Time:

A Review of Temporal Research in the Physical and Biological Sciences

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1. INTRODUCTION

What is time?

It is a position of the hands on a clock, and the difference between finding those hands in one position and another. You can be on time, in time, out of time. Time is the thing that makes the past closed and the future open, distinguishes history from prediction, and fixes cause before effect. It is the machine that turns the future into the present and the present into the past. It flows, but not steadily: sometimes it passes in a great rush, sometimes in drowsy drips, and sometimes it almost seems to freeze. It makes beginnings possible and endings inevitable.

There's no shortage of ways to describe time. *Defining* it is the hard part. Saint Augustine's comment —"What, then, is time? If no one asks me, I know; if I wish to explain to him who asks, I know not"— feels as true today as it did when he wrote it 1,600 years ago (Augustine of Hippo, ca. 400/1867). "Time" is, in fact, the most-used noun in the English language, a giveaway, perhaps, that just one definition will not do. Today's exquisitely precise timekeeping has brought us no closer to understanding the essential nature of time.

Meanwhile, the two great theories of modern physics, general relativity, describing the motion of the heavenly bodies, and quantum theory, describing the behavior of the very small, reveal contradictory faces of time. In the former, time is elastic—and inseparable from space and the objects that occupy it. In the latter, time ticks on steadily and independently, like the universe's own perfect wristwatch. And as physicists try to reconcile these two theories, physical notions of time seem to slip further and further from what most people mean when they talk about time: a past that exists only in memory, a future that exists only in imagination, and a moment called "the present" which seems to be "real" in a sense that the past and future are not.

We must start, then, by accepting that there is no universal definition of time. One approach is to divide time into three "flavors" (Buonomano, 2017). "Subjective time" is what humans experience. It can go quickly: When you're absorbed in a book, you may be scarcely aware of the hours passing. Or it can go slowly: The three minutes waiting in the cold at your bus stop seem like they will never end. When you look up from your book to the clock on the wall, or check your watch to see how much time is left before the bus arrives, you are reading the "clock time." The third flavor, "natural time," is what physicists talk about when they talk about time: the deeply true version of time, which exists independent of our perceptions and our measuring tools.

Physicists are now tackling some of our deepest questions about natural time head-on: Where does it come from? Is the flow of time real, or an illusion? Can time be reversed? The next three chapters of this review will explore how a diversity of disciplines within physics have revolutionized—and indeed still are revolutionizing—the ways we think about time. This review will then look at how, for the first time, physicists are coming together with biologists and neuroscientists to try to bridge the gaps between the different flavors of time. Is subjective time just a good-enough approximation of natural time, or is it an outright deception?

For most of history, "natural" time and "clock" time were essentially indistinguishable. That all changed with Einstein's theories of relativity. Chapter 2 will explore how Einstein dramatically reconceptualized the meaning of time, revealing natural time to be both pliable and personal: Time may objectively flow differently for me than it does for you, but neither one of us is wrong. Chapter 2 will trace how Einstein reached this startling conclusion and explore the extensive experimental tests that have shown that motion and gravity really can change the rate at which time flows.

Relativity has led some thinkers toward an even more radical conclusion: that time does not actually flow at all. Following Einstein, some physicists have taken to modeling the universe as a four-dimensional "block" with three sides representing space and the fourth representing time. This "block universe" makes no distinction between past, present, and future: it simply *is*. Chapter 2 will look at how physicists are trying to come to terms with a vision of the universe in which the passage of time is not strictly "real." Perhaps our experience of subjective time is, as Einstein put it, merely a persistent illusion. Other physicists, however, believe that it may be possible to "save" time by rethinking the block universe—or even by choosing a new mathematical language in which to write the laws of physics.

Yet physicists know that relativity cannot be the final word on physics. That is because it is in fundamental opposition to quantum mechanics, the theory described in some depth in Chapter 3, which rules atoms and the even tinier particles that make them up. Quantum mechanics is just as successful at describing the micro-world as relativity is at describing the effects of motion and mass on space and time; but wherever the two meet—in the dense center of a black hole, in the roiling soup of the early universe—they clash.

Under the rule of quantum law, particles are governed by probabilities, not certainties. Einstein's theory of general relativity makes no room for this kind of ambiguity, though; whatever you wish to measure—the position or velocity of a particle, the strength of a gravitational field—has a definite value at a particular point in space and time. As described in Chapter 3, the two theories also take wildly differing views of space and time. In quantum mechanics, physicists treat space as a static stage against which particles move and assume that time advances at the same rate everywhere. In relativity, time moves differently for everyone: There is no universal clock. (We shall also briefly revisit the block universe, outlined in Chapter 2, to see how some physicists propose modifying it in quantum terms, in an attempt to restore the difference between past, present, and future.) Ever since the two theories emerged in the early 20th century, physicists have been trying to find ways to unite them into a single, deeper theory of "quantum gravity." Could this quest also uncover the true nature of time?

The third chapter will begin by exploring how various weird features and paradoxes of quantum mechanics have led some physicists to a very unorthodox idea: That causes can come *after* effects. This concept, called "retrocausality," allows the universe to retroactively puzzle out what happens at times and places that aren't observed or measured. Though retrocausality goes against our gut feelings about cause and effect, if it is correct, it could provide a totally new way of understanding some bizarre quantum experiments.

Chapter 3 will then describe how early attempts to derive equations unifying quantum mechanics and relativity raised a new problem: time vanished from their framework, suggesting it may not exist at all at a fundamental level. This odd finding inspired physicists to posit how time might be recovered in the universe by invoking entanglement—the quantum phenomenon linking distant systems that Einstein famously called "spooky action at a distance." In recent years, physicists have put this idea to the test in the lab. Building on the concept of a "quantum clock," which was first proposed in the 1980s, they are showing how to keep time with something natively quantum—the spin of an electron, say—that is yoked to the rest of a system via entanglement. Chapter 3 will look at how different groups are developing quantum-clock models and using them to reveal startling insights about the nature of time.

This is part of a small, but growing program involving a number of physicists aiming to use table-top experiments to probe the interface at which gravitational and quantum effects come into play. Such experiments could eventually test a profound assertion. If space and time exhibit the same kind of uncertain quantum behavior that particles do, it could break the chain that unambiguously links cause and effect, resulting in situations in which cause and effect really are indistinguishable. Unlike retrocausality, which posits that effects can come before causes, this "indefinite causality" suggests that multiple timelines could occur simultaneously within the same quantum system. Physicists are now investigating the meaning of time in quantum mechanics and relativity using this indefinite causal structure. And some have even calculated that indefinite causality could one day drive a new generation of quantum computers—machines proposed to outperform the best classical supercomputers at certain tasks.

In Chapter 4, we will turn to one of the most basic truths about time: It only goes one way. This phenomenon, known as the "arrow of time," is a puzzle. All the fundamental laws of physics are "time reversible"—that is, they are indistinguishable when run forward or backward in time. Of course, this is directly at odds with human experience. You can choose to walk to the right or the left, forward or back, or up or down the stairs, but you cannot choose to rewind to yesterday. What makes time different?

Many physicists think that the answer has something to do with entropy, which goes by the popular shorthand "disorder." According to thermodynamics (the science of heat and energy transfer), the entropy of a closed system—say, a sealed box full of gas atoms—can never decrease over time. This law explains why cracked eggs don't spontaneously reform, shuffled card decks don't re-order themselves, and messy rooms don't get clean on their own (or, at least, are highly unlikely to). This is so fundamental it is codified in the second law of thermodynamics—which has an arrow of time built right in.

Figure 1: *El Infiernito*, the "Little Hell," is an ancient pre-Columbian astronomical site on the outskirts of Villa de Leyva, Boyacá, Colombia. It comprises 109 monoliths and apparently represents the Muisca calendar. (Image credit: James Wagstaff.)

Yet the second law of thermodynamics, on its own, cannot explain the existence of time's arrow. First of all, the thermodynamic arrow of time is just the most mathematically tractable example of time's arrow. We also experience the "memory" arrow, which accounts for the fact that we remember the past and not the future; the "causal" arrow, which places causes after effects; and the all-too-human "aging" arrow. Are all these arrows truly aligned? Using tools from computer science and information theory, researchers are trying to find out and, perhaps, begin to bridge the gap between "natural" time and human experience.

The thermodynamic arrow also rests on the notion that the universe must have started in a state of low entropy. But why should that be true? Statistically speaking, the odds are overwhelmingly against it. Chapter 4 will look at how physicists are trying to make sense of our low-entropy cosmic beginning, using both theory and telescope observations of the baby universe. Yet many physicists find this emerging picture incomplete. Could the speculative possibility that we live in a multiverse of many universes explain time's arrow? Can the second law of thermodynamics really be applied to the entire universe? Could the time-reversible laws of physics be hiding still-deeper laws that do depend on time? These are all current avenues of research in physics.

If physicists' progress in understanding time seems to be taking us further and further from the "subjective" time of human experience, Chapter 5 will return to the human side of the equation. Time is one of the most basic facts of the human condition: We might get a little more or a little less, but we only get so much. And there is evidence that humans have been thinking about time, and how to use it, since the beginning (Figure 1). How do living things tell time on scales ranging from milliseconds to minutes to hours to months? The answers turn out to have surprising resonances with the evolving physics of time.

The fifth chapter will begin by looking at how timekeeping is embedded in almost everything we do: speaking and hearing, waking and sleeping, learning and action. Starting with the most familiar internal clock, the 24-hour circadian rhythm, we will examine how neuroscientists are exploiting new techniques in controlling and observing neurons to reveal how apparently simple brain "circuits" can perform exquisitely precise feats of timekeeping. Chapter 5 will also dive into one of the biggest debates dividing scientists who study neural timekeeping: does the brain have specialized "time circuits," or is timekeeping something that any group of neurons can do under the right circumstances?

Chapter 5 will also look at how we understand the *concept* of time. For decades, linguists have noted that we borrow spatial words to describe time: we put the past behind us, and look forward to better things tomorrow. Is this doubling-up just a matter of linguistic convenience, or is it a sign that the brain understands time by repurposing a spatial understructure? Physicists frame this question in the context of the block universe, which treats time as just another spatial dimension. Anthropologists, meanwhile, are looking for answers by studying how different cultures talk about time. Neuroscientists are also examining the question, looking at whether the brain uses the same systems to represent time that it does to represent space.

Einstein showed that the objective passage of time is relative, and one of the most conspicuous features of subjective time is how malleable it is, too. Just as our eyes and brains are vulnerable to optical illusions, we can be fooled by time illusions that put our subjective experiences at odds with objective clocks. By tweaking the perceptual dials that control our sense of time passing, researchers are showing how factors like surprise, emotion, and memory are intertwined with our experience of time.

Memory can play tricks with time, yet by and large, we can put our experiences in the correct order. It is almost as if the brain stamps every memory with a time and place, like a digital camera coding metadata into each photo. But how? Chapter 5 examines emerging research on "time cells," groups of neurons that can work in concert to time-code memories. Neuroscientists are now exploring how time cells might work with neurons in other parts of the brain to make sense of information that occurs across milliseconds, seconds, or minutes and, remarkably, to process all these time scales simultaneously.

With echoes of retrocausality, Chapter 5 will also look at how the brain performs "backward editing"—that is, how it uses information from one moment to retroactively influence our conscious perception of moments that came before. In conclusion, we will note that discoveries like backward editing challenge the notion that we truly live in "the now," adding a new twist to the conflict between "presentists," who believe that only the present is real, and "eternalists," who consider every moment in the past, present, and future to exist equally. It is a conflict that plays out in both physics and biology, and which philosophers have been debating for at least 2,500 years (Figure 2).

The consensus is that the essential experience of living in time is the same no matter who you are, where you are, or when you are. As anthropologist Alfred Gell put it, “There is no fairyland where people experience time in a way that is markedly unlike the way in which we do ourselves, where there is no past, present and future, where time stands still, or chases its own tail, or swings back and forth like a pendulum.” (Gell, 1992)

As they move toward a new vision of time, though, physicists seem to be turning Gell’s observation on its head. In the next chapter we turn to relativity and ask, could the “fairyland” of no past, present, and future be reality, and the flow of time just a fairytale?

Figure 2: Over 5,000 years old, Stonehenge in the United Kingdom, may have served as both a solar and lunar calendar. (Image credit: Chuta Kooanantkul.)

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2. THE FLOW OF TIME

On Monday, April 16, 2007, at 9:59 a.m. Eastern Time, ten thousand runners stood ready at the starting line of the Boston Marathon. It was a cold, wet Marathon Monday, the worst in memory, and the runners shivered against the wind and stinging mist.

Meanwhile, in the climate-controlled comfort of the International Space Station, astronaut Sunita Williams was getting ready to run, too—the first ever in-orbit marathon. With her marathon bib taped to the front of the Space Station treadmill, she waited. And when the clock turned over to 10:00 a.m. Eastern, every runner—on Earth and in orbit—started off, at the *exact same time*.

We all understand what is meant when we say that two things happen at the same time. We believe that *simultaneity* gives events a special bond. If Williams had run her marathon a day earlier or later, she might not have felt a part of the race in the same way. A child home sick from school wonders what her classmates are doing *this very moment;* watching sports live on TV makes us feel that we're seeing each touchdown *as it happens*. Embedded within this notion of simultaneity is the idea that every event, everywhere, unfolds according to the ticking of a single master clock. This clock marking out absolute time across the cosmos may be imaginary, but we don't question that universally agreed-upon time actually exists.

This absolute time ticking on an imagined master clock is what Galileo used to describe how objects move. It is what Johannes Kepler had in mind when he wrote down the equations of planetary motion, and what Isaac Newton called time when he devised his laws—laws that held up quite nicely for more than 200 years.

But in the early 20th century, Albert Einstein took a different tack. His theories of relativity upended the idea of absolute time, revealing that the flow of time is actually variable, its comparative quickness or slowness dependent upon observers' relative motion. His insights also shattered the notion of simultaneity—that thing we all thought we instinctively understood. This chapter outlines the arguments that lead to the conclusion that time is malleable and which force us to give up the idea that we can define a unique present—a "now" that marks a single moment in time across the universe, separating the fixed past from the open future. Rather, we may have to accept that the past, present, and future are on equal ontological footing, a block universe. Some, however, as we shall see, dispute this and are inventing novel ways to escape the block.

I. TIME AND RELATIVITY

JTF's Cosmological Origins review (Chapter 2, Section I) provides a detailed discussion of how and why Einstein developed first his special theory of relativity (Einstein, 1905)—describing how time and space are, in some sense, flexible—and then his general theory of relativity (Einstein, 1915)—which stitched them together in a four-dimensional spacetime fabric to explain the origin of gravity. Here, we will briefly sketch those ideas, focusing specifically on their repercussions for the nature of time.

1. Time Dilation

Instead of assuming that everyone, everywhere could agree on what time it was, as physicists had done for centuries before him, Einstein took an alternative starting point that everyone, everywhere could agree on: the speed of light. Einstein had good reason to make this leap. By the early 19th century, physicists knew that light was a wave (Young, 1802). In the 1860s, James Clerk Maxwell formulated a series of equations uniting electricity, magnetism, and light that suggested that light is an electromagnetic wave produced by mutually reinforcing electric and magnetic fields that propagate with a constant speed through empty space (Maxwell, 1865).

This led Einstein to question how light waves behave when they are coming from a source that is itself in motion. To understand Einstein's thought experiments, which typically starred locomotives, in a more contemporary setting, we will return to astronaut Sunita Williams and her marathon-in-space. Imagine that, instead of being on the space station, Williams had run her marathon aboard a spaceship traveling smoothly, straight out of the solar system. And imagine that, instead of a treadmill, this spaceship was outfitted with a long, straight track. Now (last one!) imagine that marathon-watchers on Earth could peer out through their telescopes and see Williams running on her spaceship. How fast would they say she was going? Forgetting, for a moment, about the motion of Earth, they would say that her total speed was her running speed—say, 6 miles an hour—plus the speed of the spaceship—say, 25,000 miles per hour. So, 25,006 miles per hour.

Now, what if Williams put on a headlamp and continued her marathon: How fast would people on Earth say the light beam was going? At first blush, you might be tempted to carry out a similar analysis and say that it would be traveling at the speed of light plus 25,006 miles per hour. But Einstein realized that can't be right. The speed of a light beam must be the same, whether Williams is measuring it whooshing out of her own headlamp or marathon fans on Earth are looking at it emanate from her moving spaceship, viewed from the ground. The speed of light must come out to 670,616,629 miles per hour. If this wasn't the case, you could imagine a strange scenario in which someone running at the speed of light themselves might "catch up" to a light beam and see it frozen in space—something prohibited by Maxwell's laws.

But if the speed of light must be measured to be the same by both observers, regardless of whether they are standing still or whizzing through space, then what gives?

Einstein realized that *what gives* is time itself. For the speed of light to stay constant, time must pass more slowly for Williams than it does for observers on Earth. Put simply: Moving clocks tick more slowly. This effect is called time dilation (Einstein, 1905b). (Special relativity also includes a correspondingly weird effect on space: Williams' spaceship would appear to shrink along its direction of motion as it zooms past Earth. This effect is called length contraction. Time and length together shift to keep the speed of light constant.)

Time dilation is not a judgment on the rightness or wrongness of any individual clock. It is a statement that, given certain rules, *all* clocks are right. A clock on Earth and a clock on a spaceship are both correct, even when they disagree over the rate at which time is ticking away. (This led to other strange puzzles, see "The Twin Paradox.")

The Twin Paradox

Suppose that astronaut Sunita Williams (Figure 3) has a twin brother on Earth (and neglect that Earth is itself moving). And imagine that Williams is in relative motion, zooming away from Earth at a constant speed. That means that to her brother, her clocks appear to be ticking more slowly than his—even her heartbeat and biorhythms will be slowed. So, the astronaut will age more slowly than her brother, from his point of view.

Figure 3: Sunita Williams on the ISS. (Image credit: NASA.)

However, from her point of view, she is stationary on her spaceship, while the Earth is whizzing away from her ship at a constant speed—so by her reckoning, she should mature faster than her brother. Hence a paradox.

This paradox is resolved by noting that in order for the astronaut and her sibling to meet again and compare their ages to check who has aged the most, the astronaut will have to turn her ship around and return home. This requires an acceleration to change direction; but special relativity only applies to observers who travel at different constant speeds, without accelerating, and its calculations no longer apply.

In his general theory of relativity, Einstein went even further, showing that space and time are interwoven into a four-dimensional spacetime fabric that can be bent and warped by heavy objects such as stars and planets. JTF's Cosmological Origins review (Chapter 2, Section I) explains how this effect gives rise to gravity. A product of this is that time dilation also occurs in the vicinity of a massive object. A clock close to a massive object, like the Earth, will tick slower than a clock that is far away. Taking things to the extreme, a clock plunging into the gravitational field of a black hole would, to a distant observer, seem so achingly slow that it would almost stop entirely (Einstein, 1915).

2. The Test of Time

In most everyday situations, time dilation effects are tiny: Friends planning to meet up for dinner don't need to account for relativistic effects when they make their 7:30 p.m. reservation, nor can you blame Einstein if you show up late to your 9:00 a.m. meeting.

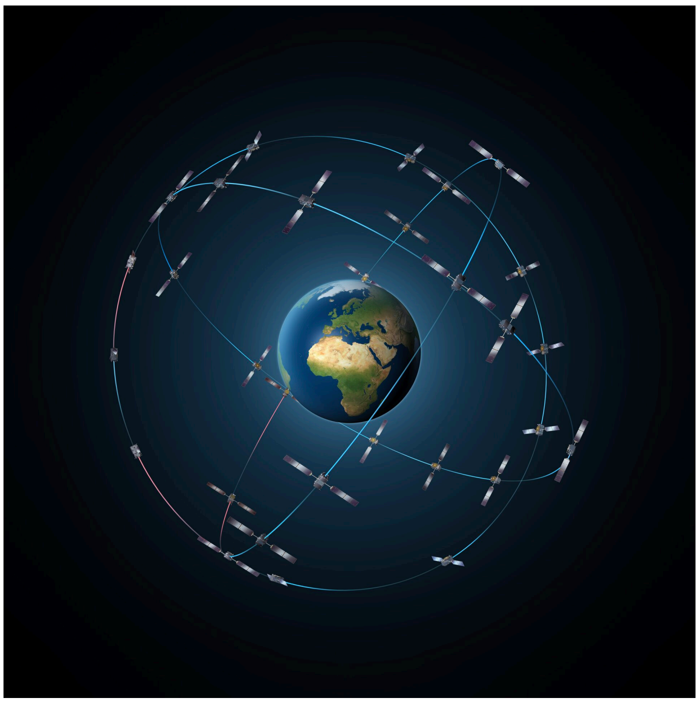


Figure 4: Galileo network. (Image credit: ESA.)

Yet even small time-warps are big enough to measure. In 1971, J. C. Hafele and Richard Keating tested Einstein's predictions by sending four atomic clocks on round-the-world airplane flights. They then compared their readouts to the time measured by a clock that stayed put on Earth (Hafele & Keating, 1972). The combined relativistic effects of the journey's altitude (a general relativistic effect) and velocity (a special relativistic effect) caused the clocks to be tens or hundreds of nanoseconds off compared to the clock on the ground: not much, but enough to prove Einstein right about time.

Since then, researchers have measured time dilation with ever-greater accuracy and precision, and they have even seen it in action at quite ordinary speeds and elevations. In 2010, physicists at the National Institute for Standards and Technology, in Gaithersburg, Maryland, set out to see whether they could measure time dilation on a more typical human scale (Chou et al., 2010). They used a nearly identical pair of extremely precise clocks, located in separate labs and linked by a 75-meter-long optical cable. The clocks keep time by the vibration of aluminum ions, which flick between energy states some million billion times per second. The physicists found that they could pick out tiny time differences even when one clock was barely a foot higher than the other, and when one was moving just 10 meters per second faster than the other. It was as if they had put one clock on the seat of a moving bicycle instead of aboard an airplane.

The most accurate test of gravity's effect on time so far, though, happened almost by accident. In August, 2014, two new navigation satellites were launched from Europe's Spaceport, in French Guiana. They were supposed to join a network of navigation satellites called Galileo (Figure 4). But a rocket malfunction sent the new satellites, Galileo 5 and 6, into tilted, elliptical orbits instead of circular ones, as intended. Through a series of delicate maneuvers, flight controllers managed to stabilize the satellites and steer them into nearly circular orbits. Still, the satellites pitched up and down by about

8,500 kilometers as they looped around the Earth. That altitude shift, plus the fact that each satellite was equipped with an extremely accurate timekeeper called a passive hydrogen maser clock, created the ideal conditions in which to test general relativity's predictions about time and gravity. Even better, because the satellites were equipped with special mirrors, the researchers could pinpoint each satellite's location using laser ranging. For three years, physicists accumulated data from the satellites and their clocks. They found that the measurements were in near-perfect agreement with Einstein's predictions, allowing for only tiny discrepancies (Delva et al., 2018; Herrmann et al., 2018).

Today, European Space Agency physicists are preparing for an even more precise test of gravity's effect on the flow of time. In 2021, they plan to send two atomic clocks to the International Space Station as part of the ACES experiment—the Atomic Clock Ensemble in Space. One clock, based on laser-cooled cesium atoms, keeps stable time over long periods; the second, which uses hydrogen atoms, keeps excellent time in the short term. By combining the two clocks, the researchers will create a timekeeping device so precise that, if it ran continuously for 300 million years, it would lose only one second (Caccianuoti & Salomon, 2009).

An equal challenge is linking the clocks to Earth. Engineers are now developing microwave and laser links that will give researchers the exquisite timing accuracy and consistency they need to compare time measurements in space with time kept by atomic clocks on the ground (Schreiber et al, 2009). By comparing the clocks in space with those down on Earth, the researchers think that they can improve on the Galileo measurements of gravitational time lag by a factor of ten.

Why keep testing Einstein's predictions when they have stood up so well over the decades? Effects like these are tiny, but the technologies used to test them with ever greater precision could have surprisingly down-to-Earth applications. Geophysicists are exploring how they might use extremely precise atomic clocks to pick up tiny drifts or vibrations in the ground. Because even small changes in elevation can generate measurable changes in the clocks' tick rate, the clocks could one day be an essential part of early-warning systems for earthquakes, volcanic eruptions, and other difficult-to-predict geological phenomena (Bondarescu et al., 2015; Grotti et al., 2018). Financial markets also now trade so fast that millisecond differences in the transmission of information can lead to advantages. As "buy" and "sell" information zips around the globe, the speed of transactions is limited by the speed of light. Traders seeking an edge are putting their computers as close as possible to stock exchange computers, so that their transactions can "beat" those traveling across the ocean, the continent, or even across town. Policymakers and traders are now thinking about how to contend with the impact of special relativity on trading regulation and market volatility (Angel, 2014).

II. IS TIME AN ILLUSION?

Relativity opened a gap between the familiar time of our everyday senses and time as it appears in physics. That the flow of time is changeable depending on the observer is strange enough. But relativity has led some thinkers toward an even more radical conclusion: that time does not actually flow at all.

1. The Block Universe

As we saw above, in relativity, the universal master clock governing absolute time—implicit in the equations of every physicist who came before Einstein—flies out the window. And it takes with it the idea that two events that aren't physically linked can ever be considered truly "simultaneous" (Figure 5). This is an established fact in relativity theory and—at least according to some—it has profound consequences about whether the future is truly open, or just as fixed as the past.

The Relativity of Simultaneity

Observers in relative motion can disagree on whether two independent events occurred at the same time, or whether one happened before or after the other. This is because the speed of light is a constant for all observers.

Sychronizing clocks while stationary

a) Imagine that Sunita and her friend Chris stand at opposite ends of a street, with identical clocks. To synchronize them, they ask a third friend, Marvin, to stand in the middle of the street and flash a light at precisely midnight. Both clocks have light sensors and will start to tick when they receive a light signal. The light must travel the same distance to each clock, and so Sunita, Chris, and Marvin all agree that when the clocks start to tick, they will be synchronized.

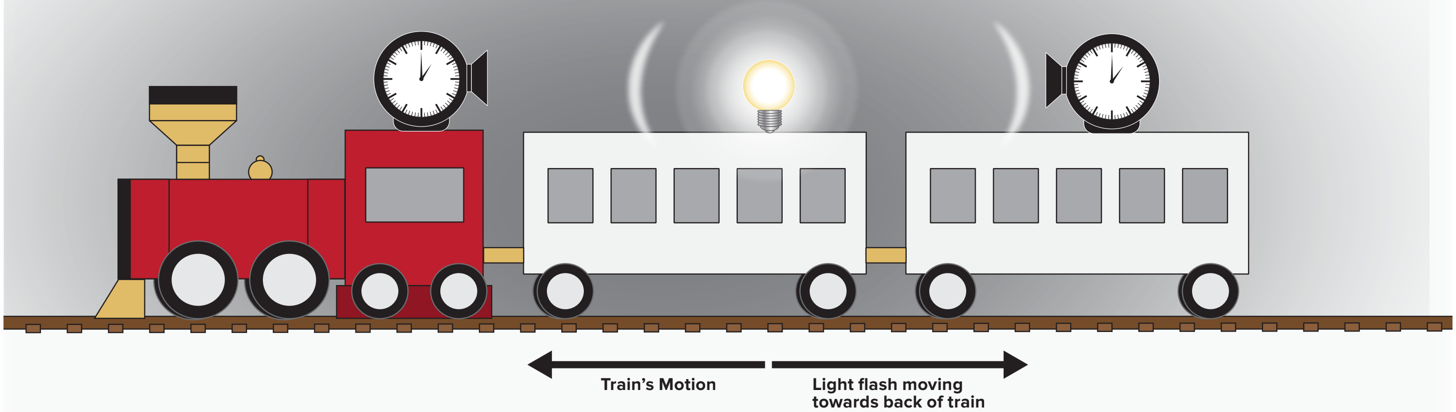
Syncronizing clocks while moving

b) Now imagine that Sunita takes the whole apparatus on a train. One clock is positioned at the front of the moving train, the other at the rear. Sunita sits in the middle, and sets off the light signal. For Sunita the process will serve to synchronize the clocks, as their sensors get hit by the light flashes at the same time, just as before.

But imagine that Marvin is sitting on the platform watching the train pass by. From his perspective, the back of the train is catching up to the light signal, so the light has less distance to cover on its trip to the second clock.

Meanwhile, the front of the car is speeding away from the point where the light was emitted, so the light has to travel farther to catch the first clock. Marvin thus sees the light hit the clock at the back of the train before it hits the clock at the front. For Marvin, the two clocks are not synchronized.

Both Sunita and Marvin are correct, from their own perspectives—even though they do not agree about which events occur at the same time. There is no unique "now" that observers in relative motion will agree on.



Created by Maayan Harel for FQXi, the Foundational Questions Institute

Figure 5: Relativity of Simultaneity. (Image created by Maayan Harel.)

Two observers in motion relative to one another will disagree on whether the same two unrelated events happened simultaneously (Figure 5a), or one event happened before the other (Figure 5b). So it is impossible to carve out a single "now" moment—a universal present at which all observers will agree certain events are all currently happening. Some may infer that some of those events already happened, while for others, in that moment, they are still to come.

This ambiguity led to the development of the block universe view (Figure 6). In this vision, past, present and future can be laid out along the time dimension, just as we can map position along a North-South axis, an East-West axis, and an axis marking elevation. The universe is then represented by a four-dimensional "block" with three sides representing the three dimensions of space and the fourth representing time. Human brains aren't equipped to picture things in four dimensions, so illustrations of this "block universe" frequently drop one spatial dimension for convenience. The result is a mental model that resembles a loaf of bread, with time running along the loaf's length.[1]

The block universe admits no ontological difference between past, present, and future, and no process of coming into being—just as there is no ontological difference between where you are standing in space and the position three feet to your left, or three feet to your right. "The universe now, the universe of relativity, simply is," Jenann Ismael has written (Ismael, 2015).

To see why, imagine that you set the loaf down on your breadboard and cut out a nice vertical slice corresponding to "now"—your now, that is. Next, imagine that an astronaut whizzing along on his spaceship also cuts out a "now" slice. Because he is in motion, the astronaut's slice seems to be at an angle (see Figure 6). Take it a step further and imagine a fleet of spaceships all traveling at different velocities, each cutting out its own unique "now." Events in the block lying on one ship's "now" might be in another's past, or even in its future. Which one is real?

Relativity implies that they *all* are. But if there is no universally agreed-upon "now," the whole universe exists at once, with past, present, and future all equally real. From the perspective of the block universe, time does not actually flow; it is static, and our subjective sense of "motion" through it is just an illusion.

2. Eternalism vs Presentism

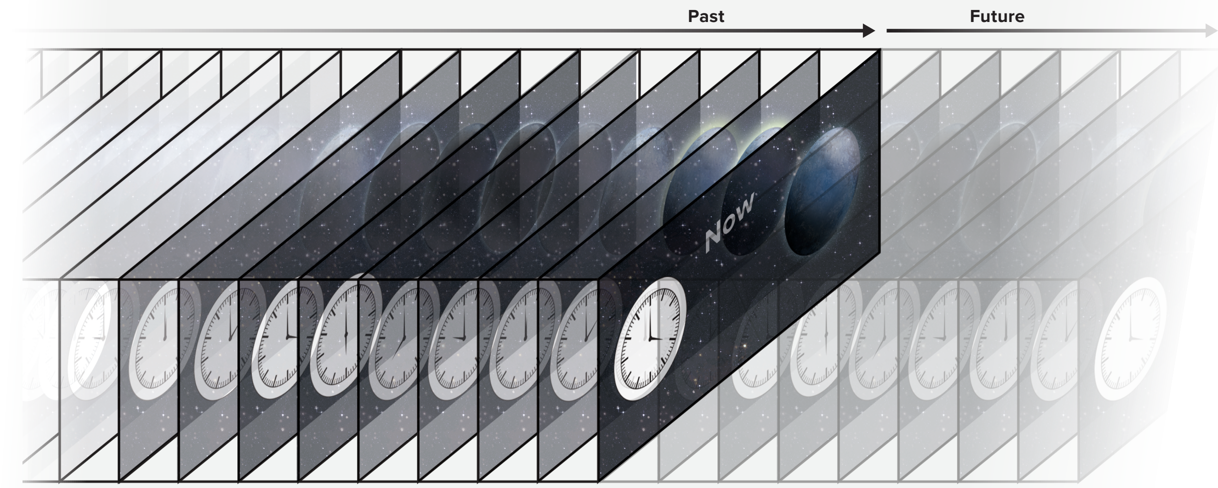
This block-universe idea can be seen as a contemporary form of the ancient "eternalist" position that all existence in time is equally real (Emery et al., 2020), contrasting the presentist view, in which "now" is privileged. It seems impossible to reconcile with our everyday experience: *Of course* time flows; *of course* we live in "the now." While all physicists and philosophers of physics agree about the implications of relativity regarding simultaneity, only some subscribe to this counterintuitive eternalist view. Julian Barbour, for instance, has been motivated to develop a fundamental framework of physics that does not directly reference time; instead the evolution of objects is defined in terms of their relation to each other, rather than against any spacetime backdrop. Such a framework has been shown to reproduce the equations of general relativity (Gomes et al., 2011). (Chapter 4 of this review delves into the implications of this model for an arrow of time, while Chapter 4 of JTF's Cosmological Origins review discusses it in the context of speculative frameworks for the origin of the universe.) Carlo Rovelli has similarly advocated "forgetting time" when building a fundamental theory of physics (Rovelli, 2011).

Barbour has gone further in developing his own picture for why we perceive the illusion of flowing time. He conceives of a series of individual complete moments, Nows, similar to the pages of a novel,

[1] The "spacetime loaf" model was popularized by Brian Greene in his book *The Fabric of the Cosmos* (Greene, 2004).

The Block Universe

The ‘presentist’ view is that only the present ‘now’ really exists. But the relativity of simultaneity suggests there is no unique ‘now’ that all observers can agree on. This has led some physicists to the view that the past, present, and future all co-exist, in the block universe.



Imagine Sunita, an astronaut on the International Space Station (ISS), starts running a marathon. According to on-board clocks, her colleague Chris strummed a chord on his guitar at that exact moment. The yellow slices show successive 'nows' as experienced by Sunita and Chris on the ISS.

But Marvin, an alien zipping past the ISS in one direction, could argue that Sunita began running after Chris played his first note because his ‘now’ slices through the block at an angle shown by the pink slice. Meanwhile, an alien, called Spock, shown by the blue slice, zooming in the opposite direction could say that Williams started first.

Observers in relative motion have different ‘now’ slices, and thus they disagree on which events occurred simultaneously from their perspective.

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Created by Maayan Harel for FQXi, the Foundational Questions Institute

Figure 6: The Block Universe. (Image created by Maayan Harel.)

ripped out and thrown randomly over the floor; each page existing outside of time. The physics of reality is applied to all these Nows in combination. But within a single Now, we only have the illusion of flow because within that Now there are objects that serve as records of "past" Nows—hinting at a sequential ordering of moments from past to present (Frank, 2012). (We shall return to the question of the human perception of time in Chapter 5.)

Other physicists, however, are less comfortable with the eternalist picture. Tony Short has criticised the block-universe view because it appears to require the entire eternal universe, stretching from its beginnings to an infinite future, with all the complexity that entails, to have come into being simultaneously—surely a hard physical ask (Jones, 2018). In Chapter 3, we will see how physicists such as Short are attempting to use aspects of quantum physics—the theory that governs the behavior of the very small—to rescue the idea of becoming in physics.

Ismael meanwhile argues that "the problem of the now" is only a problem if you take the block universe too seriously (Ismael, 2015). She sees the block universe as a useful formalism, not a deep truth about the nature of time. When physicists invoke the block universe to assert an "eternalist" viewpoint, she points out, they ask us to imagine an observer sitting outside that universe. But the universe *has* no outside, and the "outside observer" is an impossible fiction. To Ismael, the eternalist problem comes from asking a visualization to do too much.

Still it is worth noting that even Einstein struggled to accept the block universe. Rudolf Carnap, a philosopher who studied relativity in Berlin at the same time Einstein was working as a professor at the university there, has written that Einstein said "the problem of the Now worried him seriously" (Schilpp, 1964). "He explained that the experience of the Now means something special for man, something essentially different from the past and the future, but that this important difference does not and cannot occur within physics."

Someone who shares this concern is Nicolas Gisin, who, as described below, is attempting to save time by revitalising an "intuitionistic" mathematical argument that has been ignored for a hundred years.

3. Escaping the Block—Intuitionistic Mathematics

Gisin has traced the problem of the block universe to an unexpected source: mathematics itself. He notes that a century ago, mathematicians were split about how to describe numbers whose decimal digits trail off into infinity. On one side, led by David Hilbert, were those who thought every such real number was a "completed object" that exists in its entirety, timelessly, even though it has infinite digits. On the other side were adherents of a version of mathematics that most people have never even heard of: "Intuitionistic mathematics." In intuitionistic mathematics, numbers are created over time, with digits materializing in succession.

Spoiler: Hilbert's side won. "Time was expulsed from mathematics" and as a byproduct, from physics, too, writes Gisin (Gisin, 2020a). But, he wondered, what would happen if physics were re-written in the language of intuitionistic mathematics? Would time become "real" again?

Gisin asks us to consider "chaotic" systems, in which two almost-but-not-quite-identical starting points evolve to wildly different end points. A classic example is the weather. In principle, it is possible to predict next week's weather, or even next year's. You need only know the exact weather conditions right now, everywhere, with perfect precision and accuracy, and the equations that describe how they evolve. That we can't do this in practice is a limitation of measurement and computation, not of physics. The future of the weather has already been written.

But whether you are talking about the weather, the evolution of the entire universe, or just your choice of what to have for dinner tonight, it is distressing to think that the future is already fully determined. Of course, physics is not required to make us comfortable. But Gisin points out that intuitionistic mathematics could offer a natural way out of the deterministic lockup. In the intuitionistic view, numbers—like the values of pressure, wind speed, humidity, and so on—do not have definite values from the get-go, but rather develop over time, with randomly-generated digits unscrolling as time passes. This mathematical treatment allows for a universe in which time actually flows, events truly happen, and randomness and chance are injected moment by moment.

It is an open question whether intuitionistic mathematics can truly "save" time, but physicists know that relativity only gives a partial picture of how time operates. As will be discussed in the next chapter, quantum mechanics, the other dominant theory of physics that governs the realm of the tiny, takes a completely different view of time and randomness. In the world of quantum mechanics, time flows and events are fundamentally unpredictable. Intuitionistic mathematics could perhaps resolve the rift between these theories, says Gisin (Gisin, 2020b).

Whether or not intuitionistic mathematics is the answer, as physicists work to unite quantum mechanics and relativity into a single, all-encompassing theory, many think that time could be the key to resolving their contradictions, as described in Chapter 3.

While arguments continue to rage over the reality of the block universe, it is poignant that, Einstein seems eventually to have found some consolation in it. When his friend Michele Besso died, Einstein wrote to Besso's family in condolence, "Now he's gone slightly ahead of me again, leaving this strange world. That doesn't mean anything. For us believing physicists this separation between past, present and future has the value of mere illusion, however tenacious." Einstein himself died a few weeks later.

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3. UNCERTAIN TIME: FROM QUANTUM THEORY TO QUANTUM GRAVITY

Since the early 20th century, quantum mechanics and general relativity have been the two reigning theories of physics. Together, they are like two monarchs governing the same land but laying down wildly different laws, keeping a tenuous peace by dividing up the subjects over which they claim control. Quantum mechanics rules atoms and the even tinier particles that make them up; as described in Chapter 2, general relativity explains the origin of gravity and determines the motion of large objects such as planets and stars.

Each theory seems unassailable in its own domain, but this dual-rule system can't be the final word. Somehow, physicists believe, a theory of "quantum gravity" will emerge to unite them. Key to that lasting peace could be reconciling the radically different conceptions of time in each of these theories.

I. TWO VIEWS OF TIME: GENERAL RELATIVITY V QUANTUM MECHANICS

Recall from Chapter 2 that in relativity, there are no universal clocks or rulers. In fact, clocks and rulers are inseparable, and time and space are joined up into a four-dimensional spacetime fabric. Second, distance and time measurements are relative. Their malleability in special relativity is a consequence of the requirement that the speed of light through a vacuum must remain a constant to all observers, regardless of how they move. The speed of light also provides a universal speed limit according to Einstein; nothing, not even information, can surpass it. This constraint, in turn, keeps a check on causality. While relativity allows two observers to disagree on the order in which two independent events occurred, it preserves the cause-and-effect relationships between connected happenings.

General relativity, meanwhile, tells us that watches tick at a slightly different rate, depending on the massive objects around them. Take this one step further, and you see that every person and every object experiences its own personal flow of time.

Quantum theory—famed for its paradoxes—has an almost quaint view of space and time by comparison. Quantum equations assume that there is a universal background clock whose ticks are unaffected by the motion of the observer. They treat space as a static stage against which particles move, and they take for granted that time advances at the same rate everywhere. My ruler measures exactly the same inch as your ruler, and my watch ticks at exactly the same rate as your watch, no matter where we are or what we're doing.

Yet, the quantum world brings its own strangeness, thanks to its seemingly inherent uncertainty: Matter can switch between acting like a particle and a wave, apparently on a whim; influences appear to act outside of the bounds of spacetime; and future choices can affect past events. Section II of this chapter will sketch some of quantum theory's many vagaries—focusing, in particular, on those that may have implications for the nature of time. The first, "superposition," allows particles to take on multiple identities at the same time. The second, "entanglement," enables twinned particles to exert a ghostly and instantaneous control on each other, no matter how far they are separated—seemingly in contradiction of Albert Einstein's edict that nothing can communicate faster than light speed. The third, "wave-particle duality," concerns the ability of quantum entities to switch their identities, sometimes behaving like waves and other times acting as though they are discrete particles.

Section III will then turn to nascent attempts to derive a theory of quantum gravity by a cadre of physicists who are viewing the problem through the lens of time and causality. (JTF's Emergence review describes alternative approaches that are dedicated to the hunt for the quantum building blocks of space.) Approaches that investigate temporal uncertainty in the quantum realm suggest that time does not exist at the fundamental level—or at least, not as we know it. It may be that the microscopic domain admits a kind of "indefinite causality," in which one event can occur before *and* after another simultaneously—both causing it and being caused by it. This bizarre effect might even be harnessed to make proposed quantum computers—machines that are postulated to one day outperform today's best classical supercomputers at certain specific tasks—even more powerful than currently hoped.

Another major appeal of these models is that they may be experimentally testable using relatively inexpensive table-top lab tests; by contrast most predicted quantum-gravitational effects lie beyond the reach of even the world's most powerful billion-dollar particle accelerators. Some preliminary, but tantalizing, attempts to test these theories are described at the end of the chapter.

II. QUANTUM THEORY

Quantum theory was developed during the first half of the 20th century, in an effort to describe certain puzzling aspects of atomic behavior that were being revealed by cutting-edge experiments of the day. It starts from the understanding, attributed to Ludwig Boltzmann at the tail end of the 19th century, that the energy of a physical system, such as a molecule, increases in discrete jumps—it is 'quantized'—rather than growing continuously (Boltzmann, 1877). Similarly, in 1900, Max Planck proposed that an idealized object that absorbs all electromagnetic radiation that falls on it should only be able to radiate energy in chunks, not continuously (Planck, 1901). And in 1905, Einstein posited that electromagnetic radiation should be viewed not just as a wave, but also as being made up of bundles of energy, or quanta (Einstein, 1905a). This served to explain a peculiarity about the way that electrons are emitted when light hits a metal surface (Hertz, 1887) (see "The Photoelectric Effect"). Light can thus be thought of as being made of particles, or "photons."

Physicists began to use this new understanding of light and atoms to try to predict how they will behave in experiments. But in doing so they uncovered a series of startling consequences for the nature of reality on small scales that suggest we can never really know what is happening at the fundamental level with certainty. This has been verified again and again in the lab. Take a bunch of radioactive atoms, for example. Quantum theory is superb at predicting what fraction of the bunch will decay in a given time. It cannot tell you, however, when any one atom will decay, precisely. The equations only help you to calculate statistical probabilities about what will happen to a large ensemble.

To add to the fuzziness, certain pairs of particle properties—such as its position and momentum—are yoked together in such a way that you cannot know both at the same time. The more precise your measurement of one of the pair, the less certain your knowledge of the other becomes. You thus cannot know with perfect accuracy both where a particle is and where it is going, for instance. Werner Heisenberg articulated this with his famous "uncertainty principle," which essentially says that there is an impenetrable veil shrouding what we can ultimately measure about reality, no matter how advanced our technology (Heisenberg, 1927).

In fact, the textbook version of quantum theory—sometimes known as the "Copenhagen interpretation," in reference to the city where it was first formulated by Heisenberg and Niels Bohr—suggests that it makes no sense to think about definitive happenings at all, until we look.

Three weird quantum features that call our intuitive notions about time into question are outlined in detail below: (1) superposition and wavefunction collapse; (2) entanglement; and (3) wave-particle duality.

The Photoelectric Effect

When light hits the surface of a metal, electrons are released (Figure 7). Prior to the development of quantum theory, physicists interpreted this using the classical theory of electromagnetism. They reasoned that light is a wave that continuously imparts energy to electrons in the material. When enough energy has been absorbed, electrons should bubble off. They predicted that if they reduced the intensity of light hitting the surface, it would take longer for the electrons to gain enough energy to escape—but eventually they would.

That's not what happened in experiments, however. Instead, electrons would only be peeled off the surface if the light exceeded a certain frequency. If the frequency of incident light was too low, electrons would never escape, regardless of how high the intensity of light was, or how long it shone on the material.

Einstein realized that light is made up of packets of energy called photons. Each packet carries an energy that is proportional to its frequency. Electrons could only be released from the material if the photons carried a high enough frequency, and thus energy. So low-frequency photons could not trigger electron emission. Einstein's reasoning helped to establish the dual nature of light as both a wave and a particle.

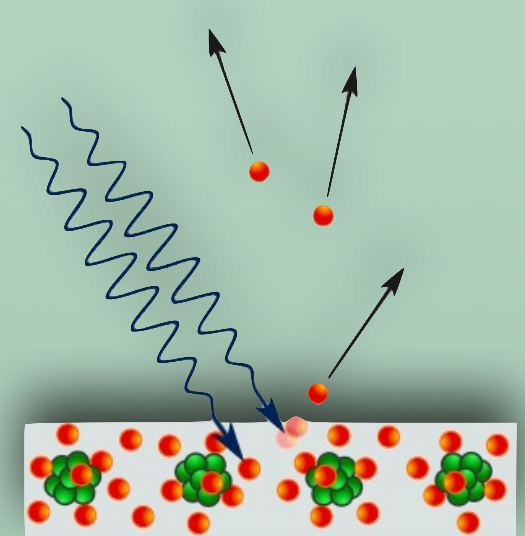

Figure 7: Photons transfer energy in discrete bundles, enabling electrons to escape a metal surface. (Image credit: Ponor, shared under the creative commons license CC BY-SA 4.0.)

1. Superposition and Wavefunction Collapse

Under the rule of quantum law, particles are governed by probabilities, not certainties. Until someone comes along to measure them, particles are not strictly here or there; they do not spin definitively this way or that; their energy does not take a specific value. Physicists can write equations that describe the probability of finding a particle in a particular state, in a specific location, or with a certain amount of energy upon observation. But crucially, until a measurement forces the particle to "choose," the particle exists in all possible states at once. And when the choice is made, it is at random. There is no way to predict in advance with certainty which result will be found.

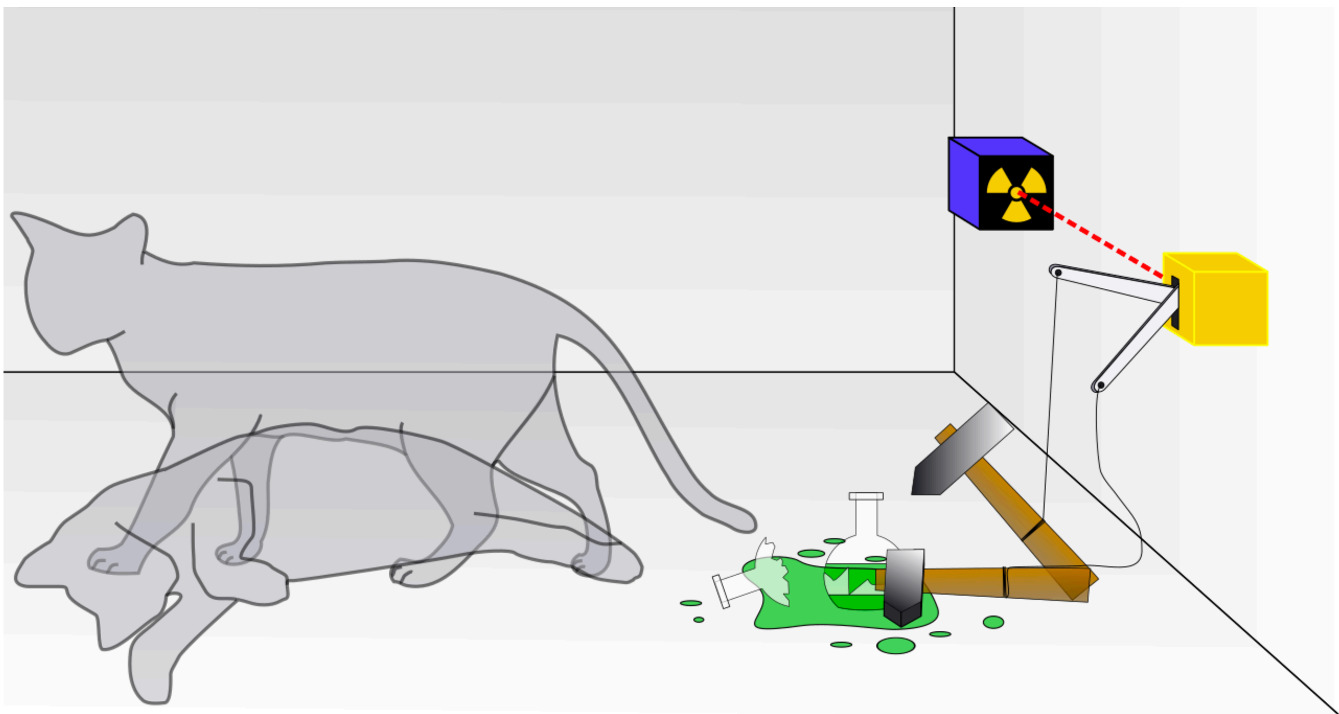

Figure 8: While the box is closed, Schrödinger's cat is in a superposition of being alive and dead. Opening the box seals its fate. (Image credit: Dhatfield shared under a creative commons license CC BY-SA 3.0).

Physicists call the bizarre state that encompasses the myriad future possibilities that any one quantum object can possess a "superposition." In the 1920s, Erwin Schrödinger developed an equation to track such fuzzy states (Schrödinger, 1926). They are mathematically described by a "wavefunction"—an entity that encapsulates all possibilities prior to measurement. Upon measurement, the textbook tale of quantum mechanics goes, this wavefunction 'collapses' from multiple potentialities to one set identity.

The oddness of superposition has been most notoriously illustrated by Schrödinger's unlucky (and imaginary) cat, trapped in a box with a vial poison that will be opened if a radioactive atom decays (Figure 8). Since radioactivity is a quantum process, unless the atom is observed, Schrödinger mused, it will be in a superposition of having decayed and not decayed. Consequently, until someone checks on the famed feline's viability, by opening the box, it exists in a superposition of the alive and dead states.

The Crystallizing Block Universe

Relativity led physicists to a vision of the universe in which the past, present, and future all exist as part of a four-dimensional block (see Chapter 2, section II.1). Yet that model implies that the future, like the past, is already determined, diverging wildly from human experience. But the uncertainty of quantum mechanics could offer an escape—giving us back the flow of time and an open, unwritten future.

Instead of a block universe that simply is, George Ellis and Tony Rothman imagine one that crystallizes over time (Ellis & Rothman, 2010). Quantum mechanics, they point out, comes with a "now" built right in. It is the moment when the wavefunction collapses, or resolves, into one particular state. At that moment, quantum uncertainty crystallizes into the definiteness of the everyday world—transforming a universe of possibilities into one actuality. Wavefunction collapse thus marks a hard boundary between the fixed past and the still-open future.

But the crystallizing block universe is not exactly a throwback to the old master clock that prevailed before Einstein. It still respects relativity. In the crystallizing model, time does not roll out uniformly everywhere. Say, for instance, two photons, created in the same instant, head toward a physics experiment where they will be observed. Prior to observations both are in superpositions. One may hit the apparatus before the other, however. If so, it would move into a fixed past just a little sooner than the other. So there is no universal "now"—in line with Einstein's predictions—yet, time still flows for each individual and their future remains open (Figure 9).

The crystallizing block universe thus suggests a new way of thinking about time that is both familiar and alien.

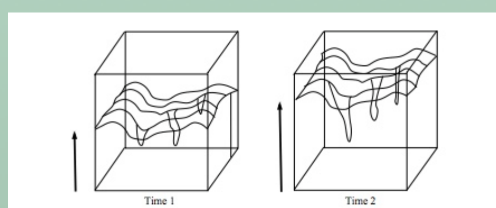

Figure 9: In an evolving curved space-time picture, small pockets of potentiality remain unresolved till later times. (Image credit: George F. R. Ellis and Tony Rothman, arXiv:0912.0808.)

Schrödinger dreamed up this thought experiment to show just how ridiculous he considered contemporary interpretations of quantum mechanics to be. But in the intervening decades, experiment after experiment has verified this weirdness in the lab; physicists have placed molecules containing up to 2,000 atoms into superposition (Fein et al., 2019). The uncertainty at the heart of quantum mechanics appears to be intrinsic and foundational. And to some, it may offer a way out of general relativity's block universe (see Chapter 2, section II.1), in which the future is just as set as the past (see "The Crystallizing Block Universe").

It's also worth noting that physicists do not yet fully understand what happens when the wavefunction collapses—nor do all agree that a collapse happens at all. This has led to the development of multiple interpretations of quantum theory and modified versions of the theory. It may never be possible to discriminate between many interpretations, since by construction they are usually designed to make the same predictions. However, some extensions to quantum theory—notably collapse models, which propose specific physical collapse mechanisms—are testable, and physicists have already succeeded in constraining their parameters (Carlesso & Bassi, 2019) and recently even ruling out the most basic versions of some models (Donadi et al., 2021). It is beyond the scope of this review to discuss them all. Section II.3 below discusses one possibility, "retrocausality," in depth, because of its profound implications for the nature of time. Table 1 lists some other prominent quantum interpretations; however, it is by no means exhaustive.

Table 1: Some popular interpretations of quantum theory.

Interpretation	Development Date	Primary Developers	Description
Copenhagen	1920s	Niels Bohr & Werner Heisenberg	Measurement causes wavefunction collapse; it is meaningless to ask what the system was like before looking (Faye, 2019).
De Broglie-Bohm Theory	1920s (de Broglie) & 1960s (Bohm)	Louis de Broglie & later David Bohm	Quantum systems have definite properties; particles are guided by the wave function; our uncertainty reflects our lack of understanding about the system—it is not inherent (de Broglie, 1959; Bohm, 1952).
Many Worlds	1950s	Hugh Everett III	There is no wavefunction collapse; upon measurement, reality splits to create parallel universes in which each possible outcome of a quantum experiment is realized (Everett, 1957).
Collapse Models, e.g. GRW theory; Penrose-Diosi model	1980s	Giancarlo Ghirardi, Alberto Rimini & Tullio Weber; Lajos Diósi & Roger Penrose	Collapse will be triggered by gravity or another interaction when a system reaches a certain threshold, in mass, say (Ghirardi et al., 1980; Diósi, 1987; Penrose, 1996).
Retrocausal interpretations	First explored in 1940s	John Wheeler & Richard Feynman	Wheeler and Feynman's "absorber theory of radiation" posited that the emission and absorption of electromagnetic radiation can be represented as an electromagnetic field made up of two different solutions to Maxwell's equations: one moving forward in time and one moving backward (Wheeler & Feynman, 1945; Wheeler & Feynman, 1949).
		Costa de Beauregard	De Beauregard developed a solution to the EPR paradox, by which one member of an entangled pair could send a wave traveling backward in time to influence their shared past (Costa de Beauregard, 1953).

Interpretation	Development Date	Primary Developers	Description
		John Cramer	The transactional interpretation, first proposed by John Cramer in the 1980s, builds on the framework developed by Wheeler and Feynman, and describes a quantum event as a "handshake" between two waves, one traveling forward in time and one traveling backward (Cramer, 1986).
		Ken Wharton	"All-at-once" Lagrangian models allow the universe to "fill in" the dynamics of physical systems given both initial and final boundary conditions (Wharton, 2015).
Quantum Bayesianism	2000s	Christopher Fuchs, Carlton Caves & Rüdiger Schack	Quantum theory is personal; it allows an agent to update her beliefs about a system—but cannot tell you about the objective state of the system (Fuchs, 2010).

If superposition were not strange enough, it also leads to a second bizarre quantum phenomenon—entanglement—which suggests that quantum influences are somehow mediated outside spacetime, as described in the next section.

2. Entanglement

Schrödinger was not the only physicist to highlight the apparent absurdities of quantum mechanics. Einstein too was deeply troubled by aspects of the new theory, in particular the notion that particles had no definitive properties until they were measured. His theory of relativity makes no room for this kind of uncertainty. Whatever you wish to measure—the position or velocity of a particle, the strength of a gravitational field—has a definite value at a particular point in space and time.

In 1935, Einstein and Boris Podolsky and Nathan Rosen described a thought experiment that highlighted a worrisome feature (Einstein et al., 1935). Imagine two photons that are created together, such that their joint momentum is conserved, and sent off in opposite directions. The momentum of one photon is now connected with its partner's, so that, for instance, if you measure the first to be traveling East at a certain speed, you instantly know the other must be traveling with the same speed West. There is nothing too mysterious about this, so far; anyone that has played pool will know that the motions of colliding balls on a table are interlinked.

But an uncomfortable problem arises when you remember that until they are measured, the properties of quantum particles—unlike balls on a pool table—are not defined. That means that the momentum of the first photon is not set until you observe it, at which point it is fixed at random. Yet, when you make a measurement of one of the particles, the second particle automatically and instantaneously assumes the opposite value. The particles are far from each other, so there is no possibility that they are "talking" with one another. They appear to have communicated with each other at a speed that is faster than light can travel between them. This defies Einstein's relativistic prescription. This connection, which stretches across all space, is now called "quantum entanglement."

It's the injection of quantum randomness that makes entangled particles so weird. Think of them as a disagreeable husband and wife who always have opposite preferences. If one wants to see a movie, the other is sure to want to stay home. If she is in the mood for Italian, he will surely be craving Thai food. The really odd part is that this holds true even if they haven't conferred at all about the evening's plans.

So, what is going on?

Surely, Einstein lamented, human observers were missing out on some important information, some "hidden variables" that would resolve a definite answer from the statistical fog. In the case of our ornery spouses, the hidden variable could be the weather. Perhaps the wife thinks that rainy evenings are just the ticket for a night at the movies, while the husband gets exhausted just thinking about his umbrella. They don't have to talk to each other to know that they will be at odds about the evening's plans; they just have to look at the sky.

Similarly the values of hypothetical hidden variables, set within entangled pairs when they are created, might also determine the outcomes of later measurements of the photons. The results of the experiment would only *appear* to be random to us because we cannot access these variables and plug them into our calculations. But there would be no inherent uncertainty in reality itself.

For years, physicists investigated the possibility that such hidden variables exist and serve to lock in the outcome of entanglement experiments from the start. But years of theoretical work, most famously by John Bell, followed later by high-precision experiments, have shown that hidden variables like this are impossible in the quantum world (Bell, 1964; Guistina et al., 2015; Henson et al., 2015; Shalm, 2015). These experiments have struck down the possibility of hidden variables, at least in the form that Einstein wanted,[2] and reinforced the idea that superpositions, ridiculous or not, really do exist.

Most physicists have taken experiments like these to suggest either that things in one location can somehow affect things in another location without touching or making a physical connection, or that "reality" simply doesn't exist independent of observation. These ideas have rattled plenty of physicists. Einstein famously objected to both, rejecting the former with the derisive nickname "spooky action at a distance" and the latter with a question—"Does that mean the Moon is not there when I am not looking at it?" Yet most physicists now accept them as essential principles in the alien logic of quantum theory.

Entanglement thus hints that quantum influences can act beyond the traditional limits set by spacetime. (JTF's Emergence review explores the possibility that the quantum is in fact the most fundamental aspect of reality and that space emerges from it.) Experiments revealing a third peculiar quantum feature—wave-particle duality, described next—stretch our intuitions about the nature of time and causality, still further.

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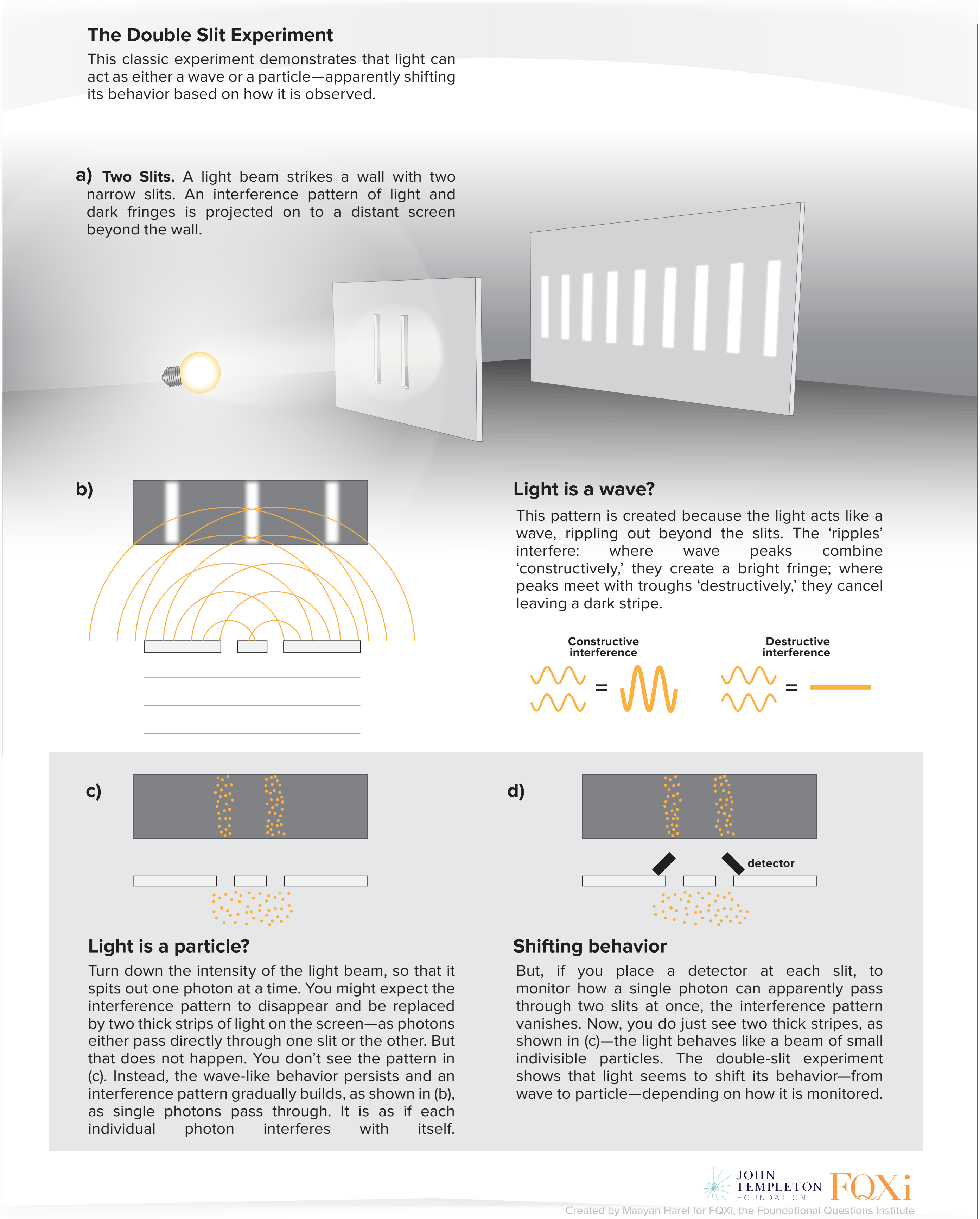
[2] de Broglie-Bohm theory, listed in Table 1, is an example of a quantum interpretation that today still posits the existence of hidden variables. However, these variables are not the sort that could appease Einstein because they still allow for instantaneous influences across huge distances. They do serve to remove the inherent randomness from quantum theory, however, which is why they hold appeal for many physicists.

3. Wave-Particle Duality and the Road to Retrocausality

Figure 10: The Double-Slit Experiment. (Image created by Maayan Harel.)



Many of the paradoxes that have bloomed around quantum theory can be broadly described as "particles knowing things they shouldn't know." This is exemplified by the iconic double-slit experiment —which was initially used to establish that light is a wave (Young, 1802), but is now used to showcase the dual nature of light as both a wave and a particle—and by the mind-boggling delayed-choice experiment (Wheeler, 1978). These tests, described in detail below, have led some physicists to propose a time-twisting interpretation of quantum theory in which future events can influence the past.

(i) The Double-Slit Experiment

In 1801, Thomas Young performed a classic experiment in which he shone light on to a wall which contains two slim cuts (Figure 10). Beyond the wall lay a screen on which an extended interference pattern of bright and dark stripes appeared (Figure 10a). This is just what physicists would expect to see if light is a wave. It's like a water wave passed through a bed of rocks, rippling out on the other side, with those waves creating an interference pattern beyond (Figure 10b).

But what happens when you turn down the intensity of your light source, so that it is spitting out one photon or particle of light at a time? You might guess that the experimenter sees two bright stripes: a simple projection of the light passing through the slits, like bullets through the gaps in the wall (Figure 10c). Instead, however, she still sees an interference pattern, as in (b). This is interesting in and of itself: Even though the photons were being fired off one by one, like particles, their interference pattern reveals that they were also acting as if they were somehow passing through both slits simultaneously—like a wave with peaks and troughs that summed up to create the pattern of "fringes."

It gets even weirder. Say that the experimenter wants to catch the photons in the act of passing through one or other of the slits, to try and work out how they are managing to build up an interference pattern. So she rigs a new set-up that will tell her which slit each photon is passing through on its way to the screen. Then she runs the experiment again. But now, suddenly, the interference pattern disappears. This time, each photon only passes through either the left or the right slit. And so the image on the screen is a simple projection of the two slits, as in Figure 10d. Somehow, the light seems to "know" what kind of experiment it is participating in and adjust whether it will behave like a wave (b) or like a beam of particles (d) accordingly.

This mind-boggling feat led John Wheeler to proposed an even more cunning experiment, in the 1970s, that would force photons to change their "choice" mid-test: the delayed-choice experiment.

(ii) The Delayed-Choice Experiment

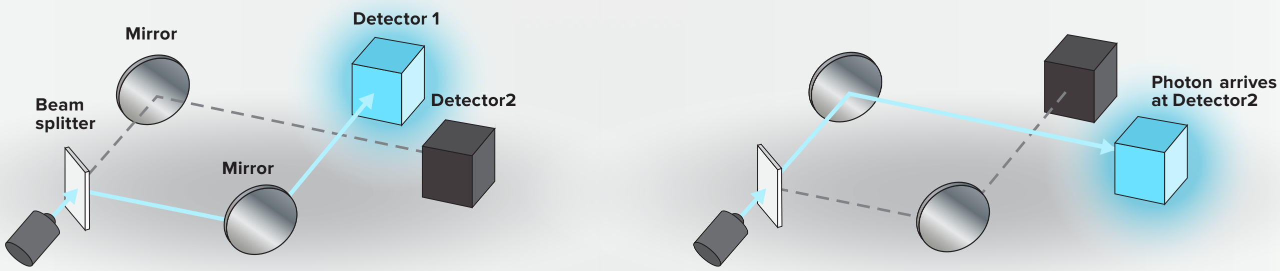
The delayed-choice experiment aims to force photons to explicitly "choose" to act like either waves or particles at the start of a test—before the experimenter sneakily changes the experimental set-up midway to see if the photon shifts its identity to match the new conditions (Figure 11). It uses either one or two "beam splitters"—a kind of mirror that divides the light waves and sends them along two perpendicular paths—and a number of light detectors to tell you which path (or paths) the light took during the test. With only one beam splitter in the apparatus, the light will behave like a particle, moving along either one path 50% of the time or the other path 50% of the time (Figure 11a). But when two beam splitters are employed, the light acts as a wave, moving through both paths simultaneously and then recombining, so you can map out the peaks and troughs of the interference pattern. In this case it will only ever exit one arm of the apparatus, being detected 100% of the time at the same detector (Figure 11b).

The Delayed Choice Experiment

The aim of this experiment is to trick photons to explicitly "choose" whether to act like waves or particles at the start of a test—and then modify the experiment midway to see if this influences their identity (a). One type of delayed-choice experiment uses either one or two "beam splitters"—a kind of mirror that divides the light and sends it along two perpendicular paths—and a number of light detectors to tell you which path (or paths) the light took during the test. With only one beam splitter in the apparatus, the light will behave like a particle, moving along either one path 50% of the time or the other path 50% of the time, as in (a). But when two beam splitters are in play, the light acts a wave, as in (b).

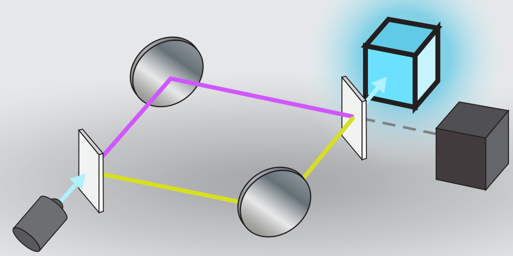
Particle behavior

(a) When light is fired at a beam splitter, it acts as though it is made up of a beam of indivisible photons. Each photon will travel along one path or the other, at random. So each of the two photon detectors registers a count 50% of the time.



Wavelike behavior

(b) When a second beam splitter is introduced, the light switches behavior. Each photon that enters splits like a wave—travelling down both paths. The two waves are recombined by a second splitter. They then add up constructively, on the path to one detector, but destructively along the path to the second detector, canceling out the signal. So, only one detector fires, 100% of the time.



Shifting behavior?

(c) You can switch set-up midway through the experiment to try and trick the light. Start with only one splitter and let a photon enter the apparatus. It *should* take only one path. *Then* suddenly add the second splitter. You will find that only one detector fires, implying that the photon was acting like wave all along—splitting, traveling along both paths and then recombining. But why would the photon 'choose' to act like a wave at the start? How could it 'know' that you would later change the experiment? The delayed-choice experiment suggests to some physicists that choices made by the experimenter *later* can affect the behavior of light at *earlier* times.

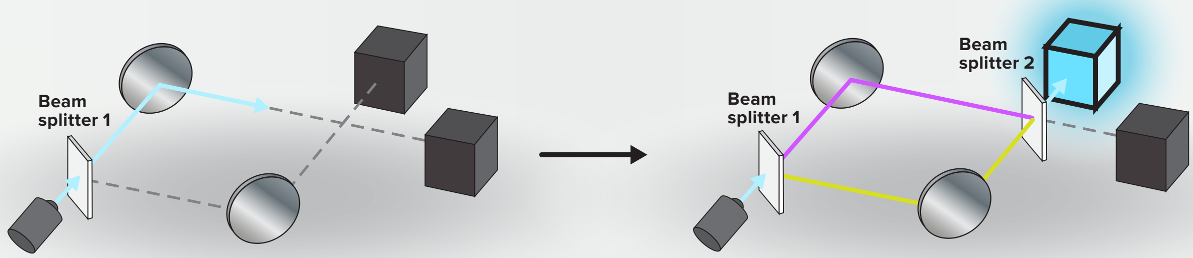


Figure 11: The Delayed-Choice Experiment. (Image created by Maayan Harel.)

Created by Maayan Harel for FQXi, the Foundational Questions Institute

Wheeler's insight was that you could wait until the experiment had already begun—that is, until the photon was already inside the apparatus—and then switch the conditions. So, you can start off with just one beam splitter when the photon enters the device, presumably stimulating it to act like a particle. But then, after the photon is safely inside, you can decide whether to insert the second beam splitter. Wheeler predicted that inserting the second splitter would result in the light acting as a wave (Figure 11c). If so, it would mean that the light must have had to have "chosen" to act like a wave from the start—even though the initial set-up should have inspired it to act like a particle. It would be as if the light based its earlier decision on some foreknowledge of what the experimenter's later choice would be.

Wheeler's version was a thought experiment, but a number of research teams have actually tried it and, sure enough, got the result Wheeler predicted (Jacques et al., 2007). It's obviously a stretch to anthropomorphize photons and talk about them making choices and having knowledge (advance or otherwise) of a human's actions. Nonetheless it is almost as if your decision to remove or retain the second splitter travels back in time influencing the light's earlier behavior. Experiments such as these have led some physicists to develop a retrocausal interpretation of quantum mechanics.

4. Retrocausality

Ken Wharton and Huw Price have described the implications of quantum experiments thus: "The consensus is that Einstein can't have what he wanted—a real world in space and time, without action-at-a-distance" (Wharton & Price, 2016). Indeed, all quantum interpretations over the years have been forced to give up at least one of these cherished common-sense notions. (Of the interpretations listed in Table 1, Copenhagen, Many Worlds, and Quantum Bayesianism reject the idea that quantum theory can lead you to a single objective reality that exists independent of measurement, while de-Broglie-Bohm and collapse models must accept action-at-a-distance, despite any apparent spookiness.)

But Wharton and Price are part of a camp of researchers who see an alternative avenue in which you can keep reality and do away with action-at-a-distance—but at a cost: causality must be sacrificed. They point out that all of these experiments can be explained if you allow for the possibility that causes can come *after* effects. This concept, called "retrocausality," allows the universe to puzzle out what happens at times and places that aren't observed or measured. In the retrocausal picture, Einstein's moon is perfectly real, even when no one is looking.

One way to imagine retrocausality is if you think of the universe as a book. A conventional writer would set the story down word by word, page by page, with each twist and turn flowing from what came before. A retrocausal writer, on the other hand, knowing key plot points throughout the narrative, would flesh out the story using information from pages both ahead and behind. The twist is that the "writer" in this case is physics itself, and the book comes together all at once rather than being composed in some time outside of time (Wharton & Argaman, 2020).[3]

Emily Adlam has compared the situation not to a book but to the sudoku puzzle you might solve in your Sunday paper. In the retrocausal picture, she has written, "the course of history is determined 'all at once' by external, global laws of nature, in much the same way as the rules of the game of sudoku

[3] There is a precedent for this kind of description in physics. While physicists traditionally work out the motion for a system by taking the starting conditions, applying equations of motion, and seeing how they evolve over time, it's also possible to work from both sides at once. The key is to find the solution that has the lowest "action," a term that describes how the system's energy changes form between the starting state and the ending state. The first example of such a solution is credited to French mathematician Pierre de Fermat, who realized that a light ray will always take the quickest route from point A to point B, no matter what substances it passes through on the way. It's almost as if the light "knows" where it will end up.

apply to the whole grid at once rather than dictating the entries column by column from left to right" (Adlam, 2018).

One advantage of this approach, argue Price and Wharton, is that it resonates with something that physicists have long known about the fundamental equations of physics (Price, 2012). These equations are all said to be "time symmetric" because they work just as well when you run time forward as when you run it backward. (This time symmetry holds a mystery of its own: If the fundamental laws of physics make no distinction between past and future, then why does time only seem to flow one way? In Chapter 4, we will look at the search for the origin of the "arrow of time," and how it has led physicists, philosophers, and astrophysicists to very different conclusions about the nature of time itself.)

Other physicists engaging in attempts to unite quantum theory and general relativity have noticed their equations have an even weirder property: time vanishes from their calculations entirely, suggesting that, at the fundamental level, time may not exist at all.

III. QUANTUM GRAVITY: UNITING QUANTUM THEORY AND GENERAL RELATIVITY

1. Building a Quantum Clock

In the 1960s, hoping to work out a new mathematical unification of quantum physics and general relativity, Wheeler and Bryce DeWitt landed on a surprising result: when they reworked the Schrödinger equation so that it incorporated gravity, time dropped out of the equation entirely (DeWitt, 1967). Since physicists usually use equations to work out how their systems might evolve over time, this raised quite a conundrum. Did it imply that at a fundamental level, time simply does not exist? Quantum physicists have been struggling to understand that result ever since.

Twenty years later, Don Page and William Wootters came up with an answer: the passage of time could be recovered, if the universe is divided into entangled sections, with one part able to observe time evolution in the other (Page & Wootters, 1983). They came to this conclusion while developing a new way of defining time that didn't rely on a perfect, universal clock; after all, clocks like that don't exist anyway. Instead, Page and Wootters proposed keeping time with something natively quantum—an electron's spin, say, or the direction of a photon's polarization (the direction along which it vibrates).

This quantum clock could be considered as separate from the rest of the universe system, but would be yoked to the rest of the system via entanglement. One feature of entanglement is that when two things are entangled, it is impossible to fully describe either independently; you can only talk about their joint properties. Thus, when you tell time with a quantum clock, you discover that time cannot exist in isolation: it emerges from the relationship between different quantum systems. Andrei Linde has interpreted this result as implying that time cannot exist in a universe without an observer (though this observer does not necessarily need to be conscious—it may be an inanimate recording device) (Merali, 2017).

The notion of a quantum clock lay dormant for decades, but is now undergirding a whole collection of new approaches to describing time in quantum physics (Giovannetti et al., 2015). Lorenzo Maccone, Marco Genovese and their colleagues are developing a host of experimental tests of quantum clocks, for instance. In 2014, they proposed using a photon's polarization as a quantum clock. Although they couldn't do very much with a polarization clock—it could only tell two different times, like a digital watch that displays noon and midnight and nothing in between—their preliminary results confirmed Page and Wootters theoretical result. When they entangled their quantum clock with another quantum system and viewed the two as a united whole, they could measure no change: time had vanished. But when they measured them in isolation, they could mark the evolution of one entangled segment in relation to its partner: time was recovered (Moreva et al., 2014).

The researchers are currently working on a new model for a quantum clock, based on the position of a photon rather than its polarization (Moreva et al., 2017). Like an analogue clock, the new photon clock moves continuously through all possible positions, so it can be used to measure the state of the system at any time. Again, they have found that an observer inside the system will see time flowing—she will have memories of events that happened at particular times on the clock—while someone outside the system sees correlations between the system and the clock, but perceives no global evolution over time.

But while these ideas were developed within a framework that sought to unite quantum theory with gravity, these quantum-clock experiments do not involve gravity itself. However, a range of others are attempting to probe aspects of the interface of quantum theory and gravity in the lab. They are already revealing some peculiar consequences for causality.

2. Indefinite Causality

(i) Table-Top Tests

To unite the disparate theories of general relativity and quantum mechanics, it seems natural to look for places where their regimes overlap, where both gravitational and quantum effects should be large enough to measure. Exploring these situations could lead to a theory of quantum gravity, and to a deeper understanding of the origin of time. The trouble: While astrophysicists speculate about how quantum mechanics and gravity could bind together in the tiny, dense heart of a black hole, or in the roiling soup of the early universe, such extremes are difficult or impossible to replicate on Earth. Meanwhile our best current candidate models for unifying physics, such as string theory, predict effects that may only be tested using particle accelerators (see JTF's Fine-Tuning review for a run-down of such future planned experiments).

Yet, over the last few years, physicists have begun inching closer to laboratory tests of predicted effects at the interface between quantum theory and gravity. In 2017, two groups, one led by Sougato Bose (Bose et al., 2017) and a second by Chiara Marletto and Vlatko Vedral (Marletto & Vedral, 2017a), proposed similar experiments that could reveal whether space and time themselves exhibit the same kind of bizarre quantum behavior that particles do. Their proposals begin with an insight credited to Richard Feynman (Feynman, 2011). Feynman imagined a mass being set into a superposition so that it has equal odds of being found in two different locations. If the rules of quantum mechanics apply to gravity, the gravitational field near the mass must also be in a superposition—and so spacetime itself must also be in a corresponding state of superposition. Time and space themselves become fuzzy.

This puts physicists who want to marry quantum mechanics with general relativity in a bind. Does it even make sense to talk about making a measurement, or doing an experiment, without referring to a particular place and time? It's like trying to time a sprinter who's running on a track you can't measure using a stopwatch you can't read.

Yet Bose, Marletto, and Vedral are laying the groundwork for tests that could expose just this kind of weirdness. In similar proposals, they suggest using a pair of devices to set two identical masses into superposition. In some states, the masses pass close by each other and feel each other's gravity. In other states, the masses stay far from each other and barely interact at all. In theory, it should be possible to check whether the gravitational field really does enter a superposition (Marletto & Vedral, 2017b).

No laboratory is ready to perform experiments like these quite yet, but the authors claim they are reasonably close to fruition and could be carried out on a table top—at a fraction of the price of billion-dollar particle-accelerator experiments. If they could show that the gravitational field can be in a superposition of states, that would mean that spacetime itself follows the strange rules of quantum mechanics, and the flow of time would be just as probabilistic as the quantum state of an electron. The implications would be even weirder than simply finding that my watch disagrees with yours: not just the pace of time, but cause and effect get jumbled up.

The Quantum Switch: Powering Quantum Computers with Indefinite Causality

Quantum computers were first conceived in the 1980s, by Paul Benioff and independently by Richard Feynman and Yuri Mann. They realized that such devices could encode data in quantum bits—or qubits—that didn't just flip between the binary digits of 0 and 1, but could encode a superposition of both. Such qubits could be strung together using entanglement allowing them to perform operations in parallel at superfast speeds, enabling them to outperform today's classical machines at certain specific tasks. Various groups are engaged in trying to harness these quantum effects to build the first quantum computer that unambiguously beats its best classical competitor. (In 2019, a group working with Google reported their quantum computing chip had succeeded in carrying out a task in 200 seconds that would have taken the world's leading supercomputer 10,000 years (Arute et al., 2019). In 2020, physicists in China reported that their photon-based quantum computer took 200 seconds to perform a calculation that it is estimated would require 2.5 billion years for a classical supercomputer (Zhong et al., 2020).)

Giulio Chiribella's group has taken this idea a step further and, building on a suggestion by Lucien Hardy (Hardy, 2009), they have argued that it may be possible to build quantum computers without definite causal structure using a "quantum switch" (Chiribella et al., 2009, 2013). While conventional quantum computers take advantage of the superposition of qubits, a quantum switch exploits the superposition of entire circuits. In a quantum switch, two communication circuits—one traveling from point A to B, and a second traveling from B to A—are put into superposition. As messages are sent along the wires, it becomes impossible to say whether a message from A caused a particular outcome at B or the other way around: Both are true. In 2014, researchers in Austria demonstrated the quantum switch for the first time in the lab (Procopio et al., 2015), showing that the switch made it possible to check the relationship between two quantum logic gates more efficiently.

Quantum communications researchers are also working to identify specific situations in which a system built with quantum switches might have an edge over other quantum systems. They have shown that the quantum switch could make it possible to achieve "perfect quantum communication"—that is, to copy a quantum state without losing a single detail—even on a noisy communication channel (Chiribella et al., 2021), and could also speed up the rate of communication (Ebler et al., 2018). Using a table-top setup involving a single photon "message," Chiribella and his colleagues have demonstrated this communication advantage.

Quantum switches can also solve certain classes of problems faster than traditional quantum computers, specifically by cutting down on the amount of communication required between multiple parties trying to compute together, as in distributed computing (Guerin et al., 2016; Wei et al., 2019).

Časlav Brukner and his colleagues have argued that it might even be possible to create a quantum switch using gravity (Zych et al., 2019).Their proposal starts with a mass in a superposition of states. Then, they imagine that the mass is flanked by two identical, synchronized clocks. (Call them A and B.) The closer the clocks are to the massive object, the faster they tick. If the massive object is closer to clock A, then clock A will be ahead of clock B. If the object is closer to clock B, B will run faster than A.

Now imagine that the superposition is arranged such that the mass is in two different locations at once: one next to A, and the other nestled up close to B. Because of gravitational time dilation, the time on clock A is ahead of B, and the time on clock B is ahead of A. Events that happen at A happen both before and after events at B.

(ii) Causaloids

The idea that causes come before effects is so basic that it seems foolish to interrogate it. Causes *cause* effects: It's right there in the words themselves. It is the assumption that silently underlies almost every physics experiment ever performed. How can we understand time if the order of things is uncertain?

In 2005, hoping to make progress toward a theory of quantum gravity, Lucien Hardy began looking for ways to combine the wildest aspects of quantum mechanics and relativity. He hoped to retain quantum mechanics' probabilistic essence—its insistence that, before they are measured, particles exist in many states at once—and marry it with relativity's dynamic treatment of time (Hardy, 2005). Hardy began composing a new notion of spacetime based on something he calls the "causaloid"—a mathematical construction that captures causal connections between events without using the sort of "background" time that quantum mechanics invokes. One of the strangest features of this approach is that it allows quantum uncertainty to burrow even deeper into the heart of physics, all the way to our basic notion of cause and effect.

Yet, as researchers explored Hardy's causaloid, they discovered situations in which cause and effect really are indistinguishable (Oreshkov et al., 2012). Časlav Brukner makes an analogy to a bizarre game of dominoes, in which it is impossible to say whether the first domino caused the last to fall, or the other way around (Brukner, 2018). The domino set is in a superposition of two states: one in which the first domino toppled the last, and a second in which the last domino toppled the first.

This "indefinite causal structure" could have practical advantages, however, potentially driving a new generation of quantum computers (see "The Quantum Switch"). Experimental physicists are already implementing preliminary set-ups in which they can demonstrate a weird mixing of causal relationships between photons (MacLean et al., 2017). But a full test of the claimed benefits of indefinite causality is still to come.

3. Recovering Causality

Given this indefinite causal structure, spacetime seems to descend into a mush in which it is impossible to describe space and time separately, even in approximation. So how do we get back to a physical picture we can handle? Hardy is hoping to show that it is possible to recover definite causal structure by setting up a "quantum coordinate system" that works in the vicinity of a particular point, even if it does not work at every point in space (Hardy, 2020).

Flaminia Giacomini and her colleagues, meanwhile, have also calculated that while entangling two quantum clocks with a gravitational field (Castro-Ruiz et al., 2020) should indeed jumble causality, a familiar, linear version of time reappears when you view the world from the perspective of one of the quantum clocks. Jump into the other clock's reference frame, and time unspools normally there, too. Whichever clock's reference frame you choose, however, the other clock continues to look quantum. Conceptually, it seems analogous to the quantum-coordinate system that Hardy is developing, though it is too soon to say if the approaches will turn out to share a mathematical underpinning. Yet both point toward a similar explanation for the persistence of time amidst such quantum weirdness; it's just a matter of perspective.

Restoring the familiar cause-and-effect relationship in our everyday world is tied to another puzzle about the nature of time. Just why do humans experience time flow in one direction? Chapter 4 turns to attempts to explain the origin of time's arrow.

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4. THE ARROW OF TIME

Whatever time is, we know one thing for sure: the *arrow of time* points only one way. We grow older, not younger. We remember the past, not the future. And as much as we might want to be able to rewind it all at will—to take back the unkind word, capture the opportunity lost, or just relive the good parts—we simply can't. Like it or not, it's an essential part of the human condition.

But is it really an essential part of physics? We *feel* that something so basic to human experience must also be fundamental. The laws of physics don't seem to care about our feelings, however: They make no distinction between past and future. Wind the clock backwards or forwards, and the laws of physics still look the same.

As they seek to understand how physics could stay silent on something so fundamental, scientists and philosophers have shown that the arrow of time actually takes many different forms. There is the "memory" arrow, which accounts for the fact that we remember the past and not the future. There is the "causal" arrow, which places causes before effects, and not the other way around. Humans experience an "aging" arrow, which specifies that we get older, not younger. Many of these arrows sit close to our human experience of time, which we will be discussing in more detail in Chapter 5.

But in this chapter, we will focus on the arrow of time that is most tractable to physics: the thermodynamic arrow of time. Physicists in the 19th century were acutely interested in how heat and energy flowed in engines, and their explorations codified the branch of physics we now know as thermodynamics. Applying the rules of thermodynamics to the universe as a whole has given physicists insights into how conditions in the early cosmos could have wound the universe up like a clock and generated the arrow of time. But it also raises mysteries about exactly how this happens, inspiring physicists to investigate the idea that we live in a multiverse of many neighboring universes, or alternatively to examine the roles of gravity, complexity, and causality in generating time's arrow.

And finally, some physicists are taking an interdisciplinary approach to try to explore how the thermodynamic arrow may be combined with information theory to help explain our personal perception of time and decision-making.

I. THE THERMODYNAMIC ARROW OF TIME

1. Entropy

Almost all physical laws are reversible in time. The equations governing the motion of particles in the microscopic realm, for instance, work equally well whether time runs backwards or forwards.[4] But there is one classical law that applies to our everyday experience that has a built-in timeline: the second law of thermodynamics. This law applies to any system, from a mundane box of gas to the cosmos in all its glory, that is "closed"—that is, any system that neither gains nor loses energy. The law says that, with the exception of brief statistical blips, the system's "entropy"—often popularly defined as a measure of its disorder—can never decrease over time. This is why cracked eggs don't put themselves together again, fragments of shell clicking into place like puzzle pieces; why deflated balloons don't spontaneously refill and rise up again in time for your next birthday; and why dropped ice cream cones can't unsplat. Broken things can't fix themselves.

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[4] In Chapter 3.II.1, we noted that quantum-wavefunction collapse provides an exception: an irreversible process at the microscale. It is worth noting that physicists are taking preliminary steps to relate the arrow of time with quantum processes such as entanglement (Goldstein et al., 2015; Linden et al., 2009; Malabarba et al., 2014; Reimann, 2008; Short & Farrelly, 2012).

But what is entropy, exactly? 19th-century physicists landed on what is now the standard technical thermodynamic definition: Entropy is the number of different ways you can arrange a system without changing it into something perceptibly different (Boltzmann, 1877). (In section III, we will meet another complementary definition of entropy, from computation and information theory.)

Physicists often cast the thermodynamic definition of entropy in terms of a box of gas particles. Some of the particles are whizzing speedily around the box while others bob about languidly. If all the fast-moving particles are on one side and all the slow-moving particles are on the other side, the box will have a hot side and a cold side. In the language of thermodynamics, the gas in the box has low entropy: it is highly ordered. But once all the particles have mixed and settled into equilibrium, and the temperature is the same all over the box, it doesn't matter how you rearrange the individual particles: the overall state of the gas stays the same, meaning that the gas is at its maximum entropy.

Or, for a more familiar example, consider lunch. A composed salad, with each roasted pepper and cheese slice artfully and purposefully arranged, has low entropy. Move an olive and the fastidious chef will complain. A tossed salad, on the other hand, has high entropy. Nobody will notice if you move a lettuce leaf from the left side of the bowl to the right side.

When the universe itself is cast as the central character in the drama, the story goes like this: Our cosmos began in a low entropy state and the arrow of time is taking us to an increasingly higher-entropy future. The universe is like an egg that is eternally cracking.

But thermodynamic entropy alone can't explain the arrow of time. First of all, because the laws of physics are totally reversible in time, it seems that entropy should increase in both the future *and* the past (Loschmidt, 1876). Furthermore, once a system is in equilibrium—the egg is scrambled, the balloon is deflated, the chocolate twist just a puddle on the sidewalk—there's nowhere else to go. You've reached maximum entropy. If you apply that thinking to the whole universe, you have to ask why we weren't at maximum entropy from the get-go.

After all, there are many more ways for the universe to be in a high-entropy state than there are for it to be at low entropy. That means that the odds should have been tipped steeply in favor of a universe that started at maximum entropy. But in a universe like that, time would end as soon as it began. Nothing would ever happen. This is not what we see, of course. But why not?

This question has been nagging at physicists and philosophers for at least a century. Even Ludwig Boltzmann, who first linked entropy to microstates, wrestled with it (Boltzmann, 1895; Price, 2004). His answer is still the one that seems to solve the problem most economically: "…the universe, considered as a mechanical system—or at least a very large part of it which surrounds us—started from a very improbable state, and is still in an improbable state" (Boltzmann, 1897).

In other words, the story of the universe, or at least our corner of the universe, hinges on a hugely improbable low-entropy origin. Time itself seems extraordinarily unlikely. So why do we have it?

2. The Past Hypothesis

To lay out the problem and its possible solution, David Albert asked an apparently simple question: How do we know what we know about the past? (Albert, 2000) How do I know, for instance, that the lukewarm coffee in the cup beside me used to be hot? How do I know that the brown leaves piled up in my backyard used to be sprouting from the branches of the old maple tree next to the fence? Our memories and experience provide the evidence. When they fail, we can call up photographs or other records to prove our case.

But if one takes seriously the notion that entropy should increase toward both the past and the future, one could argue that all those records of the past are, in fact, more likely to be fabricated by chance coincidence than they are to be "real," and any predictions we tried to make about the future would fall apart.

Albert proposed a way to rescue us from this untenable state with what he calls the "past hypothesis," an assertion that the universe must have started out at low entropy because, otherwise, we would not be able to predict anything at all. But Albert accepts that this approach is "inductive," not empirical: "The fact that the universe came into being in an enormously low-entropy macrocondition cannot possibly be the sort of fact that we know, or ever *will* know, in the way we know of straightforward everyday particular *empirical facts.* We know it *differently*, then" (Albert, 2000).

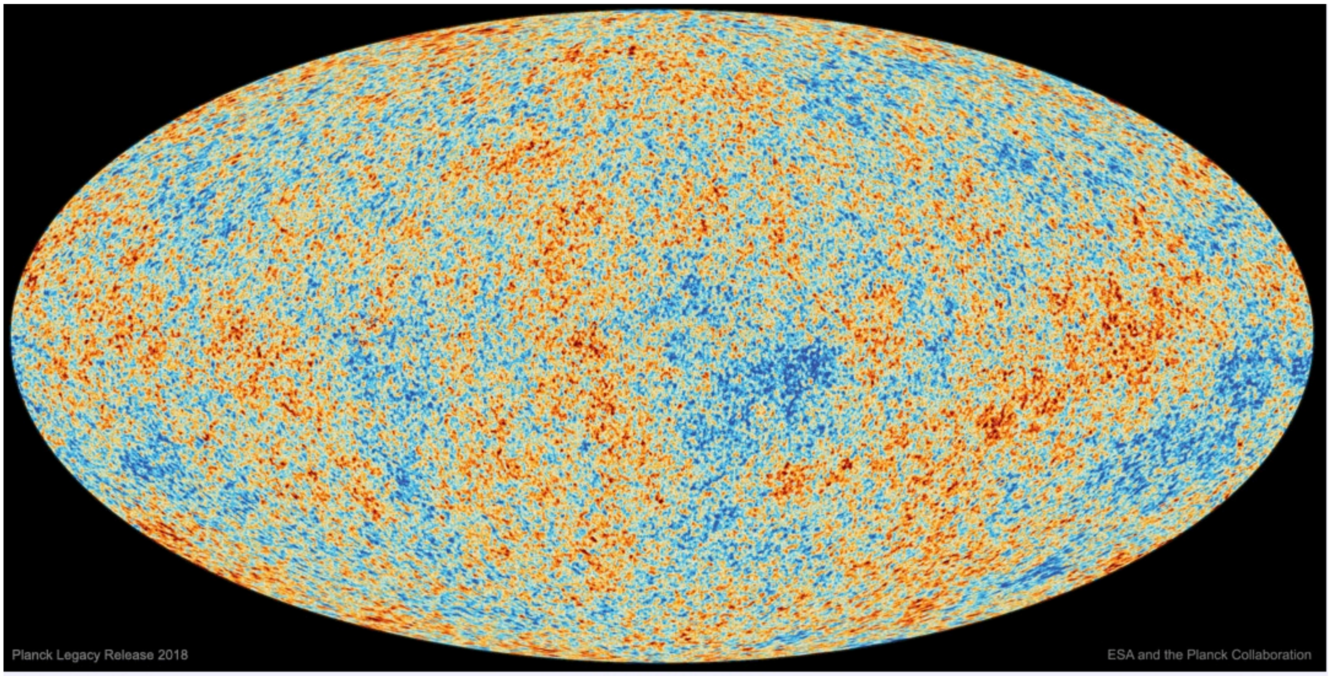

Figure 12: The Cosmic Microwave Background. (Image credit: ESA and the Planck Collaboration.)

Though Albert's reasoning does not require it, there is strong empirical evidence that the early universe really did begin in a low-entropy state. Since the 1960s (Dicke et al., 1965; Penzias & Wilson, 1965) astrophysicists have been taking progressively more detailed measurements of the microwave radiation that suffuses the cosmos (Figure 12). This "cosmic microwave background" is a relic of the Big Bang, first laid down some 380,000 years after the beginning of the universe—barely an instant, in the cosmic perspective—and now serves as the universe's first 'baby picture.' (See JTF's Cosmological Origins review for a detailed discussion of this radiation and its implications for the birth of our universe.)

Astronomers have now measured the temperature of this radiation in exquisite detail. The essential fact about the cosmic microwave background radiation is that it is startlingly uniform: The infant universe was almost exactly the same temperature everywhere. The most precise results so far, from the European Space Agency's Planck space telescope, show just how tiny the variations in the microwave background really are: its temperature varies by only about one part in 100,000 across the sky (Planck Collaboration, 2020).

At first, this seems to contradict the past hypothesis. Remember that, in thermodynamic terms, a box full of uniform-temperature gas has reached equilibrium and is thus in a state of maximum entropy. This would seem to imply that the smooth early universe, just 380,000 years after birth, was already at maximum entropy. If time's arrow points in the direction of increasing entropy, there should be no future beyond that point.

But the universe is not gas in a box. In those 19th-century thermodynamic models, gas particles collide with each other and spread out, but they do not experience any other forces (or, at least, no forces strong enough to be worth talking about). The universe, on the other hand, is not so simple. Inside the young universe, gravity attracts particles, drawing them together into clumps. Eventually, those clumps coalesce and create intricate cosmic structure. When gravity dominates, then, high-entropy systems look structured, not smooth. Thus the arrow of time should point from an early universe which looks uniform towards a later universe with increasing structure, such as galaxy clusters, stars and planets (Callender, 2010; Penrose, 1979; Wald, 2006).

Thanks to astronomical observations of the cosmic microwave background, then, we can *see* that the universe began in just the sort of low-entropy state required to generate an arrow of time. "In effect, the smooth distribution of matter in the early universe provides a vast reservoir of low entropy, on which everything else depends," Huw Price has written (Price, 2004). "In my view, this discovery about the cosmological origins of low entropy is the most important achievement of late 20th century physics."

Yet this still doesn't explain *why* the universe started out in such a smooth, low-entropy state. Was it just luck? Or was what we think of as the Big Bang—and assume was the beginning of time—just a chance moment of low entropy in a much longer history? Some argue that this is a meaningless question, calling up the "anthropic" reasoning that it isn't worth wondering since, if the universe were any other way, we wouldn't be around to ask. But physicists traditionally snub "just because" explanations. And to many, the idea that time itself began with a low-entropy fluke is simply unsatisfying. (See JTF's Fine-Tuning review for more examples of anthropic reasoning and the historical controversy surrounding such arguments.)

One possible explanation for why the early universe had such improbably low-entropy conditions invokes the speculative, but increasingly popular, notion that our universe is only one of many.

II. INTO THE MULTIVERSE

In the search for deeper explanations for the universe's low-entropy origin, Sean Carroll has taken inspiration from a radical theory that has grown in favor among cosmologists over the past few decades: The Big Bang was not really *the* Big Bang. It was just *our* Big Bang. Our universe is in fact one of many neighboring cosmoses, in an ever-growing multiverse.

In the early 1980s, Alan Guth proposed that, just after the Big Bang, our universe went through a burst of cosmic expansion called "inflation" (Guth, 1981). It wasn't long before cosmologists started wondering whether inflation could take place in different regions at different times, generating a multitude of mini universes, each born from its own private Big Bang, experiencing its own conditions, and perhaps even ruled by its own local laws (Garriga & Vilenkin, 1998; Linde, 1986; Vilenkin, 1983). This idea is called "eternal inflation." (JTF's Cosmological Origins review discusses the development of this framework in some depth. It has many tantalizing features for cosmologists, motivating many to favor it as a leading solution to a number of puzzles in physics, as outlined in JTF's Fine-Tuning review.)

Maybe, Carroll has suggested, if the Big Bang was not actually the birth of the universe, it can be regarded as something more modest: just a low-entropy "phase" that happened in one region of the multiverse some 14 billion years ago. This proposal requires that physicists make room in their theories for events that happened before our Big Bang and for places that exist beyond the bounds of our observable universe. But cosmologists typically consider these domains off-limits: how can you talk about what happened before the beginning?

But defying these orthodoxies might be the best—or the only—way to move the scientific conversation beyond the deadlock of the past hypothesis. Carroll is not the first to think along these lines. Boltzmann himself, back in the 19th century, proposed that the known history of the universe might be just a short chapter in a story with no beginning and no end, a chance fluctuation from equilibrium in an eternal universe. This downgrades the arrow of time from a universal truth into something more like a local idiosyncrasy (Boltzmann, 1897).[5]

Working with Jennifer Chen, Carroll has suggested that eternal inflation could provide a natural explanation for the low-entropy state of the early universe and thus for the arrow of time, without invoking the past hypothesis (Carroll & Chen, 2004). Carroll and Chen began by imagining an eternal universe in a state of high entropy, close to equilibrium—that is, a boring universe in which space is basically flat and empty and nothing ever really happens. But once in a very, very long while, a random fluctuation flicks on and generates a brand new "pocket" universe. That new universe is born with very low entropy and goes through its own personal stages of growth—Big Bang, inflation, the creation of ordinary matter and radiation, and so on. Along the way, its entropy increases, until it eventually settles into the near-stasis of the parent universe. The process can go on endlessly, through infinite recursions that propagate into the past as well as the future. You can therefore generate multiple universes with arrows of time pointing in opposite directions relative to one another—creating an overall time-symmetry in the multiverse.

This idea is still speculative, however, and is only one of a number of proposals that could provide more fundamental explanations for time's arrow, while evading the past hypothesis. Another tactic involves taking a closer look at the interplay between gravity and complexity in the cosmos.

III. COMPLEXITY, GRAVITY, AND THE ARROW OF TIME

For years, Julian Barbour and Lee Smolin have taken issue with the idea that the second law of thermodynamics can even be applied to the universe as a whole. The universe is not a box of particles, they argue, so it makes no sense to try to apply rules made for isolated objects with insides and outsides. Barbour and Smolin are thus not concerned with how the universe moves toward thermal equilibrium. Rather, in the 1990s, they began a program to investigate how the cosmos progresses from a featureless smear of particles to the intricate structures of stars and galaxies that we see today. Taking complexity as their theme, they began to work out a new model of the arrow of time that leaves out the past hypothesis altogether (Barbour & Smolin, 1992).

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[5] If you actually follow Boltzmann's argument all the way down, you actually find yourself in a universe populated only by disembodied consciousnesses; such "Boltzmann brains" turn out to be vastly more likely, statistically speaking, than actual human beings who evolved in our cosmos. Then cosmologists are left with a new conundrum, trying to explain why we are not all Boltzmann brains. In short, you wind up somewhere you don't want to go (Carroll, 2017). JTF's Fine-Tuning review has a longer discussion about the Boltzmann-brain problem, and what it can teach cosmologists. But Boltzmann's general theme—that the universe as we know it might actually be just a piece of something much larger—has stuck, and found new expression in contemporary cosmological theories of the multiverse.

In recent years, however, the two physicists have diverged, and now follow different approaches in tackling this question. Barbour and colleagues have developed a new framework called "shape dynamics" while Smolin has looked to causality for a clue.

1. Shape Dynamics

Along with colleagues Tim Koslowski and Flavio Mercati, Barbour has developed an approach that sets gravity, not entropy, as the driving force inside the cosmic clockwork (Barbour et al., 2013, 2014).

The team created a mathematical "toy" model of the universe that shows how a certain number of objects move in response to each other's gravity. Traditionally, models like these track objects using absolute space and time coordinates. But as Einstein showed (see Chapter 2), there *is* no absolute background against which to measure, because space and time are relative.

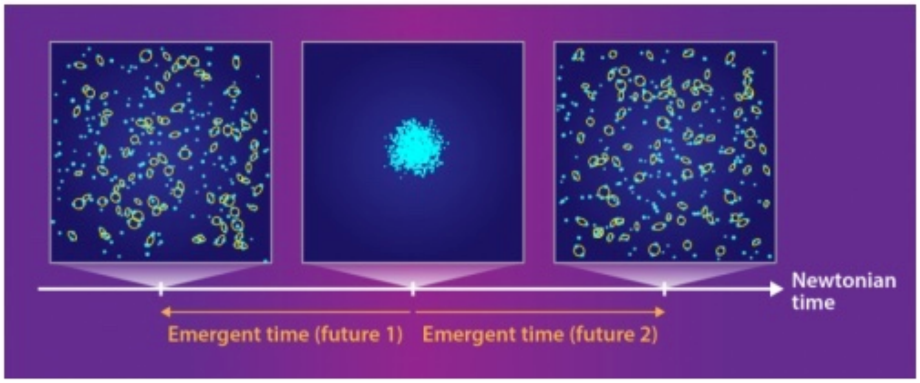


Figure 13: According to the shape-dynamics framework, the Big Bang birthed two universes, with opposing arrows of time. (Image credit: APS/Alan Stonebraker.)

While Einstein replaced the absolute background with a malleable spacetime fabric, Barbour, Koslowski, and Mercati go a step further: They represent position, size, and time purely through the relationships between objects within the universe, without reference to any background spacetime, at all. This approach describes the changing shapes created by the relative motion of the objects and is thus called "shape dynamics." Their computer simulations show that in a toy universe described by shape dynamics, gravity can naturally produce an arrow of time without any need for a special, low-entropy past. The direction of time is established by the growth of structure out of chaos (Barbour, 2019).

One oddity of the system is that every point seems to have one past but two futures. Barbour, Koslowski, and Mercati call the point from which the two futures branch off, the "Janus Point," after the two-faced Roman god of beginnings, who gazes in two directions at once. This raises the possibility that the Big Bang is actually a Janus point, and that our entire universe has a twin in which time runs backward (Barbour et al., 2015) (Figure 13). Inhabitants of one universe will never be aware of the other.

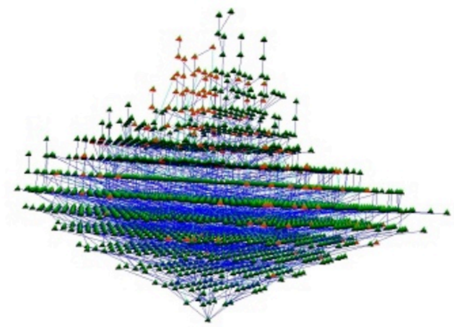
This line of thinking has also led Barbour to the conclusion that time is not strictly "real" at all: that is, it does not exist independently of events and structure in the universe. Chapter 2, section II.2 describes Barbour's explanation for why we perceive the flow of time, despite its unreality. It is possible to reach the opposite conclusion about whether or not time is an illusion from the same starting point, however. Smolin, Barbour's collaborator in the 1990s, now argues that time is perfectly real—perhaps *more* real than the laws of physics that we think are fundamental, as described in the next section.

2. A Causal Arrow of Time

(i) Energetic Causal Sets

A number of researchers have investigated the relationship between cause and effect and the origin of time's arrow. Smolin argues that the whole problem of the arrow of time begins with the idea that the time-reversible laws of physics are fundamental, which seems oddly mismatched with our perception of a direction of time. But what if, he ponders, hiding beneath those known laws, there is another law or set of laws that is *not* reversible in time? Perhaps this deeper physics can even unite the apparently incompatible theories of general relativity and quantum mechanics.

Figure 14: In causal set theory, the "atoms" of spacetime are discrete events, or mathematical points, connected by links that can only point from the past to the future. This is a depiction of the Big Bang in such a model. (Image credit: David Rideout.)



JTF's Emergence review outlines a number of proposals for the fundamental building blocks of reality—seeds that themselves have no spatial or temporal extent but from which space and time might bloom. One influential idea, called "causal set theory," is that the universe is broken down into a vast number of discrete events that can be placed into a cause-effect sequence (Figure 14). Spacetime as a continuous fabric is a human construct, in this view; we assign the events positions in order to satisfy the causal relations (Dowker, 2005; Sorkin, 2009).

Inspired by such ideas, Smolin and Marina Cortês are exploring a model of the universe based on unique events. In this model, events have energy which they can pass along to future events, and the entire history of the universe is contained in the set of cause-and-effect relationships between events. Using this model, which they call "energetic causal sets," Smolin and Cortês find that they can describe a universe that has an innate, but hidden, arrow of time, and also contains reversible physical laws that particles must obey (Cortês & Smolin, 2014a, 2014b, 2018).

(ii) Bayesian Networks

Carroll is also independently working on making a rigorous connection between the thermodynamic arrow of time and the "causal" arrow—that is, the arrow of time that guarantees that causes come before effects—but from a different angle. His approach involves first unpicking what a "cause" really is. The answer seems obvious at first—you knock your wine glass off the table, you get a stain on the carpet, say—but in more complicated cases, things get knottier. For instance, medical researchers noting that people who have a glass of wine with dinner also tend to live longer would have to ask themselves whether the wine actually causes longevity or whether,

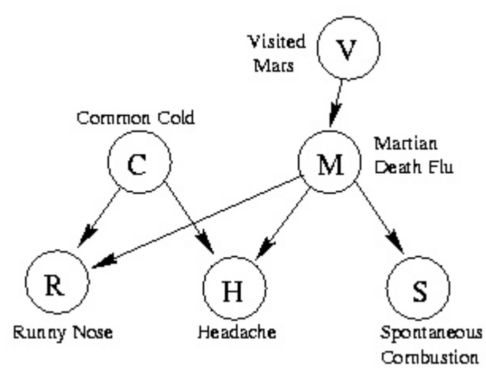


Figure 15: A sample Bayesian network for distinguishing common colds from the Martian Death Flu. (Image credit: Scott Adams, www.cs.cmu.edu/afs/cs.cmu.edu/project/learn-43/lib/photoz/.g/web/glossary/bayesnet.html.)

perhaps, both wine and long life are associated with some other variable, like eating healthier meals, getting regular check-ups, or doing more yoga. Statisticians have developed a tool to unpick such knots: Bayesian networks, which are graphs that show the relationships between multiple variables (Figure 15).

In 2017, Carroll and colleagues adapted Bayesian networks to derive a new version of the second law of thermodynamics, which states that the entropy of a closed system will tend to increase (Bartolotta et al., 2016). The novel formulation takes into account that there are other ways to define entropy beyond the thermodynamic definition given in section I.1 above, for instance in terms of information. In particular, in the 20th century, computer-communication pioneer Claude Shannon defined entropy in terms of communicating encoded data. Entropy, in this formulation, measures how much the data can be compressed, while still reliably conveying information. As such, Shannon entropy characterizes the state of our knowledge of the system, rather than simply representing an objective fact about the system itself.

In this information-centric view, because the act of measuring a system changes our knowledge of the system, measurement must also affect the entropy of the system (Lloyd, 1989; Parrondo et al., 2015). Carroll's "Bayesian Second Law" is thus a more generalized version of the thermodynamic second law that explicitly incorporates the way that an experimenter's knowledge of a system is updated by making measurements. Carroll and his colleagues point out that measurements add to the experimenter's knowledge of the system not just at the present moment, but at earlier points too. They hope that this new formalism could be applied to those rare but potentially significant situations where entropy spontaneously decreases (Carroll, 2015).

To discriminate causation from correlation, Carroll is now taking that a step further, drawing on work from Judea Pearl, who developed a "causal calculus" to help artificial intelligence algorithms independently detect links between variables. The goal is to put our familiar sense of cause and effect on a rigorous mathematical foundation, one that will show that the causal arrow and the thermodynamic arrow are one and the same. This work is still in progress.

(iii) Decision Making and Time

Cause and effect can be completely impersonal—a particle collides with another, sending it off in a new direction. To illuminate the connection with human experience, Carlo Rovelli is investigating a uniquely human version of cause-and-effect: *choice*.

Once again, such analyses lean heavily on the definition of entropy in terms of information, by Shannon. To put the act of choice on a more rigorous mathematical footing, Artemy Kolchinski and David Wolpert (Kolchinski & Wolpert, 2018) have drawn up a general description of how any physical system, living or not, takes in information about the world and applies it to the business of survival. Since Shannon's entropy measures how much encoded data can be compressed, while still reliably conveying information, it also serves as a measure of how much information is vital and how much is unnecessary. Kolchinski and Wolpert point out that, in the natural world, most of the information that's available is irrelevant to survival.

Rovelli has adapted this to describe living things (Rovelli, 2018). Of all the information bound up in every atom of a living thing, he points out, only a tiny fraction is important for that creature's survival. "Meaningful" information, Rovelli says, is the stuff that really matters: that a flower stem can tilt toward the sun; that a bacterium can propel itself toward food; that a little fish can swim away from bigger fish. A flower is not making a conscious choice to lengthen its stem, of course, but humans make choices every minute that feel free.

This strategy might establish the first link of the chain connecting Shannon entropy to human experience, choice, cause and effect, and time's arrow. Rovelli's aim is to combine aspects of physics, information theory, evolutionary biology, and psychology to reveal why our choices propagate into the future, not the past.

Jenann Ismael also favors an overarching multidisciplinary approach in her preliminary work investigating the emergence of human intelligence through culture (Ismael, 2019). She has argued that the thermodynamic gradient is the key mechanism that has powered this evolution. Without it, there would be no arrow of time, no physical way to create records of past events, and thus no way for humans to transmit knowledge across generations—essential for the development of culture.

Interdisciplinary thinking will likely prove vital in ultimately understanding the nature of time. As we have seen in this and in preceding chapters, explorations in relativity, quantum theory, and the quest to understand the arrow of time, have taken physicists far beyond the bounds of human experience. Indeed, the deeper physicists go, the further they seem to travel from what we usually mean when we talk about time.

Is it possible to bridge the gap?

In the final chapter, we will turn to researchers who are trying to do just that. They begin not with boxes of gas, or observations of the early universe, but somewhere much closer to home: the human brain.

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5. TIME AND THE BRAIN

The myriad formulations of time suggested by relativity (Chapter 2), quantum theory (Chapter 3), and the efforts to unify quantum theory with relativity (Chapter 3) and to explain time's arrow (Chapter 4), all have something in common: As mathematically and philosophically rich and textured as they are, when we look to them for deep explanations for the human experience of time, they fail us. When they are not directly contradicting our everyday experience, they nevertheless seem to be describing some entity that's entirely different from the thing we humans call time. Essential "truths" of human time—that we live in a moment called "now" that bifurcates the universe into an unchangeable past and an unwritten future—seem like footnotes in the fundamental physical description of time, if they appear on the page at all. Worse, the deeper physicists wade into the true nature of time, the greater the distance between the time of physics and that of our experience seems to become.

So, how do we get from *there* to *here*? Craig Callender begins to chart a course by clarifying where, exactly, "here" is. He calls our ordinary notion of time "manifest time" (Callender, 2017), and he distinguishes it from both physical time and from the raw sensory input that streams into the brain. "Our best science of time suggests that manifest time is more or less rubbish," writes Callender. Yet he rejects the idea that manifest time is a mere illusion, or even a tolerable shorthand. Like other familiar sensations—the sweet taste of birthday cake, the pleasing harmony of a major chord—manifest time must arise at the intersection of physics and our living senses. But humans and our animal relatives have specific organs that have evolved for taste, hearing, touch, and so on. There is no analogous "time organ" that's responsible for sensing time.

In recent years, however, neuroscientists have been making rapid progress toward understanding how the brain measures, records, and uses time. They are discovering a system that is multilayered and flexible, stacked with redundancies, cleverly exploiting the brain's intrinsic dynamics to meet the tremendous variety of timekeeping challenges we encounter every minute.

I. LIVING CLOCKS

Physicists may conclude that time is an illusion, but a living body defies that notion with literally every cell of its being. Long before the first clocks and wristwatches were invented, human bodies were keeping their own time. An individual life occupies a finite span; a body grows, matures, and ages in time; fertility cycles follow a predictable cadence; circadian rhythms loop us through waking and sleeping hours; our hearts beat and our breath moves in and out, all in tempo.

And these are only a handful of the timekeeping functions that rise to our awareness. Many others happen with such speed and precision that they slip through the sieve of consciousness. For instance, imagine yourself in your backyard. You hear a bird tweeting, but you do not see it. Your brain can locate the bird by comparing the time at which the tweet arrives at your left ear to the time it arrives at your right ear, even when the delay is as little as ten microseconds.

Without realizing it, we are also constantly timing the pauses between sounds, syllables, and words to make sense of speech. As Dean Buonomano points out (Buonomano, 2017), the difference between the letters *p* and *b* all comes down to a ten-millisecond differential in the time that passes between when a speaker releases air from her mouth and when she voices the letter. The brain's ability to measure sub-second pauses also makes the difference between *All of the other reindeer* and *Olive, the other reindeer*, or *The ants are my friends* and *The answer, my friends*. Our brains learn to parse these millisecond differences so efficiently that, when we get them wrong, it's an event.

The brain's high-precision timing also comes in when we coordinate movements. Catching a softball requires the catcher to observe the ball's trajectory and speed and move her hand into the just-right location at the just-right time to intercept it. Playing Chopin's Minute Waltz in under 60 seconds requires the pianist to move each of his ten fingers to the right keys at the right time, according to an internally-established rhythm, with the right articulation, pressure, and speed to produce a particular feeling in the listener. (Indeed, the same notes that sound sprightly and joyful at a quick tempo feel heavy and doleful when played slowly; slow them down even more and they no longer sound like music at all.)

Learning requires a sense of time, too. A child learns that, if he touches a hot stove, his hand will hurt. A puppy learns that, if he stays nicely, he will get a treat. A cow learns that, if she noses the electric fence surrounding her pasture, she will get a shock. If *cause,* then *effect*. To learn, you've got to get the order right.

Telling time is a matter of survival. But what, exactly, are the gears that make living things tick-tock?

1. Clock Watchers—Circadian Rhythms

Most artificial clocks tell time in the same way: an oscillator—anything from a pendulum to a quartz crystal to a cesium atom—ticks out a regular rhythm, and an accumulator counts up the collected ticks. A single clock can keep time on the scale of nanoseconds, minutes, and millennia; even a humble wall clock has no trouble telling time in seconds, minutes, and hours. But does the human brain work the same way?

We use at least one relatively simple oscillator system to tell time: the circadian clock, which drives the sleep-wake cycle. In experiments, even mice left in total darkness will spontaneously begin their morning wheel-running at about the same time, give or take a few minutes, day after day after day (Welsh et al., 1986). Researchers have traced this internal clock to a tiny part of the brain called the suprachiasmatic nucleus, which sits near the point where nerves from the left and right eye meet. Based on light input from the eyes, the suprachiasmatic nucleus pumps out hormones that tell the rest of the brain when it's time to go to bed and when it's time to rise and shine.

The oscillator that drives the circadian rhythm is actually a finely tuned biological feedback mechanism. Biologists studying fruit flies with mutations that affected their daily activity patterns (Bargiello et al., 1984) have identified and sequenced groups of key genes that, together, constitute a clock that runs on a biological feedback loop. One gene, called *Period*, shows how these feedback loops work (Reddy et al., 1984).

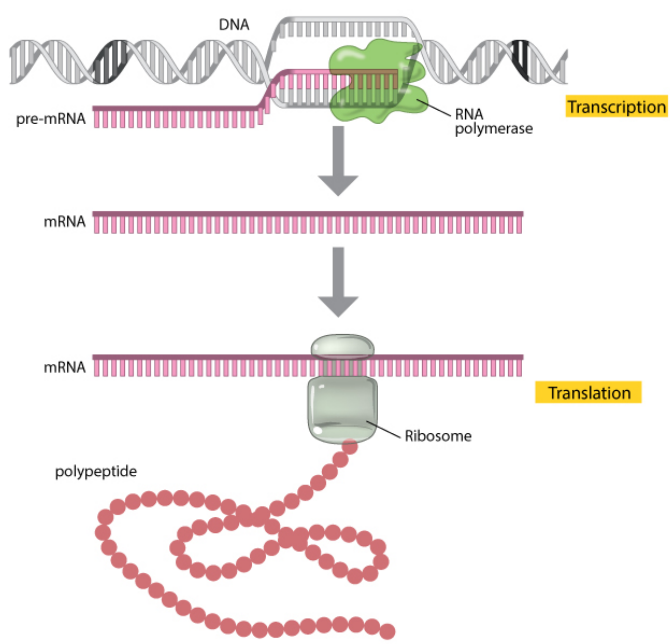

Figure 16: A gene is expressed through the process of transcription and translation. During transcription, the enzyme RNA polymerase (green) uses DNA as a template to produce a pre-mRNA transcript (pink). The pre-mRNA is processed to form a mature mRNA molecule that can be translated to build the protein molecule (polypeptide) encoded by the original gene. (Image credit: © 2013 **Nature Education**. All rights reserved.)

Every gene is made up of a double-strand of chemical "bases" that, together, make up the DNA recipes by which the body creates different proteins. Enzymes called RNA polymerase are charged with separating the two strands a bit at a time and building up a single-stranded molecule called messenger RNA, or mRNA. The mRNA functions as a copy of the DNA recipe. Structures called ribosomes can then translate it into proteins (Figure 16). In the case of *Period*, the gene is transcribed into RNA and then translated into a protein that is also called Period. The protein builds up until it reaches a certain threshold. At that point, it shuts down the gene, turning off the production of the protein. When enough of the protein breaks down, the gene turns on again and production of the protein resumes. The whole cycle takes just about 24 hours.

The circadian rhythm is so primitive that it doesn't even require a brain: Plants and even single-celled bacteria have their own built-in 24-hour clocks, though they use different genes and proteins to realize them. A tremendous, and tremendously varied, array of living things seems to have evolved this ability to align their biological clocks with Earth's rotational clock.[6]

That circadian rhythms are so robust and so widespread suggests that they matter for survival. Why? For photosynthetic life the answer is obvious: to get as much daylight as possible. We can tell a compelling behavioral story about why predators and prey, too, do better with reliable internal clocks. It's less clear why a single-celled bacterium would need to know the time of day, but researchers are

[6] You might ask whether creatures living outside the sun's immediate influence have inherited or developed similar clocks. Biologists are currently searching for circadian rhythms in a wide variety of such creatures—cave creatures, like fish and millipedes, and deep-sea tubeworms and crustaceans—with mixed results (Beale et al., 2016).

exploring the hypothesis that cells "prefer" to divide at night, when they are protected from ultraviolet radiation that causes glitches in DNA replication (Nikaido & Johnson, 2000).

The circadian rhythm runs deep. It crosses the boundaries of species and even domains of life. If living things did share some master internal clock, it's natural to think that the circadian rhythm would be geared directly to it. Yet the current consensus is that the circadian clock is, as Buonomano puts it, "a one-trick clock." It can measure days, but it cannot count them up into months or subdivide them down into milliseconds.

2. Chirps and Tweets—Fine-Scale Timekeeping for Communication

Researchers now believe that, rather than running according to the ticks of a single master clock, the brain is more like an entire clock shop, stocked with different timekeepers for different tasks. They know where to find the 24-hour circadian clock, and they know how it works. But what about the clock that does much finer time-keeping, like measuring the millisecond-scale pauses between words?

To find it, neurobiologists are studying how non-human animals communicate with others of their species. Birds, frogs, insects, fish, whales, dolphins, gerbils, and many more use sound to communicate, and rhythm is often an essential constituent of the message. The animal chirping out the message and the animal receiving it both need to be able to do fine-scale time-keeping to make this communication strategy work.

Crickets, for instance, use a sort of insect Morse code to call to other crickets. Male two-spotted crickets call out to females with a series of three, four, or five chirps lasting between 30 and 40 milliseconds (Figure 17). Females hear these chirps through their legs, which generate a response signal that travels up to the brain.

Figure 17: African Field cricket, *Gryllus bimaculatus*, at Bristol Zoo, England. (Image credit: Photographed by Adrian Pingstone, 2005.)

Berthold Hedwig and colleagues have discovered that female crickets use a "circuit" of just five neurons to single out the male's distinctive chirp pattern (Kostarakos & Hedwig, 2012; Schöneich et al., 2015). The researchers began by using tiny electrodes to pick out the specific neurons that responded to male chirps. Then they squirted fluorescent dye into the neurons, so that each one would light up as it fired. They found that the chirp signal was sent down two neural paths: one signal passed straight to a "detector" neuron, while the other was held back for one "beat" before being released to the detector neuron. When the female hears the next chirp, the process repeats. If the chirps have the right rhythm, the pulses will align, triggering a final neuron to fire: the female has found her match.

Crickets are not the only animals whose brains are so exquisitely tuned in to rhythm. The male zebra finch—a member of a species of small, orange-beaked birds common in Australia—spends months learning and practicing his own personal courtship song. According to Michael Long and Michale Fee, during this course of painstaking practice, the finch may drill each element of the song a million times, until he is at last ready to perform it for a female (Long & Fee, 2008) (Figure 18).

Figure 18: Zebra finches. (Image credit: Korbinian Mueller.)

To the human ear, the zebra finch's call may sound like a clown car's alarm—a high-pitched squawk of baroque rhythms in miniature—but the song tells the female zebra finch everything she needs to know to choose (or refuse) a lifelong mate. What most impresses researchers, though, is how remarkably consistent the zebra finch's song is. Time after time, the finch executes his song flawlessly, its tempo wavering by only two or three percent over the bird's entire lifetime.

How does the zebra finch achieve and maintain this impeccable performance? According to Long and Fee, it all happens in a part of the brain called HVC.[7] While the male zebra finch sings, neurons in HVC fire in a very particular order, like a team of runners in a relay race. Long and Fee wondered: do zebra finches use the HVC neurons to keep time as they sing?

To answer that question, Long and Fee exploited a quirk of the brain: when brain cells get cold, they operate more slowly. The researchers built a tiny device that could sit on top of the area just above HVC and chill it by a few degrees Celsius, just enough to slow brain activity but not stop it entirely. The structure of the bird brain lent them some luck. HVC is located just a tenth of a millimeter below the

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[7] HVC was formerly known as the *hyperstriatum ventrale*, *pars caudalis* (HVc), or high vocal center.

surface of the brain and it is physically isolated from other brain areas involved in singing. That made it possible for them to target HVC with extreme precision.

They discovered that when they cooled HVC, the birds sang the exact same songs, but in slow motion, as if they were orchestra musicians following a conductor who had just slackened her baton from *allegro* to *largo*. Long and Fee then performed the same cooling trick on a motor area of the zebra finch brain that sits downstream of HVC. But cooling that area had almost no effect on the timing of the bird's song, suggesting that HVC is the master timekeeper for the zebra finch's song.

Such experiments suggest that animals have evolved specific timekeeping circuits; but that may tell only part of the story. Buonomano, for instance, argues that, while the brain may have specialty clocks for tasks like discriminating mating-call rhythms, most neural circuits may actually be able to perform timing computations (Goel & Buonomano, 2016).

To test the idea that most any neural circuits can be used for timing, Buonomano and Anubhuti Goel asked whether a "brain in a dish" could be capable of primitive timekeeping. They isolated small slices of rat brain, implanted them with electrodes, and stored them in an incubator capable of sustaining them for weeks (Johnson & Buonomano, 2009). They then genetically modified the neurons to respond to light and stimulated the brain slices with a targeted one-two punch: a zap of electricity, then a pulse of light. For some slices, the interval between the electrical zap and the light pulse was 100 milliseconds. For others, the interval was 250 milliseconds. For a third group, it was 500 milliseconds. Could slices be trained on these patterns so that they would learn to "expect" the next pulse and change their activity accordingly?

The researchers repeatedly pulsed the slices over the course of four hours. Then, they zapped them with electricity once more and recorded how the light-sensitive neurons responded. They found that the neurons "anticipated" the arrival of the light pulse, generating a small electrical current at the moment when the light pulse was scheduled to arrive. The timing was very precise for neurons trained on the 100 millisecond interval, but got progressively sloppier for those trained on 250 and 500 millisecond intervals. That is not surprising, because it's how people work, too. In experiments, humans are most accurate at timing short intervals; bigger intervals mean bigger errors (Gibbon, 1977; Rakitin et al., 1998).

The experiment also shows that timing is performed by a whole network of neurons, not just one or even a handful. Just as it takes hundreds of baseball fans to make a stadium wave, it takes an entire network of neurons to tell time. And while more complicated timekeeping tasks might use more complex networks, Buonomano and Goel argue the experiment supports the idea that timekeeping does not necessarily require a dedicated mechanism in the brain. Under the right circumstances, any brain circuit can do it.

3. Ripples in Time—Synaptic Plasticity

But how can brain circuits perform this timekeeping feat? Many brain processes have natural time constants—that is, characteristic timescales of neural activity—of tens or hundreds of milliseconds (Paton & Buonomano, 2018). These processes did not evolve for the purpose of timing, yet, just as clockmakers have exploited the natural vibration of quartz crystals to engineer wristwatch movements, evolution may have found a way to repurpose these neural processes as timekeepers.

Buonomano has proposed that a phenomenon called short-term synaptic plasticity could be one of the gears that drives the neural clock (Buonomano, 2000; Motanis et al., 2018). Synapses, the junctions where neurons pass messages from one to another, can become stronger or weaker over time (Figure 19). A strong synapse serves to amplify the signal as it passes to the receiving neuron, while a weak synapse effectively muffles it. Over long periods of time, the selective strengthening and weakening of synapses manifests itself as learning. Whether it's a baby trying out his first words, a five-year-old steadying herself on a two-wheeler, or a pianist practicing a new piece, the "plasticity" of these neuronal connections is what makes learning possible.

But plasticity also happens on much shorter timescales, ranging from tens of milliseconds to a few seconds. Some synapses, once pinged by a spike from a neuron, become temporarily stronger. Others become weaker. If you know the inclination of a particular synapse, you can thus deduce the short-term firing history of its input neuron by the strength of signal at the output neuron. The brain could then decode this history to "tell time."

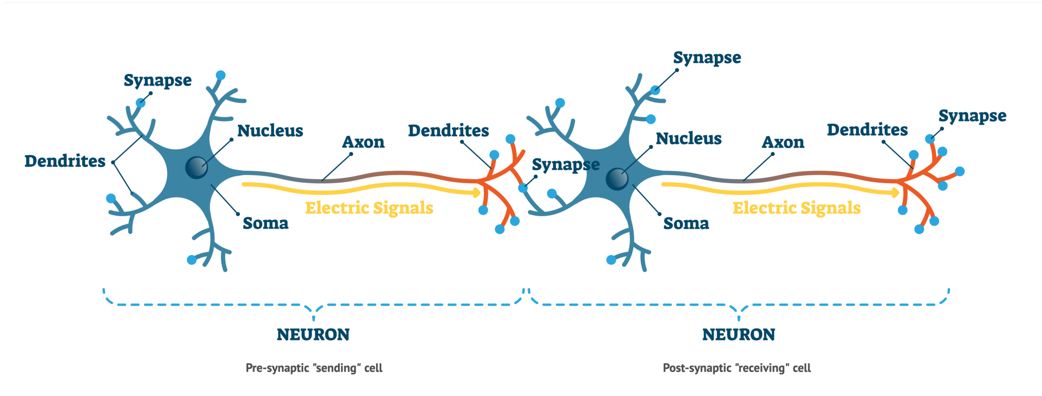

Figure 19: Neurons pass messages via synapses, which can amplify or muffle them. (Image credit: Adapted from original image by VectorMine.)

To approach the size and complexity of a real brain, this simple one-synapse model has to be scaled up enormously. Trillions of synapses connect the neurons that make up a human brain, and the strength of each one is changing by the millisecond. Buonomano and his colleagues describe the system as a "state-dependent network" (Buonomano & Maass, 2009; Buonomano & Merzenich, 1995)—that is, a dynamic atlas of connections that is defined not only by what is happening in the present, but also what happened in the past.

Computer scientists and neuroscientists have built computer simulations that demonstrate how state-dependent networks can parse patterns in time, but to explain things qualitatively, Buonomano turns to the humbler model of a pond on a rainy day. When a raindrop falls on the pond, the drop creates a characteristic pattern of ripples. When a second drop falls, it creates its own ripples, which combine with the first to create a new pattern, and so on. When you look at the surface of the pond, you see a history of all the drops that have fallen there in the recent past. This model suggests a way that the brain could use activity at a single moment to encode information about what is happening right now and what happened a few milliseconds or seconds ago.

The next step is to "read" those ripples and turn them into units of time. Buonomano thinks that the brain may accomplish this using what he calls a "population clock" (Buonomano & Laje, 2010). Building on work by Michael Mauk (Buonomano & Mauk, 1994), Buonomano argues that neurons could activate in unique patterns that encode both time and memory, like a battery of kitchen timers with different beeps and rings: *Bing* means it's been ten minutes and the eggs are boiled, *brrring* means the cake has been in the oven for half an hour. Like a veteran cook at a bustling restaurant, the brain manages to keep track of every dish at once and turns each one out just in time. It's a deliciously complicated trick—one that we accomplish with no conscious effort at all.

II. FROM PERCEPTION TO COGNITION

Still, it is not clear how to cross the rift between the split-second actions of neurons and synapses and the human experience of time continuously flowing from past to present to future. Here cognitive science comes into play. Rafael Núñez and Kensy Cooperrider describe this gap as the difference between *perception* and *conceptualization* (Núñez & Cooperrider, 2013).

Conceptualization has roots in perception but, they point out, accounts that rely on perception alone will come up short. A detailed biological description of temperature perception still cannot capture the feeling of sun on your face on a summer day.

1. Time as a Spatial Construct

Núñez and Cooperrider argue that humans conceptualize time in terms of something even more fundamental: space. For decades, linguists have been studying how we borrow spatial words to describe time. We imagine going "back" in time; we look "ahead" to the future; we hope that all our troubles are "behind" us. The specific metaphors vary with language and culture. Mandarin speakers often take vertical metaphors, reflecting the axis of written language (Boroditsky, 2001). The Yupno, an indigenous group from the mountains of Papua New Guinea, repurpose the uphill and downhill topographical metaphors they use for spatial relationships to describe time (Núñez et al., 2010). "These are not just a willy-nilly sprinkling of spatial words, but the systematic recruitment of spatial contrasts to construe temporal contrasts," write Núñez and Cooperrider. By aligning time with a single axis in space, these metaphors also capture the limitations of our movement in time: the arrow of time, discussed in Chapter 4, is embedded within them.

How deep does this go? Is it just a matter of word choice, or does our conceptualization of time hang on a more fundamental spatial understructure? To find out, cognitive scientists have been looking at how we build mental timelines. Most English speakers picture a timeline running from left to right; native speakers of languages like Hebrew and Arabic, which run the opposite direction when written on the page, draw their timelines from right to left (Fuhrman & Boroditsky, 2010).

Lera Boroditsky and her colleagues have investigated how "breaking" that spatial timeline might affect how we think about time (Saj et al., 2013). They worked with the University Hospital of Geneva, in Switzerland, to identify stroke patients diagnosed with a condition called "spatial neglect," which happens when damage to one half of the brain causes a person to "ignore" information from the opposite side of the body. A patient with damage to the right hemisphere might brush the hair on the right side of her head but not the left and eat food only from the right side of her plate; if you ask her to draw a picture of a clock, she might leave the left half of the circle blank.

Would patients with left spatial neglect also neglect the "left side" of time? To find out, Boroditsky's team presented subjects with a group of facts about a fictional man named David. Some of the facts came from David's past, and some came from his future—for instance, pictures of foods David liked in the past and foods that he will enjoy in the future. Then, they quizzed the participants to see which items they remembered and whether they could place those items in David's past or future.

Participants with left spatial neglect remembered "future" items about as well as participants in the control group. But when it came to items associated with David's past, there was a stark difference. The group with spatial neglect was less likely to remember having seen the "past" items, and, if they did remember them, they often incorrectly believed that they were from David's future. This suggests that the brain uses at least some of its spatial systems to represent time.

2. Temporal Illusions

Much of what neuroscientists know about the brain is the fruit of scientifically opportune malfunctions. By studying patients with brain injuries, researchers have been able to map function onto structure: An injury *here* produces a deficit *there*. In this way, researchers have located brain areas responsible for speech, comprehension, the laying down of new memories, and so on.

That there is no such thing as "time blindness"—no injury or condition that wipes out timekeeping across timescales—supports the premise that there is no single "time area" in the brain. Yet one of the most conspicuous features of the human "time sense" is how malleable it is, how very unlike the objective report of a stopwatch. Depending on the circumstances, time can "fly" or "stand still." When we are fully engaged in an activity—writing, coding, performing, competing—we often do not feel time pass at all. And, of course, this all depends on an individual's particular passions. The hours may melt away as one person turns the pages of *The Brothers Karamazov*, while for another an eternity seems to pass between each paragraph.

This subjectivity is, of course, totally different from what Einstein meant when he talked about relativity, though there is a poetic resonance between the biology and the physics here. And for more than half a century, researchers in neuroscience and psychology have been probing and measuring it, turning the perceptual dials that control our sense of time passing. One of those dials is motion: For example, when experimental volunteers are briefly shown a stationary picture—a square, for instance —and then shown a moving version of the exact same picture, they report that the moving picture lasted longer than the static one, even when they were displayed for the exact same time. The faster the object moves, the greater the psychological "time dilation" effect (Brown, 1995).

Another dial is novelty: In a series of experiments, Vani Pariyadath and David Eagleman showed volunteers a series of identical images with one "oddball" randomly thrown in. The volunteers consistently believed that the oddball image lasted longer than the repeated images. The researchers tried a similar test in which they showed volunteers a "train" of identical images. The volunteers found that the first image seemed to last longer than the images that followed. But when the researchers presented random images rather than identical ones, the time distortion disappeared. To Eagleman and his colleagues, this suggests that our sense of time is bound up with our sense of surprise; new and unpredictable events seem to last longer than those to which the brain has become accustomed (Pariyadath & Eagleman, 2007).

Emotion also influences how quickly time seems to pass. In a result that will come as a surprise to exactly no one, marketing researchers have found that when you dial up a call center with an urgent issue and have to wait on hold, the wait seems longer than if your issue is not pressing (Whiting & Donthu, 2009). Studies in psychology support these findings. Sylvie Droit-Volet, Sophie Brunot, and Paula Niedenthal, for instance, found that, when volunteers were presented with a series of faces, the emotionally-charged faces seemed to last longer on screen than the neutral ones (Droit-Volet et al., 2010).

Life-threatening moments—a car spinning out on the road, a mountain-climbing accident, a jet-launch failure—can also trigger a dramatic sense of time slowing down (Arstila, 2012). Neuroscientists and psychologists trying to understand this slow-motion effect have wondered whether the brain might actually be "overclocking" itself, taking in information at hyper-speed to enable the lightning-fast, life-saving reactions that some people seem to be capable of.

It's a difficult hypothesis to test: how do you safely and ethically put volunteers in a life-threatening situation? Eagleman and his colleagues surprisingly found a solution, at an amusement park called Zero Gravity, where customers pay for the privilege of taking a 31-meter free fall into a catch net. Eagleman wanted to use the thrill ride to find out if the brain really does "speed up" during scary events. So he recruited volunteers and outfitted them with what he called a perceptual chronometer. The chronometer, which looks like an oversized digital wristwatch, was actually an LED array programmed to display two numbers at a time. After a short interval, the LEDs would flip—black pixels would flip to red, and vice versa—creating a negative of the original number pair. The images would continue to alternate for about two seconds (Figure 20).

Volunteers could easily distinguish the digits as long as the flips were relatively slow. But as Eagleman's team sped up the flip rate, participants had more trouble distinguishing the numbers. After a certain threshold, the positive and negative images blended into one and the volunteers could not pick out the numbers at all.

First, the researchers tested the volunteers on the ground to measure that threshold under normal circumstances. Then, they sped up the flips by six milliseconds. If the brain really did overclock, they hypothesized that volunteers hurtling down through the air should be able to read the numbers thanks to the perceptual speed-up they experienced during their freefall.

The fall took about two and a half seconds. Though the free-fallers said that it felt much longer than that, they still couldn't make out the flipping digits any faster than they could on the ground. Perhaps they simply weren't scared enough. But Eagleman and his colleagues conclude that the slow-motion effect is not related to a true real mental speed-up. More likely, they say, highly emotional experiences lay down richer memories, which only seem longer in retrospect (Stetson et al, 2007).

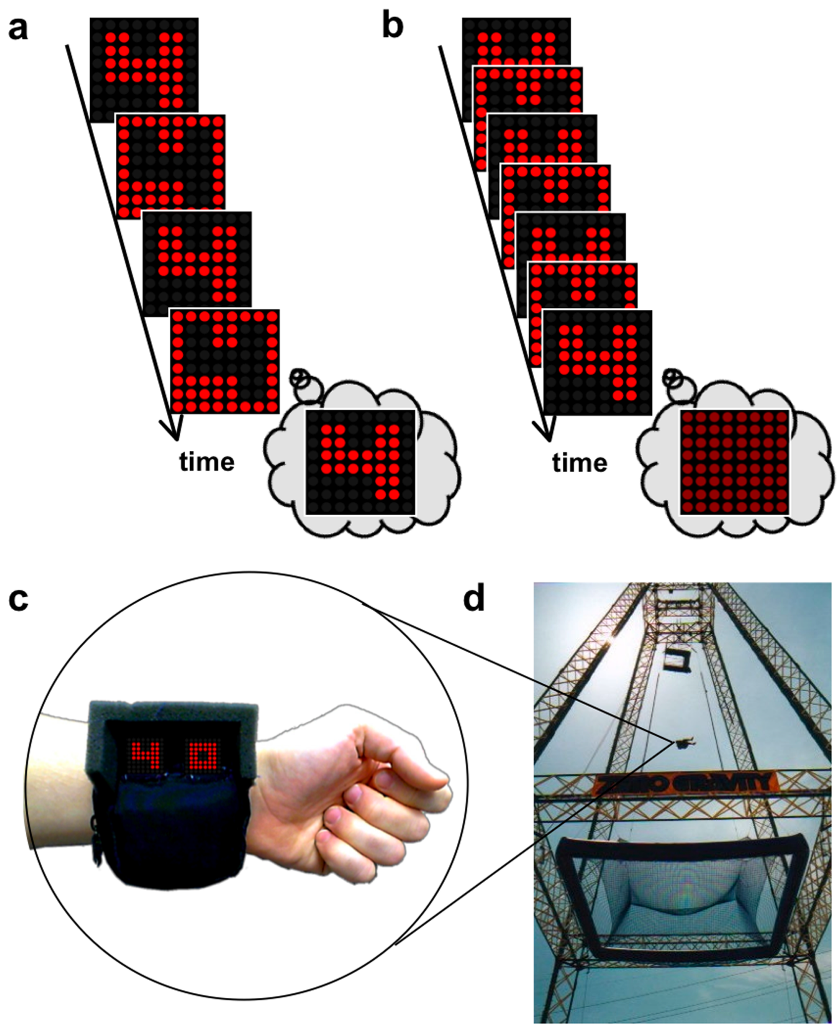

Figure 20: Measuring temporal resolution during a fearful event. (a) When a digit is alternated slowly with its negative image, it is easy to identify. (b) As the rate of alternation speeds up, the patterns fuse into a uniform field, indistinguishable from any other digit and its negative. (c) The perceptual chronometer is engineered to display digits defined by rapidly alternating LED lights on two 8×8 arrays. The internal microprocessor randomizes the digits and can display them adjustably from 1–166 Hz. (d) The Suspended Catch Air Device (SCAD) diving tower at the Zero Gravity amusement park in Dallas, Texas (www.gojump.com). Participants are released from the apex of the tower and fall backward for 31 m before landing safely in a net below. (Image credit: Stetson C, Fiesta MP, Eagleman DM (2007) "Does Time Really Slow Down During a Frightening Event?" *PLoS ONE* 2(12): e1295. https://doi.org/10.1371/journal.pone.0001295.)

III. MEMORY

Memory can play funny tricks with time. Most everyone has experienced the holiday paradox: On the way to an action-packed vacation, your jet is stuck on the tarmac for what seems like forever. But when you look back on it, the delay occupies barely a blip of memory, while the vacation itself, which flew by only too fast while you were holidaying, seems long in hindsight.

Yet, by and large, we can put our experiences in the correct order. *I ate dinner, had a bowl of ice cream, washed the dishes, read a book, and went to bed.* It is as if the brain stamps every memory with a time and place, like a digital camera coding metadata into each photo. Without these time stamps, not only would our memories be jumbled in a heap, but learning would become practically impossible: *Was it two right turns and a left, or a left and two rights? Do I mix the batter and then put it in the oven, or put it in the oven and then mix it?*

1. Temporal Cues

In 2007, Joseph Manns, Marc Howard, and Howard Eichenbaum looked at the source of these time stamps. Their hypothesis was that the brain might lay down memories against a background of gradually changing "temporal cues" that could be attached to each memory and later decoded to place it in time. In particular, the part of the brain known as the hippocampus is frequently implicated in learning and memory (Figure 21).

To test this idea, they gave their lab rats a challenge. First, each rat was introduced to a series of unique odors, one by one. After checking out the smells, the rats were then presented with just two of the odors—the odor #1 and odor #5, for example. To get a reward, the rats had to pick the odor that was presented first.

While the rats worked on this task, the researchers monitored a group of neurons in the hippocampus. They found that the neurons fired in a pattern that changed gradually as the rats encountered the new odors. The bigger the change, the likelier the rat was to correctly pick the correct scent when the researchers quizzed it in the second phase of the experiment.

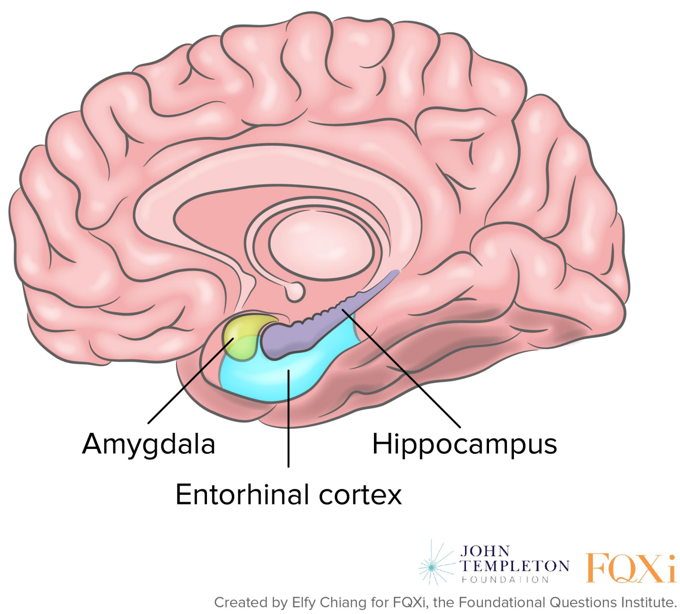

Figure 21: The location of the hippocampus in the human brain. (Image created by Elfy Chiang.)

The neurons' firing pattern also changed based on the locations at which the rats encountered the odors, but there was no link between the strength of those patterns and the rats' performance on the memory test (Manns et al., 2007). To Eichenbaum's team, that suggested that the slowly-changing background patterns could help generate the "time stamps" that organize memories over seconds, minutes, hours, and even days and weeks.

2. Time Cells

But were the rats really using these background patterns to line up the scents in the right sequence? In 2008, Eva Pastalkova, György Buzsáki, and their colleagues devised another way to test that idea. They began by teaching a group of laboratory rats a new exercise regimen (Pastalkova et al., 2008). First, the rats ran one half of a figure-eight-style maze. Then, they ran on a running wheel for ten or twenty seconds. After that, the rats finished the second half of the figure-eight. The rats continued alternating sides of the maze, always with a stop in the middle at the running wheel. All the while, the researchers were monitoring the activity of hundreds of neurons in each rat's hippocampus. They compared the rats' brain activity during the maze intervals, when the rats were using visual cues to navigate, to their brain activity during the wheel runs, during which their visual cues stayed constant while they worked to remember which direction they were supposed to run next.

The researchers saw that, in trial after trial, particular neurons fired at specific times as the rats ran on the wheel. The rats' environment was not changing, but their brains were still generating characteristic activity sequences—one in preparation for right turns, another in preparation for lefts—that could also be used for time-keeping. The researchers called the neurons that were recruited for these sequences "episode cells."

In 2011, Eichenbaum, along with Christopher MacDonald, Kyle Lepage, and Uri Eden, showed that rats' brains generated these patterns even when the rats were just waiting around (MacDonald et al, 2011). This time, the rats were put in a box and presented with one of two objects, either a set of rails or half of a green rubber ball mounted on a block of wood (Figure 22). After a ten-second pause, a small wall was removed from the box, revealing a flowerpot filled with scented sand. The sand could have two possible scents, cinnamon or basil. After several practice sessions, the rats learned that, if they matched the right scent with the right object, they could dig in the sand and get a bite of Fruit Loop as a reward. If the scent and the object were not a match, on the other hand, the rat could proceed down the box to get *two* bites of Fruit Loop. In either case, the rat would have to keep the first object in mind for the whole ten-second delay.

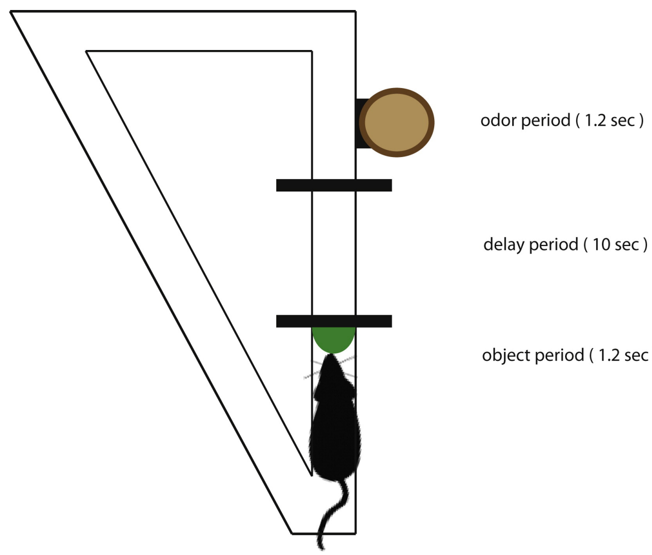

Figure 22: The Trial Structure for Object-Delay-Odor Sequences. The succession of events on each trial included an object period when the rat explored one of two objects, a delay period, and an odor period, when the rat sampled and responded to one of two odors. Green shape illustrates an object, brown circle illustrates an odor cup, and horizontal bars indicate removable walls that constrained the rat within each component of the apparatus during successive trial periods. (Image credit: Christopher J. MacDonald, Kyle Q. Lepage, Uri T. Eden, and Howard Eichenbaum, "Hippocampal "Time Cells" Bridge the Gap in Memory for Discontiguous Events," *Neuron*, DOI 10.1016/j.neuron.2011.07.012.)

After the training was complete, the researchers tested the rats' performance while simultaneously recording the activity of hundreds of hippocampal neurons. They tracked which neurons were active at each stage in the experiment—when first encountering the object, during the ten-second delay period, and when sniffing the flowerpot—and plotted out the firing patterns.

They were especially interested in examining activity during the delay period when, in addition to remembering which object it had seen, each rat was presumably also "counting down" until it would have a chance to earn a reward at the flowerpot. They discovered activity patterns corresponding to the animal's location, its speed, and the direction that its head was facing, and they also singled out activity patterns that seemed to code exclusively for time. They called the neurons that were involved in these patterns "time cells." No single time cell, on its own, could "tell time" but, as in the stadium wave, their behavior as a group functioned as a high-precision timekeeper.

3. Time Coding

But where are the gears driving the time cell clockwork? In 2018, Albert Tsao and colleagues zeroed in on neurons in a part of the brain called the lateral entorhinal cortex, or LEC (see Figure 21). The LEC feeds information to the hippocampus. Tsao thinks that the LEC could be the missing link that explains what drives time cells and how the brain organizes "episodic" memories—that is, memories of specific experiences—in time (Tsao et al., 2018). Tsao and his colleagues let rats run in a box whose walls were sometimes black and sometimes white. While the rats explored, the researchers recorded the activity of many neurons in the LEC. Some of the neurons seemed to activate in response to the wall color or the rat's location in the box, but many of the neurons seemed to be time-keepers, ramping their activity up and down on a variety of different timescales.

Meanwhile, Howard and Karthik Shankar were developing a mathematical framework that could explain how the brain does its time-coding (Howard et al., 2014). To illustrate the challenge, they compared how the brain processes a musical chord to the way it processes a melody. A chord is relatively simple. Each note has a particular frequency, which is picked up by frequency-sensitive hair cells in the ear and passed along to the brain. But if the notes in the chord are separated out and presented within a melody, it is no longer enough for the brain to process each tone at a single point in time: to turn the string of notes into melody, the brain needs to retain a memory of what came before. Howard, Shankar, and their colleagues, described how a group of neurons could respond to a single note while also containing the history of the melody leading up to it, coded into the rate at which each neuron's activity dies down.

Despite their name, however, time cells are not actually specialist time-keepers. Like other neurons, they will pick up any odd job the brain requires. When timekeeping is most pertinent, they are clocks. When navigating, they can be map beacons. Time is not confined to a single "time center" or even a single class of cells. Living things do not *use* body clocks; they *are* body clocks.

IV. ETERNALISM AND PRESENTISM REVISITED

The clocks discussed in this chapter are trapped in the present. We travel forward and backward in time in daydreams, regrets, and fantasies, not in reality. The brain is capable of coding its past into its present, but neuroscientists, like the philosophical presentists described in Chapter 2.II.2, still consider "now" to be something special and qualitatively different from the past and the future.

Yet neuroscientists have also shown that time is, in a sense, a mental construct. To offer up a coherent story about what is happening in the world, the brain has to align signals coming in from different senses. In the real world, sound and sight are often out of sync, thanks to the difference in travel times for light and sound. But even when the delay is perceptible in principle, we rarely actually perceive it: the brain "airbrushes" it away.

Sometimes, this airbrush—technically, the "temporal window of integration"—uses information from one moment to influence our conscious perception of moments that came before. Buonomano offers an everyday example from speech (Buonomano, 2017). When you encounter an ambiguous word in a sentence—*There's a bug*—you are rarely conscious of the time spent waiting for the speaker to make it clear whether she is describing a fly (*There's a bug in my soup)* or a glitch (*There's a bug in my code)*.

It's as if the whole sentence comes in one big gulp, not lots of little nibbles. The brain performs a similar trick with the sense of touch. If an experimenter taps two different points on your arm twice in quick succession, you will feel a "phantom" sensation of taps moving across the distance between both points (Geldard & Sherrick, 1972). The brain seems to be performing "backward editing in time" on every experience, a retroactive touch-up act that leaves us with the impression of continuously flowing time.

Physics and biology seem to converge on this point: "Human" time is something our brains make up. It does not exist "out there" in the universe, only "in here" in the mind. Beyond that meager common ground, though, the gap between neuroscientists' presentist view and the eternalist view embodied by the block universe model yawns wide as ever. The gap is unlikely to be closed by physicists, neuroscientists, or philosophers alone. "As physicists and philosophers continue to grapple with the problem of time within physics, the neuroscience of our perception of time's flow should be part of the debate," Buonomano has written (Buonomano, 2017). Callender echoes that. "If I'm right, success requires an all-out interdisciplinary attack on the problem," he has written (Callender, 2017). "Especially with a topic as puzzling as time, we need all the angles and tools we can get."

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The irony of writing about time during 2020 and 2021, when time itself seemed to have suffered some grotesque transformation—now crawling, now racing, now stuck in a loop—is not lost on me, and I am especially grateful to all of those who shared some of their time with me at every stage of this project. My thanks to Craig Callender and Jenann Ismael, who helped me navigate the badlands between "ordinary" time and natural time; Carlo Rovelli, for his gem box of a book, *The Order of Time*, and for recognizing the poetry and humanity of his subject; Časlav Brukner and Lucien Hardy, for illuminating the murky intersection of quantum mechanics and general relativity; Flaminia Giacomini, for her patient and painstaking explanations in two wildly different reference frames—inside the pandemic and outside of it; Ken Wharton, for reasoning that makes the impossible practically compulsory; Dean Buonomano, whose uncommonly lucid book, *Your Brain is a Time Machine*, and conversation were invaluable to my own brain; Marc Howard, for revealing the elegance of Laplace transforms and inverse transforms; Michael Long, for giving me the delightful relief of thinking and writing about birds for a change; and Anu Goel, for getting to the heart of what it means to learn. Thanks also to Thomas Burnett at the John Templeton Foundation for his invaluable insights on this review, and to Maayan Haarel and Elfy Chiang for crafting images that bring clarity to the fuzziness and contradictions inherent in the subject. Finally, the thanks I owe to Zeeya Merali—for her keen editing and deep knowledge, for her curiosity, humor, and patience—would overflow this page. And since she is responsible for making sure that my words do *not* overflow the page, I will make a closing gesture of gratitude to her by stopping here.

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