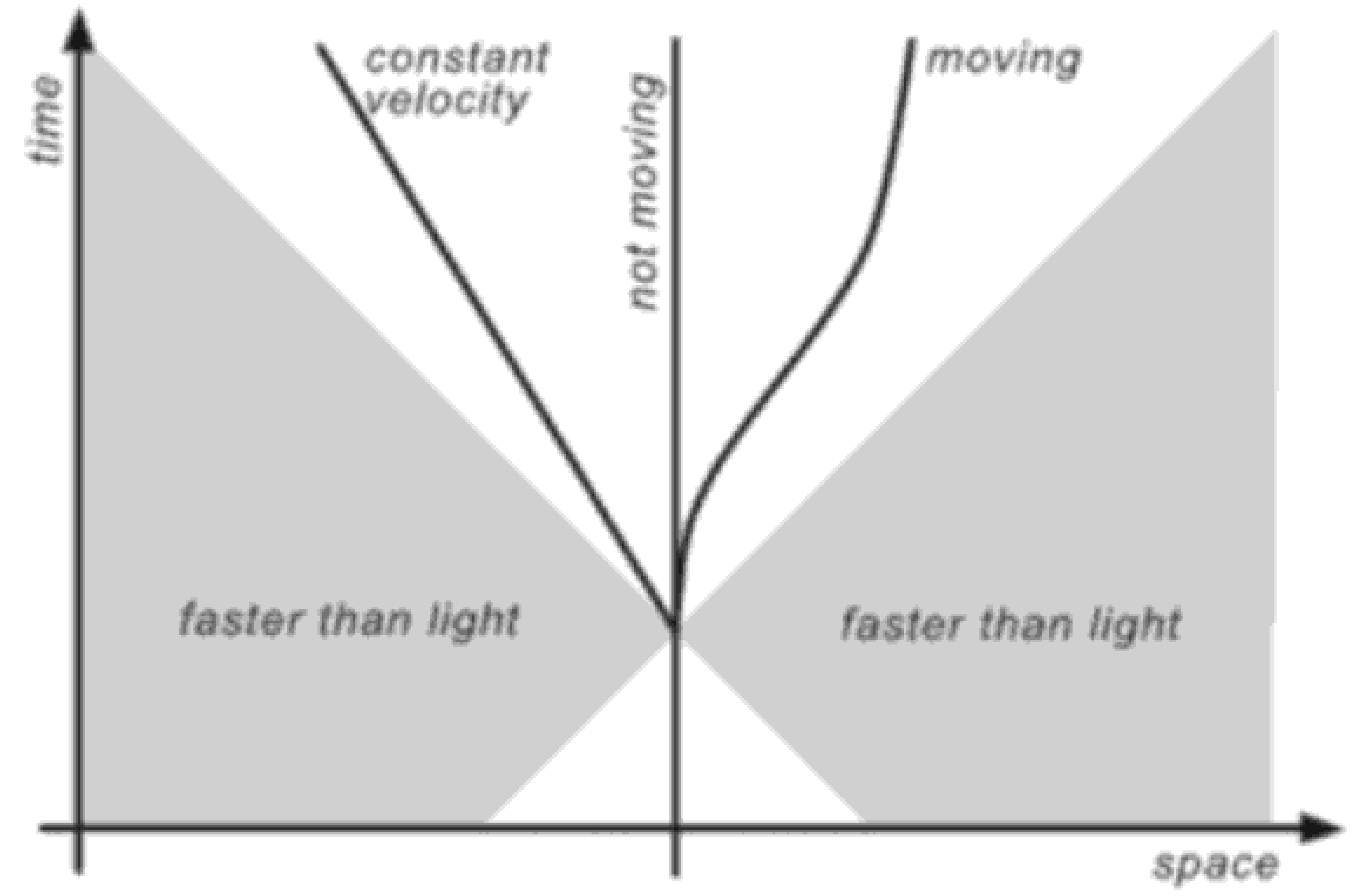

Figure 1: How space-time diagrams work.

Einstein now argued as follows. Let's say you want to construct a notion of simultaneity by using pulses of laser beams that bounce off mirrors that are at rest relative to you.[a] You send one pulse to the right and one to the left and shift your position between the mirrors until the pulses return to you at the same moment (see figure 2a). Then you know you are exactly in the middle and the laser beams hit both mirrors at the same moment.

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[a] I myself used to be perplexed about what makes lasers so special that they constantly appear in books about space-time. The answer is "Nothing really." It's just that because we know laser light moves at the speed of light (duh) and doesn't spread (much), lasers are particularly handy to illustrate the relation between space and time.

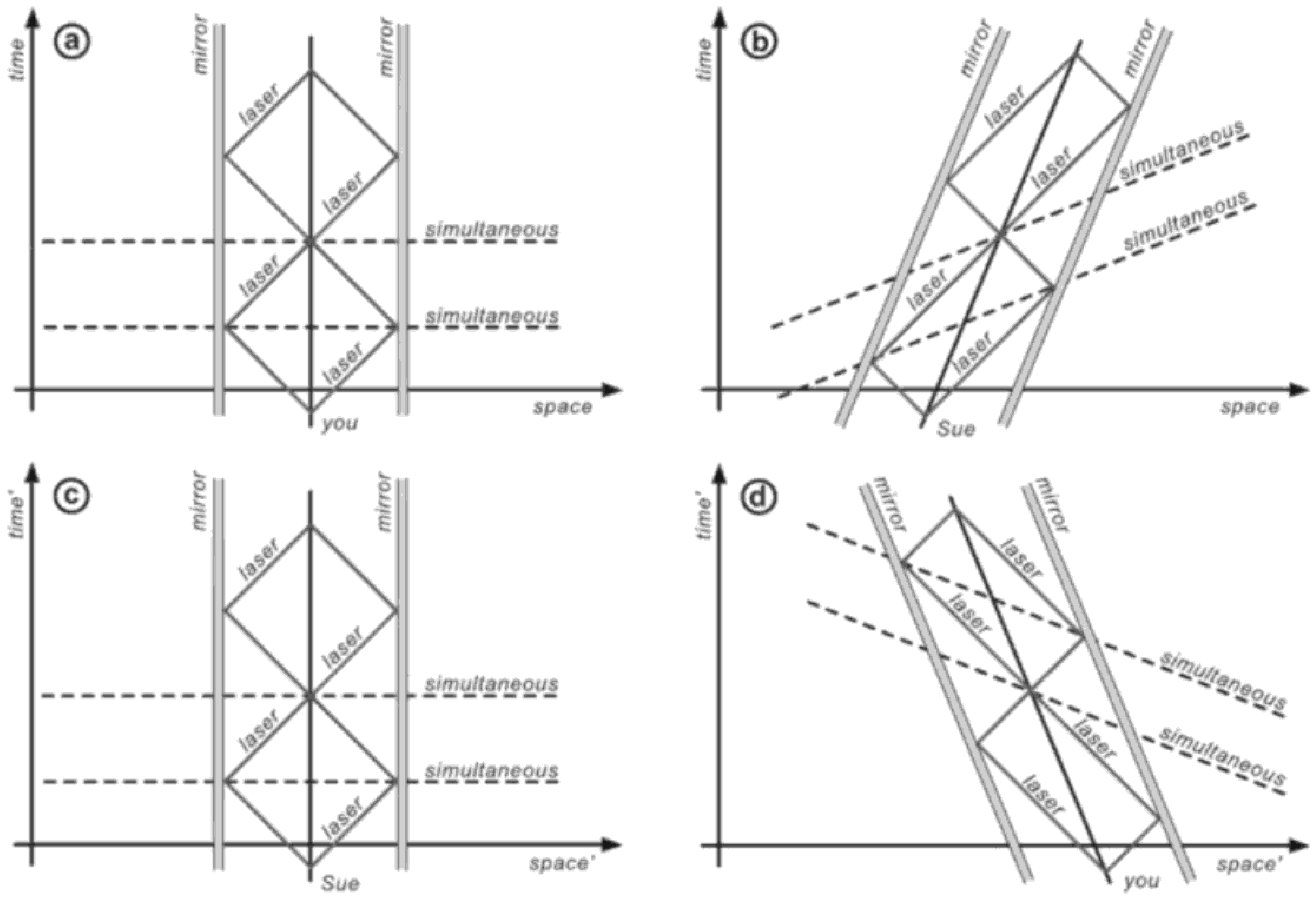

Figure 2: Space-time diagrams for construction of simultaneous events. Top left (a): You in your rest frame with coordinates labeled space and time. Top right (b): Sue in your rest frame. Bottom left (c): Sue in her rest frame with coordinates labeled space' and time'. Bottom right (d): You in Sue's rest frame.

Once you have done that, you know at exactly which moment in your own time the laser pulse will hit both mirrors, even though you can't see it because the light from those events hasn't yet reached you. You could look at your clock and say, "Now!" This way, you have constructed a notion of simultaneity that, in principle, could span the whole universe. In practice you may not have the patience to wait ten billion years for the laser pulse to return, but that's theoretical physics for you.

Now imagine that your friend Sue moves relative to you and tries to do the same thing (figure 2b). Let's say she moves from left to right. Sue, too, uses two mirrors, one to her right and one to her left, and the mirrors move along with her at the same velocity—hence, the mirrors are in rest relative to Sue, like your mirrors are relative to you. Like you, she sends laser pulses in both directions and positions herself so the pulses come back to her from both sides at the same moment. Like you, she then knows that the pulses hit the two mirrors at the same moment, and she can calculate just which moment that corresponds to on her own clock.

The trouble is, she gets a different result than you do. Two events that Sue thinks happen at the same time would not happen at the same time according to you. That's because from your perspective she is moving toward one of the mirrors and away from the other. To you it seems that the time it takes the pulse to reach the mirror on her left is shorter than the time it takes for the other pulse to catch up with the mirror on her right. It's just that Sue doesn't notice, because on the pulses' return paths from the mirrors, the opposite happens. The pulse from the mirror to Sue's right takes longer to catch up with her, while the pulse from the mirror on her left arrives faster.

You would claim that Sue is making a mistake, but according to Sue, *you* are making the mistake because, to her, you are the one who is moving. She would say that actually *your* laser pulses do not hit your mirrors at the same time (figures 2c and 2d).

Who is right? Neither of you. This example shows that in special relativity the statement that two events happened at the same time is meaningless.

It's worth stressing that this argument works only because light doesn't need a medium to travel in, and the speed of light (in vacuum) is the same for all observers. This argument does not work with sound waves, for example (or any other signal that isn't light in vacuum), because then the speed of the signal really will not be the same for all observers; it will instead depend on the medium it's traveling in. In that case, one of you would be objectively right and the other one wrong. That your notion of now might not be the same as mine is an insight we owe to Albert Einstein.

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We just established that two observers who move relative to each other don't agree on what it means for two events to happen at the same time. That isn't only odd, but it entirely erodes our intuitive notion of reality.

To see this, suppose you have two events that are not in causal contact with each other, which means you cannot send a signal from one to the other, not even at the speed of light. Diagrammatically, "not in causal contact" just means if you draw a straight line through the two events, the angle between the line and the horizontal is less than 45 degrees. But look at figure 2b again. For two events that are not in causal contact, you can always imagine an observer for whom everything on this straight line is simultaneous. You just need to choose the observer's velocity so the return points of the laser pulses are on the line. But if any two points that are not causally connected happen at the same time for someone, then every event is "now" for someone.

To illustrate the latter step, let us say the one event is your birth and the other event is a supernova explosion (see figure 3). The explosion is causally disconnected from your birth, which means the light from it hadn't reached Earth at the time you were born. You can then imagine that your friend Sue, the space traveler, sees these events at the same time, so they happened simultaneously according to her.

Suppose further that by the time you die the light from the supernova still hasn't reached Earth. Then your friend Paul could find a way to travel in the middle between you and the supernova so he would see your death and the supernova at the same time. They both

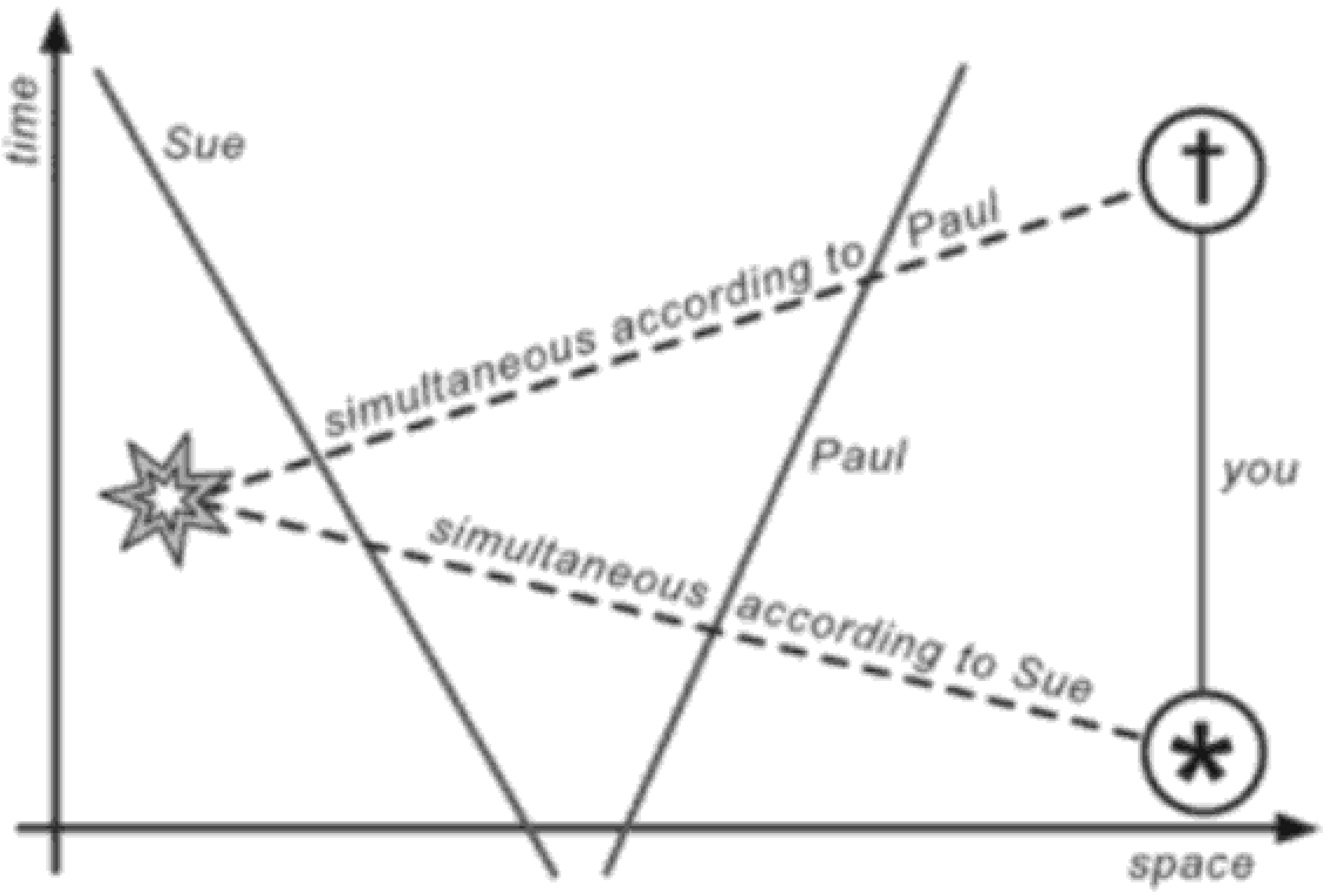

Figure 3: Any two causally disconnected events are simultaneous for some observers. If all observers' experiences are equally valid, then all events exist the same way, regardless of when or where they are.

happened simultaneously according to Paul. I swear that's it for introducing imaginary friends on spaceships!

We can then put together everything we learned. I believe most of us would say the clouds exist now, even though we can see them only as they were a fraction of a second ago. For this, we use our own, personal notion of simultaneity that depends on how we move through space-time—that is, usually much below the speed of light and on the surface of our planet. Therefore, we all pretty much mean the same thing by "now," and it doesn't normally cause confusion.

However, all notions of "now" for observers who move elsewhere and potentially close to the speed of light—like Sue and Paul—are equally valid, and in principle they span the entire universe. And because there could be some observer according to whom your birth and the supernova explosion happen simultaneously, the supernova exists at your birth according to your own notion of existence. Therefore, because there could be another observer according to whom the explosion happens together with your death, your death exists at your birth.

You can advance this argument for any two events anywhere in the universe at any time and arrive at the same conclusion: the physics of

Einstein's special relativity does not allow us to constrain existence to merely a moment that we call "now." Once you agree that *anything* exists now elsewhere, even though you see it only later, you are forced to accept that *everything* in the universe exists now.

This perplexing consequence of special relativity has been dubbed the *block universe* by physicists. In this block universe, the future, present, and past exist in the same way; it's just that we do not experience them the same way. And if all times exist similarly, then all our past selves—and grandparents—are alive the same way our present selves are. They are all there, in our four-dimensional space-time, have always been there, and will always be there. To sum it up in the words of the British comedian John Lloyd, "Time is a bit like a landscape. Just because you're not in New York doesn't mean it's not there."

More than a century has passed since Einstein put forward his theories of special and general relativity. But here we are today, still struggling to understand what it really means. It sounds crazy, but the idea that the past and future exist in the same way as the present is compatible with all we currently know.

Eternal Information

The notion that the present moment has no special relevance can be seen another way. All successful theories in the **foundations of physics** require two ingredients: (1) information about what it is that you want to describe at one moment in time, called the **initial condition**, and (2) a prescription, called an **evolution law**, for how to calculate from this **initial state** what happens at another moment of time.

I want to caution you that the word *evolution* here has nothing to do with Charles Darwin; it merely means that the law tells us how a system evolves—that is, changes in time. For example, if you know the is that the universe keeps a faithful record of the information about all you have ever said, thought, and done.

I use the word *information* here loosely to refer to all numbers you need to put into the evolution law to be able to make a prediction with it. Information, hence, is merely all the details you need in order to completely specify the initial state of the system at one particular time. In other areas of physics, information has properties beyond that, but that's the way I will use the term here.

The evolution law maps the initial state at any one time to the state at any other time, so it really just tells us how matter in the universe and space-time reconfigures. We start with particles in one arrangement, we apply the equation to it, and we get another arrangement. The information in these arrangements is completely maintained. To recover an earlier state, all you need to do is apply the evolution law and run it backward. In practice, this is unfeasible. But in principle, information—including every oh-so-minute detail about your identity—cannot be destroyed.

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Let us then talk about the two exceptions to time-reversibility: the measurement in quantum mechanics, and the evaporation of black holes.

Quantum mechanics has a time-reversible evolution law (the Schrödinger equation) for a mathematical object called the *wave function*. The wave function is usually denoted by Ψ (the Greek capital letter psi) and it describes whatever it is you want to observe (the "system" again). From the wave function, we compute probabilities for measurement outcomes, but the wave function itself is not observable.

To see how this works, consider the following example. Suppose we use quantum mechanics to calculate the probability for a particle to be measured at a particular place. To detect the particle, we use a luminous screen that emits a flash where the particle hits it. Let us say our calculation predicts there's a 50 percent chance we will find the particle on the left side of the screen and a 50 percent chance we'll find it on the right side. According to quantum mechanics, this probabilistic prediction is all there is to say. It is probabilistic not because we are missing information. There just isn't any more information. The wave function is the full description of the particle—that's what it means for the theory to be fundamental.

However, the moment we actually measure the particle, we know for sure whether it's on one side of the screen or the other. This means we have to update the wave function from 50:50 to either 100:0 or 0:100, depending on which side of the screen we saw the particle on. This update is sometimes also called the *reduction* or the *collapse* of the wave function. 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*. Without the update, quantum mechanics just does not describe what we observe.

"But what is a measurement?" you may ask. Yes, good question. This certainly bothered physicists a lot in the early days of quantum mechanics. By now this question has, luckily, largely been answered. A measurement is any interaction that is sufficiently strong or frequent to destroy the quantum behavior of a system. Only what it takes to destroy quantum behavior can be (and, for many examples, has been) calculated.

Most important, these calculations show that a measurement in quantum mechanics does not require a conscious observer. In fact, it doesn't even require a measurement apparatus. Even tiny interactions with air molecules or light can destroy quantum effects so that we have to update the wave function. Of course, in this case, speaking of a measurement is quite the abuse of language, but physically there isn't any difference between interactions with a man-made apparatus and interactions with a naturally present environment. And because in everyday life we can't ever get rid of the environment, we don't normally see quantum effects, like dead-and-alive cats, with our own eyes. Quantum behavior just gets destroyed too easily.

This is also why you shouldn't listen to anyone who claims that quantum leaps allow you to think your way out of illness or that you can improve your life by drawing energy from quantum fluctuations and so on. This isn't just off-the-mainstream science; it's incompatible with evidence. Under normal circumstances, quantum effects don't play a role beyond the size of molecules. That they're difficult to maintain and measure is the very reason physicists like doing experiments at temperatures near absolute zero, preferably in vacuum.

We understand fairly well what constitutes a measurement, but the fact that we need to update the wave function upon measurement makes quantum mechanics both indeterministic and time-irreversible. It is indeterministic because we cannot predict what we will actually measure; we can predict only the probability of measuring something. And it is not time-reversible, because once we have measured the particle, we cannot infer what the wave function was prior to measurement. Suppose you measure the particle on the left side of your screen. Then you cannot tell whether the wave function previously said the particle should be there with 50 percent probability or with a mere 1 percent probability. There are many different initial states for the wave function that will result in the same measurement outcome. This means the measurement in quantum mechanics destroys information for good.

However, if you know one thing about quantum mechanics, it's that its physical interpretation has remained highly controversial. In 1964, more than half a century after the theory was established, Richard Feynman told his students, "I can safely say that nobody understands quantum mechanics." After another half century, in 2019, the physicist Sean Carroll wrote that "even physicists don't understand quantum mechanics."

Indeed, the fact that the wave function can't itself be observed is a dilemma that has kept physicists and philosophers up at night for the better part of a century, but we don't need to go through the whole discussion here. If you want to know more about the interpretations of quantum mechanics, please have a look at my reading suggestions in the endnotes. Let me just sum it up by saying that if you don't believe the measurement update is fundamentally correct, that's currently a scientifically valid position to hold. 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 should add that in one of the currently most popular interpretations of quantum mechanics—the many-worlds interpretation—the measurement update does not happen at all, and the evolution of the universe just remains time-reversible. I am not a big fan of the many-worlds interpretation for reasons I will lay out in chapter 5, but to give you an accurate impression of the current status of research, the many-worlds interpretation is another reason that believing in time-reversibility is presently compatible with scientific knowledge.

This brings us to the other exception to time-reversibility: the evaporation of black holes. Black holes are regions where space-time bends so strongly that light is forced to go around in circles and can't escape. The surface within which light gets trapped is called the *horizon* of the black hole; in the simplest case, the horizon has the shape of a sphere. Because nothing can move faster than light, black holes will trap everything that crosses the horizon. If something happens to fall in—an atom, a book, a spaceship—it can't get back out, ever. Once inside the black hole, it's eternally disconnected from the rest of the universe.

However, just because something is out of sight doesn't mean it has stopped existing. If I put a book into a box, I can also no longer see it, but that doesn't destroy the information in the book. The mere presence of a black hole horizon is therefore not a problem for the preservation of information. It certainly is a problem for the *accessibility* of the information, but if black holes just continued to store information indefinitely, that'd be entirely unproblematic.

And that was the status until, in 1974, Stephen Hawking showed that black holes don't live forever. Because of quantum fluctuations, space-time around the black hole horizon becomes unstable. In this region, previously empty space decays into particles, primarily into photons (the particles of light) and particles of tiny mass called *neutrinos*. This creates a steady stream, called *Hawking radiation,* that carries energy away from the horizon. The black hole evaporates, and because energy is conserved, the black hole shrinks.

However, because Hawking radiation does not come from inside the black hole, it cannot contain information about what originally formed the black hole or what fell in later. Remember that what's inside the black hole is disconnected from the outside. The radiation does carry a few bits of information. For example, if you catch it all, you can infer the total mass and angular momentum of the black hole. But the radiation does not carry remotely enough information to encode all details of what vanished behind the horizon. Therefore, when the black hole has entirely evaporated, and the only thing that's left is the Hawking radiation, you have no way to figure out what the initial state was. Was it once a white dwarf or a neutron star? Did it eat up a small moon, or a hydrogen cloud, or an unlucky space traveler? What were the space traveler's final words? You can't tell. The evaporation of a black hole is thus time-irreversible: there are many different initial states that result in the same final state.

This is most obvious in Max Tegmark's idea of the "mathematical universe." According to Tegmark, all of mathematics is real and it's all equally real, not just the math that describes our observations, but literally any math: Euler's number, the zeros of the Riemann zeta function, pseudometric non-Hausdorff manifolds, moduli spaces of p-adic Galois representations—all as real as your big toe.

You may find that a little hard to swallow. But however you feel about it, it's not wrong; it's just not scientific. We clearly don't need all of mathematics to describe our observations—the universe is one way and not any other, so describing it requires only very specific math. And scientific hypotheses should not have superfluous assumptions, for that would allow adding statements like "and God made it." Postulating that all math is real is such an unscientific, superfluous assumption—it doesn't help us describe nature any better. But just because there's a lot of math that we don't need doesn't mean it does not exist either. Postulating that it doesn't exist is also superfluous to describing our observations. So, as with God, science can't say anything about whether or not all that math exists.

Frankly, I think Tegmark came up with the mathematical universe only to make sure everyone knows he is a seriously weird fellow. He was probably successful at that, but whatever his motivation, I will admit that to me the thought that reality is just a manifestation of absolute mathematical truths is a comforting belief. If it were so, then at least the world would make sense; it's just that we don't know or don't understand the mathematics to make sense of it.

However, while I find it comforting to think that reality is mathematics, I can't actually get myself to believe it. It strikes me as presumptuous to think that humans have already discovered the language in which nature speaks, basically on the first try and right after we appeared on the surface of the planet. Who is to say there may not be a better way to understand our universe than mathematics, one that may take us a million years to figure out? Call it the *principle of finite imagination*: Just because we can't currently think of a better explanation doesn't mean there isn't one. Just because we don't yet know a better way to describe natural phenomena than mathematics doesn't mean there isn't one.

So if you want to believe that the past exists because it's math and all of math exists, that is up to you. The arguments in the previous sections of this chapter do not depend on whether you believe in the reality of math. However, they implicitly assume that mathematics itself is timeless, that mathematical truth is eternal, and that logic doesn't change. This is an assumption that cannot be proved, because what would you prove it true with? It's one of the usually unstated articles of faith that our scientific inquiry is based on.

>> *THE BRIEF ANSWER*

According to the currently established laws of nature, the future, the present, and the past all exist in the same way. That's because, regardless of exactly what you mean by *exist*, there is nothing in these laws that distinguishes one moment of time from any other. The past, therefore, exists in just the same way as the present. While the situation is not entirely settled, it seems that the laws of nature preserve information entirely, so all the details that make up you and the story of your grandmother's life are immortal.

Chapter 2

HOW DID THE UNIVERSE BEGIN? HOW WILL IT END?

What Does It Mean to Explain Something?

Planet Earth formed around 4.5 billion years ago. The first primitive forms of life appeared about 4 billion years ago. Natural selection did the rest, giving rise to species increasingly better adapted to their environment. The evidence, as they say, is overwhelming.

Or is it? Imagine that planet Earth began its existence a mere six thousand years ago, with all fossil records in place and stones well weathered. From there on, however, evolution proceeded as scientists say. How would you prove this story wrong?

You couldn't.

I am sorry, but I told you it wouldn't be easy!

It is impossible to prove this story wrong, because of the way our current natural laws work. As we discussed in the previous chapter, they work by applying evolution laws to initial states, and we can apply those evolution laws both forward and backward in time. If we want to make a prediction for the path of a celestial object, we measure its present location and velocity and evolve it forward. If we want to know how the universe looked billions of years ago, we use our observations from the present time and then run the equations backward.

This method creates the following problem, however. If I take a present state, like the Earth in the year 2022, and apply an evolution law to it, then that will give me a past state in 3978 BCE. If I then take that past state and evolve it forward in time again, I will correctly get back to the year 2022. Trouble is, I can do that for *any* evolution law. There is always *some* state six thousand years ago that, together with the right evolution law, will correctly result in what we observe today.

Indeed, if I wanted to, I could suddenly switch to a different evolution law more than six thousand years in the past, to accommodate a creator, or the construction of a supercomputer that runs the cosmic simulation we all reside in, or really whatever I want. This is why, with natural laws like the ones we currently use, the idea that Earth was created by someone or something with everything in place is impossible to rule out.

Because such creation stories can't be falsified, we can't tell if they are false, but being false is not their problem. The problem with these stories is that they are bad scientific explanations.

The distinction between scientific and nonscientific explanations is central to this book, so it deserves a closer look. Science is about finding useful descriptions of the world; by *useful* I mean they allow us to make predictions for new experiments, or they quantitatively explain already existing observations. The simpler an explanation, the more useful it is. For a scientific theory, this explanatory power can be quantified in a variety of ways that come down to calculating how much input a theory needs to fit a set of data to a certain level of accuracy. Exactly how one quantifies explanatory power doesn't matter for our purposes. Let us just note that it can be done, and that it's