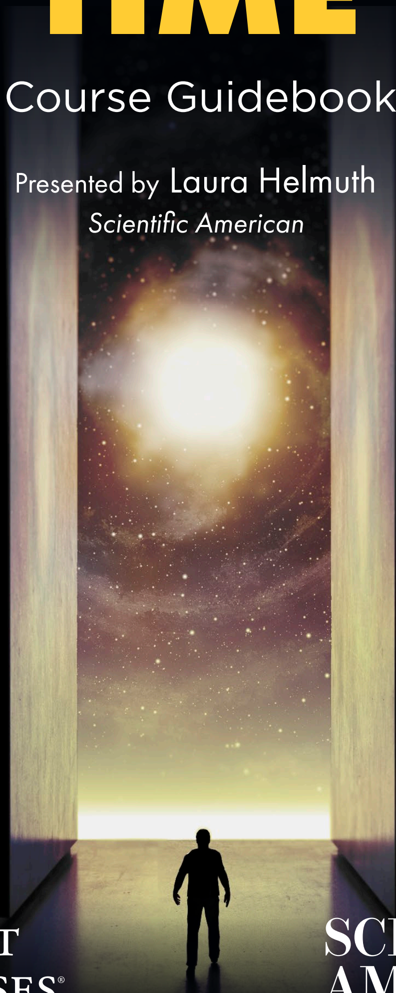
EXAMINING THE BIG QUESTIONS OF TIME

Course Guidebook

Presented by Laura Helmuth

Scientific American



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SUPPLEMENTARY MATERIAL

ABOUT OUR PARTNER

Scientific American covers the advances in research and discovery that are changing our understanding of the world and shaping our lives. Founded 1845, it is the oldest continuously published magazine in the United States and now reaches more than 10 million people around the world each month through its website, print and digital editions, newsletters, and app. Authoritative and engaging features, news, opinion, and multimedia stories from journalists and expert authors—including more than 200 Nobel Prize winners—provide need-to-know coverage, insights, and illumination of the most important developments at the intersection of science and society. *Scientific American* is published by Springer Nature. As a research publisher, Springer Nature is home to other trusted brands, including Springer, Nature Research, BMC, and Palgrave Macmillan.

Based on several articles from "A Matter of Time"—a special edition of *Scientific American*—this course provides an overview of what the world's foremost thinkers and researchers have surmised about time as well as perplexing questions that remain. For more information on specific topics within this course, refer to the course scope on page 1.

SCIENTIFIC AMERICAN

EXAMINING
THE BIG QUESTIONS OF
TIME

This course's content was adapted from the special issue of *Scientific American* titled "A Matter of Time." The course draws on many of the issue's articles, and its first lesson provides a general overview of time, its units, and how we interpret it. Next, lessons cover topics such as the beginning of time (lesson 2), how time flows (lesson 3), and whether time is an illusion (lesson 4).

Then, the course turns to time travel and the practical difficulties and paradoxes presented by it (lesson 5). After that, the course examines timekeeping throughout past centuries (lesson 6) as well as modern efforts at ultraprecise methods of tracking time (lesson 7).

Lesson 8 focuses on how humans experience the passage of time—and how it affects us. Subsequent topics include how the mind organizes and interprets time (lesson 9) and the potentially inconstant nature of supposedly constant quantities (lesson 10).

The penultimate lesson covers quantum loop gravity, which presents the idea that discrete pieces form time and space. The course concludes with a lesson based on a haunting question: Could time end?

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A MATTER OF **TIME**

Time defines us; it frames our experiences. We can't live, or understand our lives, without it. Intuitively, it seems to shape reality as an elemental aspect of our universe along with space. Yet the more we investigate it, the more elusive it becomes. This lesson looks at different interpretations of time, especially how ours have changed over the years. First, though, it discusses some common units of time.

WINDOWS OF TIME

Time is a powerful scientific tool. It's the way we measure duration, and as such it's a variable in almost every experiment scientists perform. As the following examples show, the units of time we commonly use range from the infinitesimally brief to the interminably long.

ATTOSECOND: A BILLIONTH OF A BILLIONTH OF A SECOND. The most fleeting events that scientists can clock are measured in attoseconds. Using high-speed lasers, researchers have created light pulses lasting just 53 attoseconds. Although the interval seems unimaginably brief, it's an aeon compared with the Planck time—about 10^{-43} second—which is believed to be the shortest possible duration.

FEMTOSECOND: A MILLIONTH OF A BILLIONTH OF A SECOND.
An atom in a molecule typically completes a single vibration in 10 to 100 femtoseconds, with each being a million of a billionth of a second.

PICOSECOND: A THOUSANDTH OF A BILLIONTH OF A SECOND.
The bottom quark, a rare subatomic particle created in high-energy accelerators, lasts for one picosecond before decaying. The average lifetime of a hydrogen bond between water molecules at room temperature is three picoseconds.

NANOSECOND: A BILLIONTH OF A SECOND. In one nanosecond, a beam of light shining through a vacuum will travel only 30 centimeters (just under a foot).

MICROSECOND: A MILLIONTH OF A SECOND. In a microsecond, that beam of light will have traveled 300 meters, about the length of three football fields.

MILLISECOND: A THOUSANDTH OF A SECOND. A normal camera flash lasts about a millisecond.

TENTH OF A SECOND. A blink of an eye is about a tenth of a second. The human ear needs this much time to discriminate an echo from the original sound.

SECOND. A healthy person's heartbeat lasts about one second. Traditionally, the second was the 60th part of the 24th part of a day, but science has given it a more precise definition: it's the duration of 9,192,631,770 cycles of one type of radiation produced by a cesium 133 atom.

MINUTE. In a minute, a shrew's heart beats 1,000 times. The average person can speak about 150 words or read about 250 words. When Mars is closest to Earth, sunlight reflected off Mars's surface reaches us in about four minutes.

HOUR. Reproducing cells generally take about an hour to divide in two. The Old Faithful geyser in Yellow Stone National Park erupts about every hour and a half. Light from Pluto arrives at Earth in five hours and 20 minutes.

DAY. For humans, the day is perhaps the most natural unit of time. Currently clocked at 23 hours, 56 minutes and 4.1 seconds, our planet's rotation is constantly slowing because of gravitational drag from the Moon and other influences. The human heart beats about 100,000 times in a day.

YEAR. In a year, Earth makes one circuit around the Sun and spins on its axis 365.26 times. It takes 4.3 years for light from Proxima Centauri, the closest star to our Sun, to reach Earth.

CENTURY. The Moon recedes from Earth by 3.8 meters each century. A baby born today has about a one in three chance of living to 100, and giant tortoises can live as long as 177 years.

A MILLION YEARS. After traveling for a million years, a spaceship moving at the speed of light would not yet be halfway to the Andromeda galaxy (which is 2.3 million light-years away). Because of the movement of Earth's tectonic plates, Los Angeles will creep about 40 kilometers north-northwest of its present location in a million years.

A BILLION YEARS. It took approximately a billion years for the newly formed Earth to cool, develop oceans, give birth to single-celled life, and exchange its carbon dioxide–rich early atmosphere for an oxygen-rich one.

CLOCKING **CULTURES**

- Social scientists have recorded wide differences in the pace of life in various countries and in how societies view time—whether as an arrow piercing the future or as a revolving wheel in which past, present, and future cycle endlessly. Some cultures even conflate time and space: The Australian Aborigines' concept of the Dreamtime encompasses not only a creation myth but a method of finding their way around the countryside.

- The study of time and society can be divided into the pragmatic and the cosmological. On the practical side, in the 1950s anthropologist Edward T. Hall Jr. wrote that the rules of social time constitute a "silent language" for a given culture. The rules might not always be made explicit, he stated, but "are either familiar and comfortable or unfamiliar and wrong."

- In 1955, he described in *Scientific American* how differing perceptions of time can lead to misunderstandings between people from separate cultures. He uses the example of a visitor to a foreign country keeping an ambassador waiting "for more than half an hour" and then "mutters an apology." This, per Hall, "is not necessarily an insult." Differences in time units between the two cultures may make the visitor not feel so late.

- Most cultures around the world now have clocks and calendars, uniting the majority of the globe in the same general rhythm of time. But that doesn't mean we all march to the same beat. Some people feel rushed by the pace of modern life, while in other societies, people feel little pressure to "manage" their time.

- Kevin K. Birth, an anthropologist, has examined time perceptions in Trinidad. Birth's 1999 book, *Any Time Is Trinidad Time: Social Meanings and Temporal Consciousness*, refers to a commonly used phrase to excuse lateness. In that country, Birth observes, "if you have a meeting at 6:00 at night, people show up at 6:45 or 7:00 and say, 'Any time is Trinidad time.'"

- When it comes to business, however, that loose approach to timeliness works only for the people with power. A boss can show up late and toss off "any time is Trinidad time," but underlings are expected to be more punctual.

- However, the nebulous nature of time can make it difficult for anthropologists and social psychologists to study. How people deal with time day-to-day often has nothing to do with how they conceive of time as an abstract entity.

- Some cultures don't draw neat distinctions among the past, present, and future. Aboriginal people in Australia, for instance, believe that their ancestors crawled out of the earth during the Dreamtime. The ancestors "sang" the world into existence as they moved about naming each feature and living thing. Even today an entity doesn't exist unless an Aborigine "sings" it.

REAL TIME

- More than 200 years ago, Benjamin Franklin equated passing minutes and hours with shillings and pounds, which has been shortened to the phrase "time is money." Time has become to the 21st century what fossil fuels and precious metals were to previous epochs. Constantly measured and priced, this vital raw material continues to spur the growth of economies built on a foundation of terabytes per second.

- Our commodification of time results from a radical alteration in how we view the passage of events. Our fundamental human drives haven't changed from the Paleolithic era: we have the same impulses to eat, procreate, fight, or flee. But in the long transition from then to now, our subjective experience of time has been completely transformed.

- By one definition, time is a continuum in which one event follows another from the past through to the future. But today the number of occurrences packed inside a given interval, be it a year or a nanosecond, increases relentlessly. The technological age has become a game in which more is always better.

- In his 2000 book *Faster: The Acceleration of Just About Everything*, James Gleick notes that before Federal Express shipping became commonplace in the 1980s, the exchange of business documents didn't usually require a package to be delivered "absolutely positively overnight."

- At first, FedEx gave its customers an edge. Soon, though, the whole world expected goods to arrive the next morning. "When everyone adopted overnight mail, equality was restored," Gleick writes, "and only the universally faster pace remained."

- The advent of the internet eliminated the burden of having to wait until the next day for a delivery. In internet time, everything happens everywhere at once: Connected computer users can witness an update to a web page at an identical moment in New York City or Dakar. Time has, in essence, triumphed over space.

ABOUT THIS LESSON

This lesson is largely based on the introduction to the *Scientific American* special issue "A Matter of Time" and an overview of time units created by David Labrador for the same edition. Additional source articles within the issue include "Clocking Cultures" by *Scientific American*'s editors and "Real Time" by Gary Stix.

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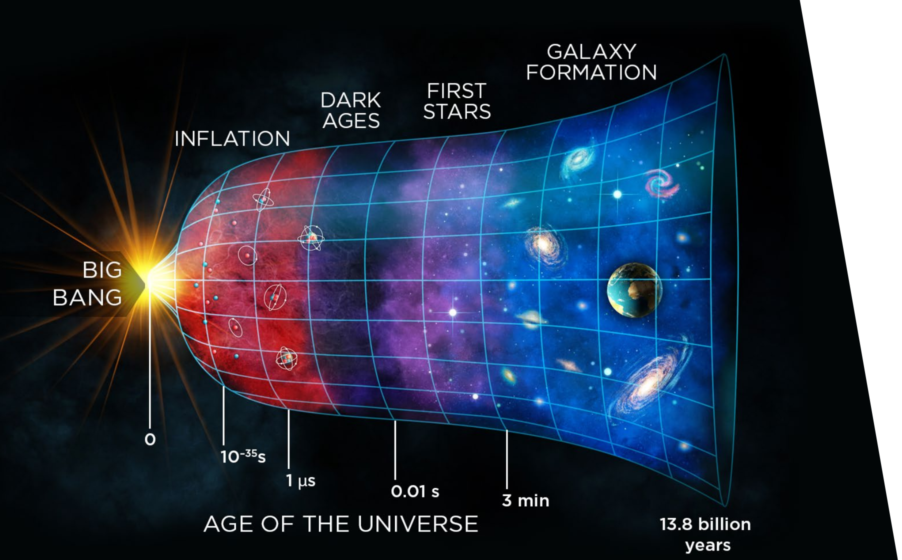
THE MYTH OF THE BEGINNING OF TIME

Was the big bang really the beginning of time, or did the universe exist before then? That question is the focus of this lesson, and it is a question that seemed almost blasphemous only decades ago. Most cosmologists insisted that it made no sense. But developments in theoretical physics, especially the rise of string theory, have changed their perspective. The pre-bang universe has become a frontier of cosmology.



GOING **BACK** TO THE **BIG BANG**

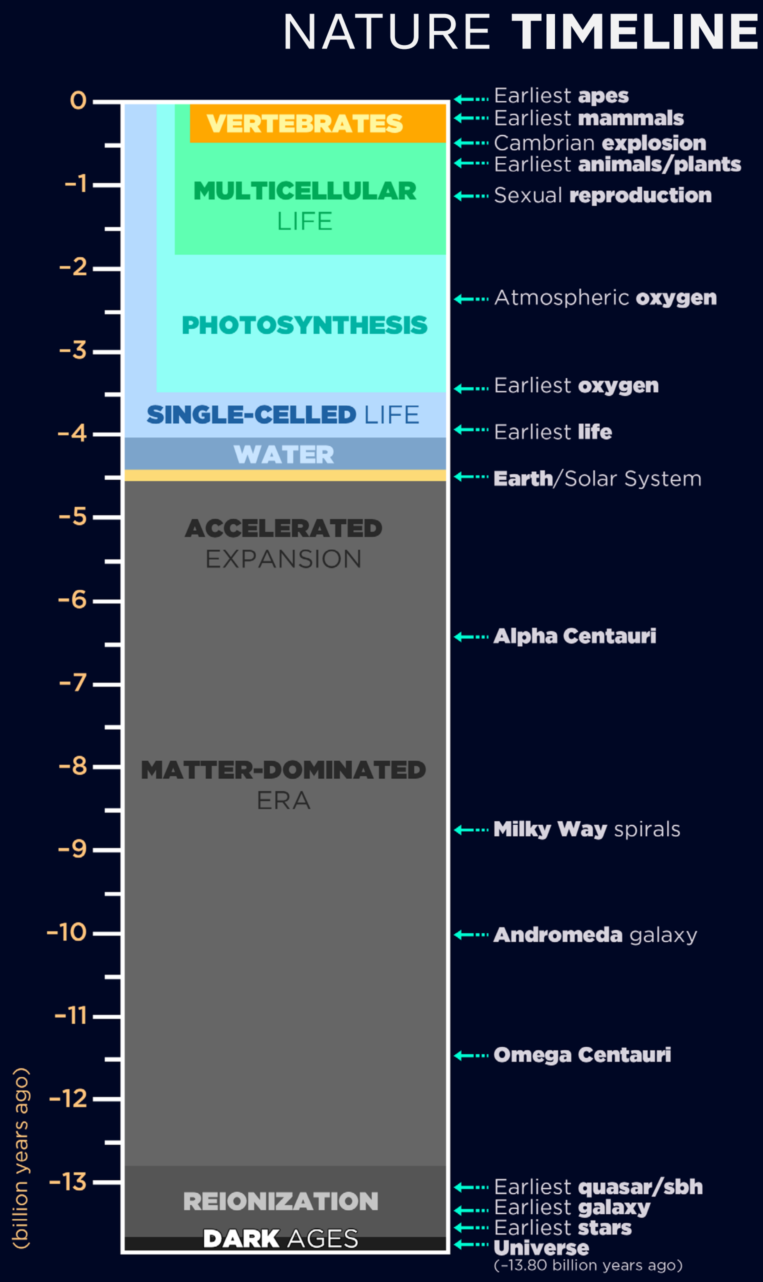
- Einstein's general theory of relativity holds that space and time are malleable. On the largest scales, space is naturally dynamic, expanding or contracting over time, carrying matter like driftwood on the tide.

- In the 1920s, astronomers confirmed that our universe is currently expanding: Distant galaxies move apart from one another. One consequence, as physicists Stephen Hawking and Roger Penrose proved in the 1960s, is that time can't extend back indefinitely.

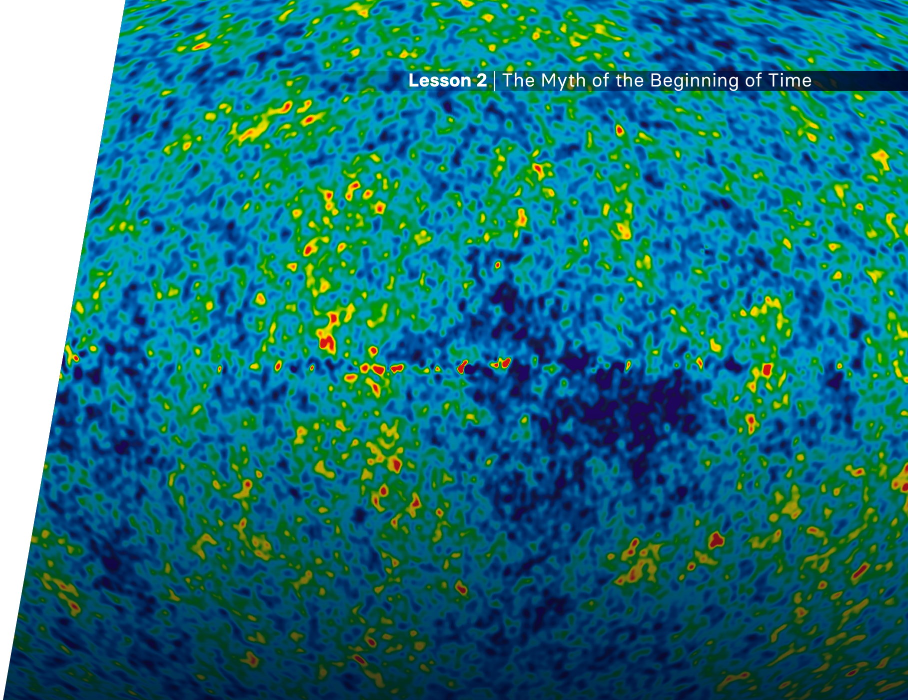
- As cosmic history plays backward in time, the galaxies all come together to a single infinitesimal point, known as a singularity. Each galaxy or its precursor is squeezed down to zero size. Quantities such as density, temperature, and spacetime curvature become infinite. The singularity is the ultimate cataclysm, beyond which our cosmic ancestry cannot extend.

- The unavoidable singularity poses serious problems for cosmologists. For the cosmos to look broadly the same everywhere, some kind of communication had to pass among distant regions of space, coordinating their properties. Yet the idea of such communication contradicts the standard understanding of cosmology.

- Consider what has happened over the 13.8 billion years since the big bang. The distance between galaxies has grown by a factor of about 1,000 because the universe is expanding, while the radius of the observable universe has grown by the much larger factor of about 100,000 because light outpaces the expansion.



NATURE TIMELINE
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
(billion years ago)
VERTEBRATES
MULTICELLULAR LIFE
PHOTOSYNTHESIS
SINGLE-CELLED LIFE
WATER
ACCELERATED EXPANSION
MATTER-DOMINATED ERA
REIONIZATION
DARK AGES
Earliest apes
Earliest mammals
Cambrian explosion
Earliest animals/plants
Sexual reproduction
Atmospheric oxygen
Earliest oxygen
Earliest life
Earth/Solar System
Alpha Centauri
Milky Way spirals
Andromeda galaxy
Omega Centauri
Earliest quasar/sbh
Earliest galaxy
Earliest stars
Universe
(~13.80 billion years ago)



IDENTICAL REGIONS OF SPACE

- We see parts of the universe today that we couldn't have seen 13.8 billion years ago. Indeed, this is the first time in cosmic history that light from the most distant galaxies has reached the Milky Way. Nevertheless, the properties of the Milky Way are basically the same as those of distant galaxies.

- Here is an analogy: A person shows up to a party to find he's dressed in the exact same outfit as a dozen of his friends. This suggests that everyone coordinated their attire in advance. In cosmology, it's not clothes but tens of thousands of independent yet statistically identical patches of sky in the cosmic microwave background radiation, which is the afterglow from the big bang.

- One possible explanation is that all those regions of space were endowed at birth with identical properties. However, physicists have come up with two more natural ways out of the impasse: that the early universe was either much smaller or much older than in standard cosmology. Either (or both, acting together) would have made intercommunication possible.

- One explanation follows the first alternative. It postulates that the universe went through a period of accelerating expansion, known as inflation, early in its history. Before this phase, galaxies or their precursors were so close that they could easily coordinate their properties.

- During inflation, they fell out of contact because light couldn't keep pace with the frenetic expansion. After inflation ended, the expansion began to decelerate, so galaxies gradually came back into one another's view.

- Proposed in 1981, inflation has explained a wide variety of observations with precision. But a number of possible theoretical problems remain, beginning with the questions of what exactly the inflation was and what gave it such a huge initial potential energy.

- Another way to solve the puzzle follows the second alternative by getting rid of the singularity. If time didn't begin at the big bang, and if a long era preceded the onset of the present cosmic expansion, then matter could have had plenty of time to arrange itself smoothly. This has led some researchers to reexamine the reasoning that led them to infer a singularity.

- One of the assumptions—that relativity theory is always valid—is questionable. Close to the putative singularity, quantum effects must have been important. Standard relativity takes no account of such effects, so accepting the inevitability of the singularity amounts to trusting the theory beyond reason.

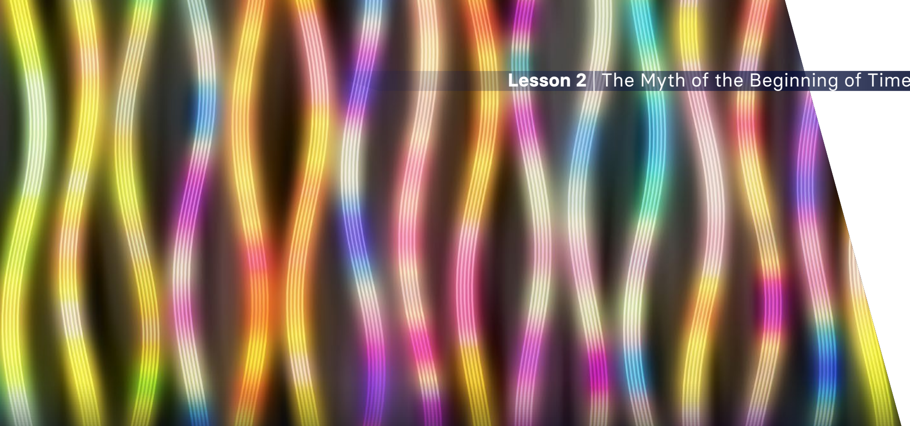
STRING THEORY

- To know what really happened, physicists need to include relativity in a quantum theory of gravity. Today, two approaches stand out. One is called loop quantum gravity. The second approach is string theory—a truly revolutionary modification of Einstein's theory. String theory is this lesson's focus, although proponents of loop quantum gravity reach many of the same conclusions.

- String theory grew out of a model that physicist Gabriele Veneziano wrote in 1968 to describe the world of nuclear particles (such as protons and neutrons) and their interactions. Despite much initial excitement, the model was abandoned several years later in favor of quantum chromodynamics, which describes nuclear particles in terms of more elementary constituents called quarks.

- Quarks are confined inside a proton or a neutron, as if they were tied together by elastic strings. In retrospect, the original string theory had captured those stringy aspects of the nuclear world. Only later was it revived as a candidate for combining general relativity and quantum theory.

- The basic idea is that elementary particles are not point-like but rather infinitely thin, one-dimensional objects—the strings. The large zoo of elementary particles, each with its own characteristic properties, reflects the many possible vibration patterns of a string.



QUANTUM STRING **MAGIC**

- How can such a "simple-minded theory," as Veneziano calls it, describe the complicated world of particles and their interactions? The answer can be found in what he dubbed "quantum string magic." Once the rules of quantum mechanics are applied to a vibrating string—just like a miniature violin string, except that the vibrations propagate along it at the speed of light—new properties appear. All have profound implications for particle physics and cosmology.

- First, quantum strings have a finite size. The irreducible quantum of length, denoted as l_s, plays a crucial role in string theory, putting a finite limit on quantities that otherwise could become either zero or infinite.

- Second, quantum strings may have angular momentum even if they lack mass. In classical physics, a massless object can have no angular momentum. But quantum fluctuations change the situation. A tiny string can acquire a certain amount of angular momentum without gaining any mass. Angular momentum clued physicists in to the quantum-gravitational implications of string theory.

- Third, quantum strings demand the existence of extra dimensions of space. The equations describing the quantum string vibrations become inconsistent unless spacetime is either highly curved (contrary to observations) or contains six additional spatial dimensions.

- Fourth, physical constants no longer have arbitrary, fixed values. They occur in string theory as fields that can adjust their values dynamically.

  - These fields may have taken different values in different cosmological epochs or in remote regions of space, and even today the physical "constants" may vary by a small amount. Observing any variation would provide an enormous boost to string theory.

  - One such field, called the dilaton, is the master key to string theory; it determines the overall strength of all interactions. The dilaton fascinates string theorists because its value can be reinterpreted as the size of an extra dimension of space, giving a grand total of 11 spacetime dimensions.

- Finally, quantum strings have introduced physicists to some striking new symmetries of nature known as dualities, which alter our intuition for what happens when objects get extremely small. Typically, a short string is lighter than a long one, but if we attempt to squeeze down its size below the fundamental length l_s, the string becomes heavier again.

T-DUALITY

- Another form of the symmetry, T-duality, holds that small and large extra dimensions are equivalent. This symmetry arises because strings can move in more complicated ways than point-like particles can. Consider a closed string (a loop) located on a cylindrically shaped space, whose circular cross-section represents one finite extra dimension. Besides vibrating, the string can either turn as a whole around the cylinder or wind around it.

- The energetic cost of these two states of the string depends on the size of the cylinder. The energy of winding is directly proportional to the cylinder radius. The energy associated with moving around the circle, on the other hand, is inversely proportional to the radius.

- If a large cylinder is substituted for a small one, the two states of motion can swap roles. Energies that had been produced by circular motion are instead produced by winding, and vice versa. An outside observer notices only the energy levels, not the origin of those levels. To that observer, the large and small radii are physically equivalent.

- Although T-duality is usually described in terms of cylindrical spaces, where one dimension (the circumference) is finite, a variant of it applies to our ordinary three dimensions, which appear to stretch on indefinitely. An infinite space's overall size can't change; it remains infinite. But it can still expand in the sense that bodies embedded within it, such as galaxies, move apart from one another.

- The crucial variable is not the size of the space as a whole but its scale factor—by which the distance between galaxies changes. According to T-duality, universes with small scale factors are equivalent to ones with large scale factors. No such symmetry is present in Einstein's equations; it emerges from the unification that string theory embodies, with the dilaton playing a central role.

- For years, string theorists thought that T-duality applied only to closed strings, as opposed to open strings, which have loose ends and thus can't wind. But scientists in the 1990s realized that T-duality did apply to open strings, provided the switch between large and small radii was accompanied by a change in the conditions at the end points of the string. Certain boundary conditions describe how the ends stay put.

- For instance, electrons may be strings whose ends can move around freely in three of the 10 spatial dimensions but are stuck within the other seven. Those three dimensions form a subspace known as a Dirichlet membrane, or D-brane. In 1996, Petr Hořava and Edward Witten proposed that our universe resides on such a brane.

AN ABHORRENCE OF **INFINITY**

- The magic properties of quantum strings point in one direction: Strings abhor infinity. They can't collapse to an infinitesimal point, so they avoid the paradoxes that collapse entails. They have nonzero sizes and novel symmetries that set upper bounds to physical quantities that increase without limit in conventional theories, and they set lower bounds to quantities that decrease.

- String theorists expect that when you play the history of the universe backward in time, the curvature of spacetime starts to increase. But instead of going all the way to infinity (at the traditional big bang singularity), it eventually hits a maximum and shrinks again. Before string theory, physicists were hard-pressed to imagine any mechanism that could so cleanly eliminate the singularity.

- Conditions near the zero time of the big bang were so extreme that no one yet knows how to solve the equations. Nevertheless, string theorists have hazarded guesses about the pre-bang universe. Two popular models are floating around.

- The first is known as the pre–big bang scenario, which Gabriele Veneziano and his colleagues began to develop in 1991. It combines T-duality with the better-known symmetry of time reversal, whereby the equations of physics work equally well when applied backward and forward in time.

- The combination gives rise to new possible cosmologies in which the universe, for example, five seconds before the big bang expanded at the same pace as it did five seconds after the bang. Yet the rate of change of the expansion was opposite at the two instants: If it was decelerating after the bang, it was accelerating before.

- The second popular model for the pre-bang universe is the so-called ekpyrotic (or conflagration) scenario. It relies on the idea that our universe sits at one end of a higher-dimensional space and a "hidden brane" sits at the opposite end.

- The two branes exert an attractive force on each other and occasionally collide, making the extra dimension shrink to zero before growing again. The big bang would correspond to the time of collision. In a variant of this scenario, the collisions occur cyclically.

- The pre–big bang and ekpyrotic scenarios share some common features. Both begin with a large, cold, nearly empty universe, and both share the difficult (and unresolved) problem of making the transition between the pre- and the post-bang phase.

ABOUT THIS LESSON

This lesson was adapted from the article "The Myth of the Beginning of Time" by Gabriele Veneziano, one of the founders of string theory and one of the first to later apply the theory to black holes and cosmology.

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THAT MYSTERIOUS **FLOW**

This lesson looks at the passage of time, which is probably the most basic facet of human perception: We feel time slipping by in our innermost selves in a manner that is far more intimate than our experience of, for instance, space or mass. However, nothing in known physics corresponds to the passage of time. Physicists insist that time doesn't flow at all; it merely is. Some philosophers argue that the very notion of the passage of time is nonsensical.

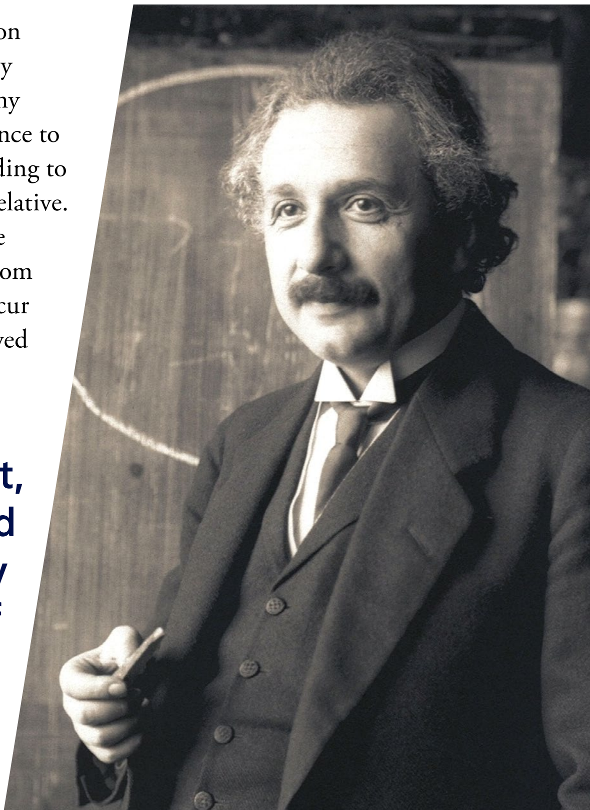
PAST, PRESENT, AND FUTURE

- In daily life, we divide time into three parts: past, present and future. Reality is associated with the present moment. The past we think of as having slipped out of existence, whereas the future is even more shadowy, its details still unformed.

- In this simple picture, the “now” of our conscious awareness glides steadily onward, transforming events that were once in the unformed future into the concrete-but-fleeting reality of the present—and then relegating them to the fixed past. However, this is at odds with modern physics. Albert Einstein famously expressed this point when he wrote to a friend, “The past, present, and future are only illusions, even if stubborn ones.”

- Einstein’s startling conclusion stems from his special theory of relativity, which denies any absolute, universal significance to the present moment. According to the theory, simultaneity is relative. Two events that occur at the same moment if observed from one reference frame may occur at different moments if viewed from another.

“The past, present, and future are only illusions, even if stubborn ones.”



INFERRING ANSWERS

- An innocuous question such as "What's happening on Mars now?" has no definite answer. The key point is that Earth and Mars are a long way apart—up to about 20 light-minutes.

- Because information can't travel faster than light, an Earth-based observer is unable to know the situation on Mars at the same instant. They must infer the answer after the event, when light has had a chance to pass between the planets. The inferred past event will be different depending on the observer's velocity.

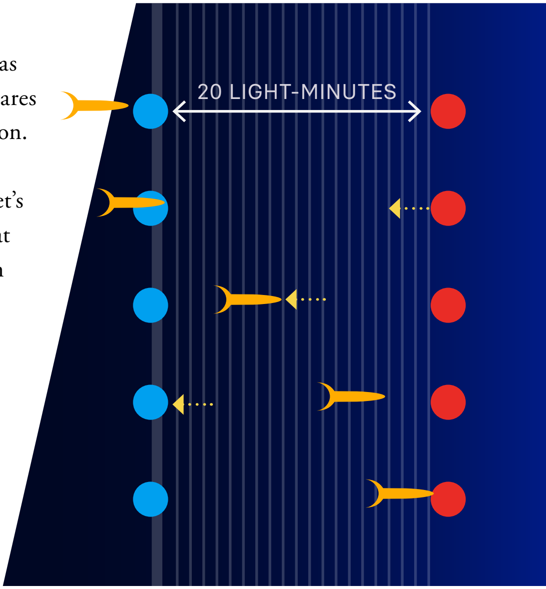
- For example, during a future crewed expedition to Mars, mission controllers back on Earth might say, "I wonder what Commander Jones is doing at Alpha Base right now." The trouble stems from the phrase "right now." Different people who are moving at different velocities have different perceptions of what the present moment is. This strange fact is known as the relativity of simultaneity.

- In the following scenario, two people—an earthling sitting in Houston and an astronaut crossing the solar system from Earth to Mars at 80% of the speed of light—attempt to answer the question of what's happening with a third person, Commander Jones, on Mars right now. On Mars, Commander Jones at Alpha Base has agreed to eat lunch when her clock strikes 12:00 pm and to transmit a signal at the same time.

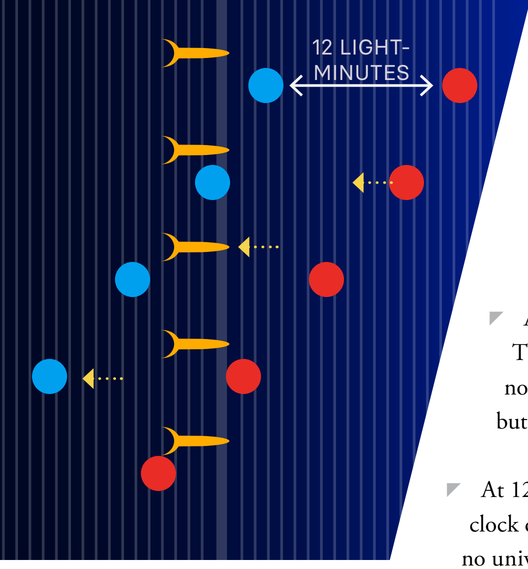
  - From the earthling's perspective, Earth is standing still, Mars is a constant distance (20 light-minutes) away, and the rocket ship is moving at 80% of the speed of light. The situation looks exactly the same to the martian, Commander Jones.

  - Before noon, by exchanging light signals, the earthling and martian measure the distance between them and synchronize their clocks.

- At 12:00 pm, the earthling hypothesizes that the martian has begun to eat her lunch. He prepares to wait 20 minutes for verification.
- At 12:11 pm, knowing the rocket's speed, the earthling deduces that it encounters the signal while on its way to Mars.
- At 12:20 pm, the signal arrives at Earth. The earthling has confirmed his earlier hypothesis. Noon on Mars is the same as noon on Earth.
- At 12:25 pm, the ship arrives at Mars.



- However, the situation as seen from the rocket is different. From the rocket man's perspective, the rocket is standing still. It is the planets that are hurtling through space at 80% of the speed of light.
- His measurements show the two planets to be separated by 12 light-minutes—a different distance from what the earthling inferred. This discrepancy, an effect of Einstein's theory, is called length contraction.
- A related effect, time dilation, causes clocks on the ship and planets to run at different rates. As the ship passes Earth, it synchronizes its clock to Earth's. Before noon, by exchanging light signals with his colleagues, the rocket man measures the distance between the planets.
  - At 12:00 pm, while passing Earth, the rocket man hypothesizes that Commander Jones has begun to eat. He prepares to wait 12 minutes for verification.



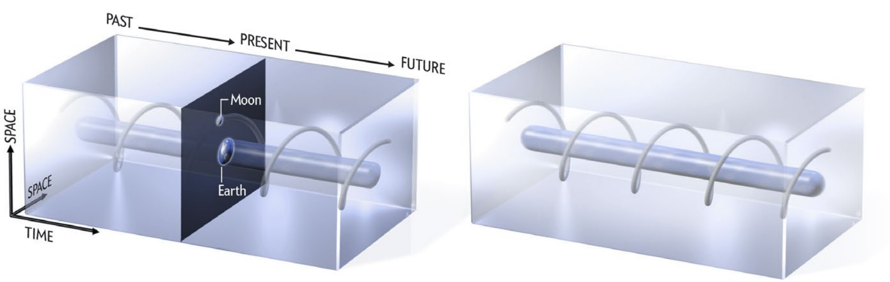
- At 12:07 pm, the signal arrives, disproving the hypothesis. The rocket man infers that the Martian ate sometime before noon (rocket time).

- At 12:15 pm, Mars arrives at the ship. The rocket man and Commander Jones notice that their two clocks are out of sync but disagree as to whose is right.

- At 12:33 pm, the signal arrives at Earth. The clock discrepancies demonstrate that there is no universal present moment.

- Such mismatches make a mockery of any attempt to confer special status on the present moment, for whose "now" does that moment refer to? If two people are in relative motion, an event that one might judge to be in the as-yet-undecided future might already exist in the fixed past for the other.

- The most straightforward conclusion is that both past and future are fixed. For this reason, physicists prefer to think of time as laid out in its entirety—a timescape, analogous to a landscape—with all past and future events located there together. It's a notion sometimes referred to as block time. Under this line of thought, the time of the physicist does not pass or flow.



Conventional view: Only the present is real

Block universe: All times are equally real

PHILOSOPHERS' CONCLUSIONS

- A number of philosophers over the years have arrived at the same conclusion by examining what we normally mean by the passage of time. They argue that the notion is internally inconsistent. The concept of flux, after all, refers to motion.

- It makes sense to talk about the movement of a physical object, such as an arrow through space, by gauging how its location varies with time. But what meaning can be attached to the movement of time itself?

- Although we find it convenient to refer to time's passage in everyday affairs, the notion imparts no new information that can't be conveyed without it. Consider the following description:

    Alice was hoping for a white Christmas, but when the day came, she was disappointed that it only rained. However, she was happy that it snowed the following day.

- Although that description is replete with tenses and references to time's passage, exactly the same information is conveyed by simply correlating Alice's mental states with dates. Thus, the following cumbersome and rather dry catalogue of facts suffices:

    December 24: Alice hopes for a white Christmas.
    December 25: It rains. Alice is disappointed.
    December 26: It snows. Alice is happy.

- In this description, nothing happens or changes. There are simply states of the world at different dates and associated mental states for Alice. Similar arguments go back to ancient Greek philosophers such as Parmenides and Zeno.

- A century ago, the British philosopher John McTaggart sought to draw a clear distinction between the description of the world in terms of events happening, which he called the A series, and the description in terms of dates correlated with states of the world, the B series. Each appears to be a true description of reality, and yet the two points of view are seemingly in contradiction.

- For example, the event "Alice is disappointed" was once in the future, then in the present, and afterward in the past. But past, present, and future are exclusive categories, so how can a single event have the character of belonging to all three?

- McTaggart used this clash between the A and B series to argue for the unreality of time as such. Most physicists would put it less dramatically: The flow of time is unreal, but time itself is as real as space.

TIME ASYMMETRY

- A great source of confusion in discussions of time's passage stems from its link with the so-called arrow of time. To deny that time flows is not to claim that the designations *past* and *future* are without physical basis. Events in the world undeniably form a unidirectional sequence.

- Imagine an egg dropped on the floor. It will smash into pieces. The reverse process—a broken egg spontaneously assembling itself into an intact egg—is something we never see.

- This is an example of the second law of thermodynamics, which states that the entropy of a closed system—roughly defined as how disordered it is—will tend to rise with time. An intact egg has lower entropy than a shattered one.

- Because nature abounds with irreversible physical processes, the second law of thermodynamics plays a key role in imprinting on the world a conspicuous asymmetry between past and future directions along the time axis. By convention, the arrow of time points toward the future.

- This does not imply, though, that the arrow is moving toward the future any more than a compass needle pointing north indicates that the compass is traveling north. Both arrows symbolize an asymmetry, not a movement.

AN ILLUSION?

- Some researchers have contended that the subtle physics of irreversible processes make the flow of time an objective aspect of the world. But theoretical physicist Paul Davies and others argue that it's really just an illusion.

- After all, we don't really observe the passage of time. In reality, we observe that later states of the world differ from earlier states we still remember. The fact that we remember the past, rather than the future, is an observation not of the passage of time but of the asymmetry of time.

- Only conscious observers can register the flow of time. Much as a measuring tape measures distances between places, a clock measures durations between events. However, that is all it measures. It doesn't measure the speed with which one moment succeeds another. It appears the flow of time is subjective, not objective. This illusion cries out for explanation, and that explanation is to be sought in psychology, neurophysiology, and perhaps linguistics or culture.

PERCEPTIONS OF TIME

- Since modern science has barely begun to consider the question of how we perceive the passage of time, we can only speculate about the answer. It might have something to do with the functioning of the brain. There are two aspects to time asymmetry that might create the false impression that time is flowing.

- The first is the thermodynamic distinction between past and future. As physicists have come to realize, the concept of entropy is closely related to the information content of a system. For this reason, the formation of memory is a unidirectional process: New memories add information and raise the entropy of the brain. We might perceive this unidirectionality as the flow of time.

- A second possibility is that our perception of the flow of time is linked in some way to quantum mechanics. From the earliest days of the formulation of quantum mechanics, physicists recognized that time enters into the theory in a unique manner, quite unlike space. The special role of time is one reason it is proving so difficult to merge quantum mechanics with general relativity.

- The Heisenberg uncertainty principle, which says that nature is inherently indeterministic, implies an open future (and, for that matter, an open past). This indeterminism manifests itself most conspicuously on an atomic scale of size and dictates that the observable properties that characterize a physical system are generally undecided from one moment to the next.

- For example, an electron hitting an atom may bounce off in one of many directions, and it is normally impossible to predict in advance what the outcome in any given case will be. Quantum indeterminism implies that for a particular quantum state, there are many (possibly infinite) alternative futures or potential realities. Quantum mechanics supplies the relative probabilities for each observable outcome, although it won't say which potential future is destined for reality.

- However, when a human observer makes a measurement, only one result is obtained; for example, the rebounding electron will be found moving in a certain direction. In the act of measurement, a single, specific reality becomes projected out from a vast array of possibilities.

- Within the observer's mind, the possible makes a transition to the actual. It transitions from the open future to the fixed past—which is precisely what we mean by the flux of time.

- Unfortunately, physicists disagree on how this transition from many potential realities into a single actuality takes place. Many have argued it has something to do with the consciousness of the observer—that it's the act of observation itself that prompts nature to make up its mind. A few researchers maintain that consciousness—including the impression of temporal flux—could be related to quantum processes that take place in the brain.

ABOUT THIS LESSON

This lesson was adapted from the article "That Mysterious Flow" by Paul Davies, a theoretical physicist and cosmologist at Arizona State University, where he is director of the Beyond Center for Fundamental Concepts in Science.

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IS TIME AN **ILLUSION?**

This lesson considers the question posed by its title: Is time an illusion? To us, it feels like time flows. However, as natural as this way of thinking is, it isn't reflected in science. Physics equations are like a map without the "You Are Here" symbol. The present moment doesn't exist in them, and therefore neither does the flow of time. In fact, Einstein's theories of relativity suggest not only that there is no single special present but also that all moments are equally real. The future is no more open than the past.

EMERGENT TIME

- The gap between our scientific understanding of time and our everyday experience has troubled thinkers throughout history. It has widened as physicists have gradually stripped time of most of the attributes we commonly ascribe to time. This rift is reaching its logical conclusion, for many theoretical physicists have come to believe that time fundamentally does not exist.

- A timeless theory faces the challenge of explaining how we see change if the world isn't really changing. Recent research attempts to pull off just this feat. Although time may not exist at a fundamental level, it may arise at higher levels—just as a table feels solid even though it is actually a swarm of particles composed mostly of empty space. Solidity is a collective, or emergent, property of the particles. Time, too, could be an emergent property of whatever the basic ingredients of the world are.

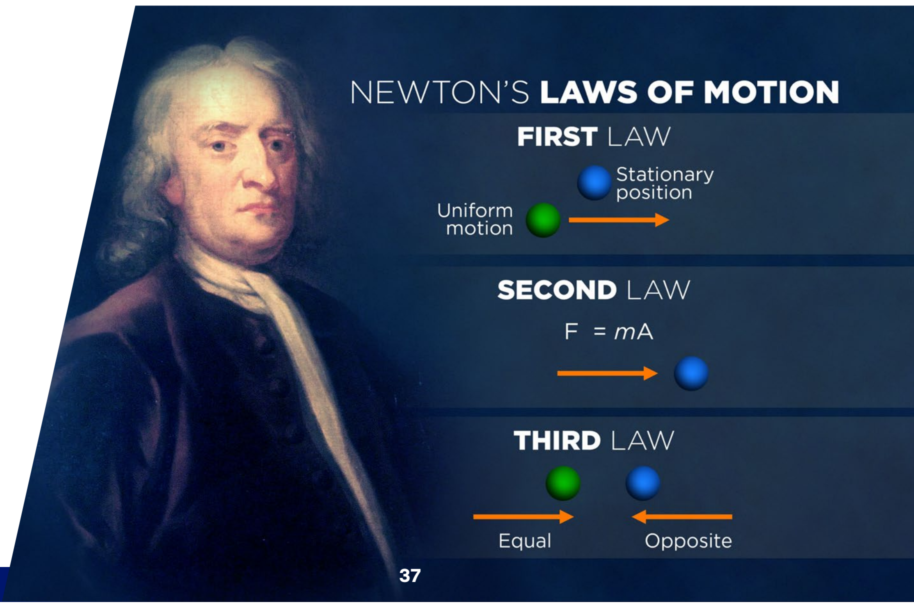
- This concept of emergent time seems as revolutionary as the theories of relativity and quantum mechanics a century ago. Einstein said that the key step forward in developing relativity was his reconceptualization of time. As physicists pursue his dream of unifying relativity with quantum mechanics, they believe time is again central.

NEWTONIAN TIME

- Newton's laws of motion require time to have many specific features. No matter when or where an event occurs, classical physics assumes all observers can objectively say whether it happens before, after, or simultaneously with any other event in the universe.

- Simultaneity is absolute—an observer-independent fact. And time must be continuous so that we can define velocity and acceleration. Classical time must also have an observer-independent notion of duration—what physicists call a metric—so that we can tell how far apart events are in time.

- Essentially, Newton proposed that the world comes equipped with a master clock that carves the world up into instants of time. Newton's physics listens to the ticking of this clock and no other. In classical physics, time flows and gives us an arrow pointing us toward the future.



- Order, continuity, duration, simultaneity, flow, and the arrow are all logically detachable, but they all stick together in the master clock that Newton dubbed *time*. This model succeeded so well that it survived unscathed for almost two centuries.

CHALLENGES TO TIME

- Then came the challenges of the late 19th and early 20th centuries. The first was the work of Austrian physicist Ludwig Boltzmann, who reasoned that because Newton's laws work equally well going forward or backward in time, time has no built-in arrow. Instead, Boltzmann proposed that the distinction between past and future is not intrinsic to time but arises from asymmetries in how the matter in the universe is organized.

- Einstein mounted the next challenge by doing away with the idea of absolute simultaneity. According to his special theory of relativity, which events are happening at the same time depends on how fast an observer is moving.

- The true arena of events is neither time nor space but rather their union: spacetime. Two observers moving at different velocities disagree on when and where an event occurs, but they agree on its spacetime location.

- The year 1915 brought Einstein's general theory of relativity, which extends special relativity to situations where the force of gravity operates. Gravity distorts time such that a second's passage in one location may not mean the same thing as it does in another.

- Only in rare cases is it possible to synchronize clocks and have them stay synchronized, even in principle. In extreme situations, the world might not be divisible into instants of time at all. It then becomes impossible to say that an event happened before or after another.

- With that in mind, one might be tempted to think that the difference between space and time has nearly vanished and that the true arena of events in a relativistic universe is a big four-dimensional block. Relativity appears to spatialize time—that is, to turn it into merely one more direction within the block.

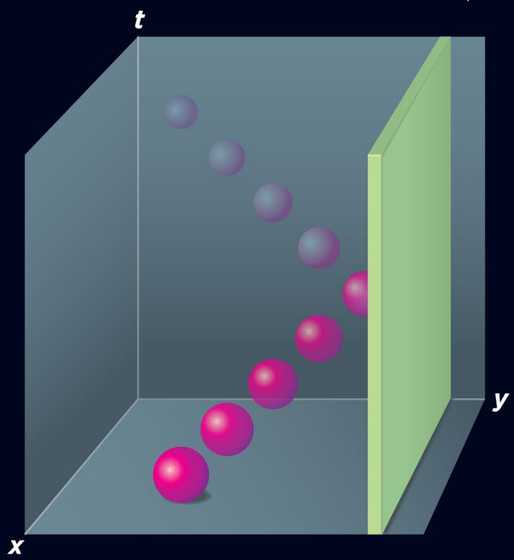
TIMELIKE AND SPACELIKE **DIRECTIONS**

- Even in general relativity, time retains a distinct and important function: that of distinguishing between timelike and spacelike directions. Timelike-related events are those that can be causally related. An object or signal can pass from one event to the other, influencing what happens. Spacelike-related events are causally unrelated.

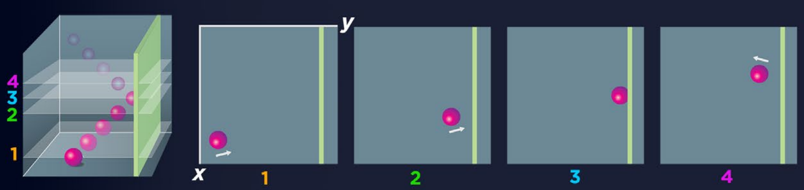
- Observers disagree on the sequence of spacelike events, but they all agree on the order of timelike events. If one observer perceives that an event can cause another, all observers do.

- In his essay for a 2008 contest sponsored by the Foundational Questions Institute, philosopher Craig Callender explored what this feature of time means. Imagine slicing up spacetime from past to future. Each slice is the three-dimensional totality of space at one instant of time. The sum of all these slices of spacelike-related events is four-dimensional spacetime.

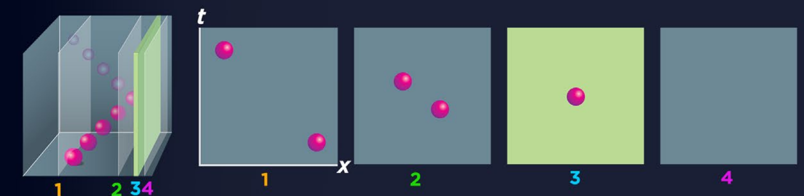
- Alternatively, imagine looking at the world sideways and slicing it up accordingly. From this perspective, each three-dimensional slice is a strange amalgam of events that are spacelike-related (in just two dimensions) and timelike-related.



THE USUAL WAY takes slices of space at successive moments of time.



AN ALTERNATIVE considers slices not from past to future but from left to right.



- The first method is familiar to physicists and moviegoers alike. The frames of a movie represent slices of spacetime: They show space at successive moments of time. Like film buffs who instantly figure out the plot from just one scene, physicists can take a single complete spatial slice and reconstruct what happens on the other spatial slices, simply by applying the laws of physics.

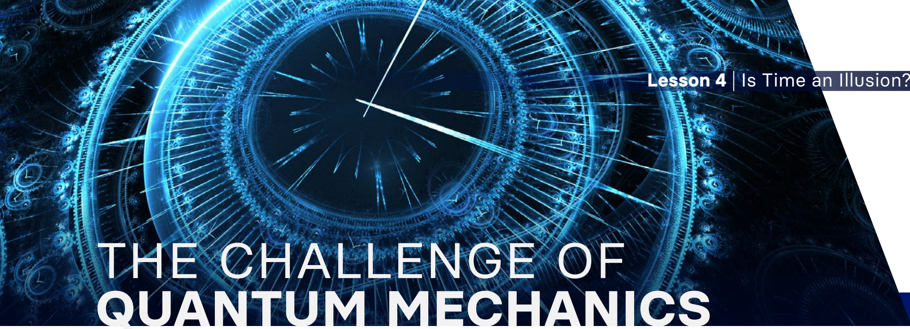
- The second method of slicing has no simple analogy. Rather than slicing up spacetime from past to future, it involves carving from east to west. An example might be the north wall in a house plus what will happen on that wall in the future. From this slice, one could try to apply the laws of physics to reconstruct what the rest of the house (and indeed the rest of the universe) looks like.

- It's not immediately obvious whether the laws of physics allow such an analysis. But as mathematician Walter Craig of McMaster University and philosopher Steven Weinstein of the University of Waterloo have shown, it is possible, at least in some simple situations.

- In the normal, past-to-future slicing, the data needed from a slice are fairly easy to obtain. For instance, a physicist might measure the velocities of all particles. The velocity of a particle in one location is independent of the velocity of a particle someplace else, making both of them easy to measure.

- But in the second method, the particles' properties aren't independent; they have to be set up in a very specific way, or else a single slice wouldn't suffice to reconstruct all the others. A physicist would have to perform extremely difficult measurements on groups of particles to gather the data needed. Only in special cases would even these measurements allow reconstruction of the full spacetime.

- In a very precise sense, time is the direction within spacetime in which good prediction is possible—the direction in which we can tell the most informative stories. The narrative of the universe doesn't unfold in space. It unfolds in time.



THE CHALLENGE OF **QUANTUM MECHANICS**

- One of the highest goals of modern physics is to unite general relativity with quantum mechanics, producing a single theory that handles both the gravitational and quantum aspects of matter—a quantum theory of gravity. One of the stumbling blocks has been that quantum mechanics requires time to have properties that contradict information covered previously in this lesson.

- Quantum mechanics says that objects have a much richer repertoire of behaviors than we can possibly capture with classical quantities such as position and velocity. The full description of an object is given by a mathematical function called the quantum state, which evolves continuously in time. Using it, physicists are able to calculate the probabilities of any experimental outcome at any time.

- If we send an electron through a device that will deflect it either up or down, quantum mechanics may not be able to tell us with certainty which outcome to expect. Instead, the quantum state may give us only probabilities. An example would be giving a 25% chance the electron will veer upward and a 75% chance it'll veer downward. The outcomes of experiments are probabilistic. Two systems described with identical quantum states may give different outcomes.

- The theory's probabilistic predictions require time to have certain features. First, time is what makes contradictions possible. For instance, a rolled die can't have two different numbers facing up at the same time. Additionally, the probability of landing on each of the six numbers must add up to 100%.

- Second, the temporal order of quantum measurements makes a difference. Suppose a researcher passes an electron through a device that deflects it first along the vertical direction, then along the horizontal direction. As it emerges, the researcher measures its angular momentum. The researcher repeats the experiment, this time deflecting the electron horizontally, then vertically. The researcher then measures its angular momentum again. The values collected will be vastly different.

- Third, a quantum state provides probabilities for all of space at an instant of time. If the state encompasses a pair of particles, then measuring one particle instantaneously affects the other no matter where it is—leading to the infamous "spooky action at a distance" that so troubled Einstein. The reason it bothered him was that for the particles to react at the same time, the universe must have a master clock, which relativity expressly forbids.

UNIFICATION EFFORTS

- Physicists fret about the absence of time in relativity, but perhaps a worse problem is the central role of time in quantum mechanics. It's the reason unification has been so hard.

- A slew of research programs have sought to reconcile general relativity and quantum mechanics: superstring theory, causal triangulation theory, noncommutative geometry, and more. They split roughly into two groups.

- Physicists who think quantum mechanics provides the firmer foundation, like superstring theorists, start with a robust version of time. Those who believe general relativity provides the better starting point begin with a theory in which time is already demoted and hence are more open to the idea of a timeless reality.

- To convey the basic problem that time poses, focusing on the second approach is helpful. The leading instance of this strategy is loop quantum gravity, which descends from an earlier program known as canonical quantum gravity.

- Canonical quantum gravity emerged in the 1950s and 1960s, when physicists rewrote Einstein's equations for gravity in the same form as those for electromagnetism. The idea was that the techniques applied to electromagnetism could also be applied to gravity.

- When John Archibald Wheeler and Bryce DeWitt attempted this procedure in the late 1960s, they arrived at a very strange result. In the so-called Wheeler-DeWitt equation, shown below, the symbol *t* denoting time simply vanished.

$$\left[-G_{ijkl}\frac{\delta^2}{\delta\gamma_{ij}\delta\gamma_{kl}} - {}^3R(\gamma)\gamma^{1/2} + 2\Lambda\gamma^{1/2}\right]\Psi[\gamma_{ij}] = 0$$

$$G_{ijkl} = \frac{1}{2}\gamma^{-1/2}\left(\gamma_{ik}\gamma_{jl} + \gamma_{il}\gamma_{jk} - \gamma_{ij}\gamma_{kl}\right)$$

- Decades of consternation followed for physicists: How could time just disappear? In retrospect, this result isn't very surprising, since time had already nearly disappeared from general relativity even before physicists attempted to merge it with quantum mechanics.

- If one takes this result literally, time doesn't really exist. Carlo Rovelli, one of the founders of loop quantum gravity, called his Foundational Questions Institute essay "Forget Time." He and English physicist Julian Barbour are the foremost proponents of this idea, and they've attempted to rewrite quantum mechanics in a timeless manner, as relativity appears to require.

- The reason they think this is possible is that general relativity still manages to describe change. It does so by relating physical systems directly to one another rather than to some abstract notion of global time.

GETTING RID OF **TIME**

- Although getting rid of time has its appeal, it inflicts collateral damage. For one, it requires quantum mechanics to be thoroughly rethought. Consider the famous case of Schrödinger's cat.

- The cat is suspended between life and death, its fate hinging on the state of a quantum particle. In the usual way of thinking, the cat becomes alive or dead after a measurement takes place. But Rovelli would argue that the status of the cat is never resolved. The cat may be dead with respect to itself, alive relative to a human in the room, dead relative to a second human outside the room, and so on.

- It's one thing to make the timing of the cat's death depend on the observer, as special relativity does. It's rather more surprising to make whether it even happens relative, as Rovelli suggests, following the spirit of relativity as far as it will go. Because time is so basic, banishing it would transform our worldview.

- Even if the world is fundamentally timeless, it still seems to contain time. Anyone espousing timeless quantum gravity still has to explain why the world *seems* temporal. General relativity, too, lacks Newtonian time, but at least it has various partial substitutes that together behave like Newtonian time when gravity is weak and relative velocities low.

PIECES AS CLOCKS

- Canonical quantum gravity offers a more developed idea. Known as semiclassical time, it goes back to a 1931 paper by English physicist Nevill F. Mott describing the collision between a helium nucleus and a larger atom. To model the total system, Mott applied an equation lacking time that is usually applied only to static systems. He then divided the system into two subsystems and used the helium nucleus as a "clock" for the atom.

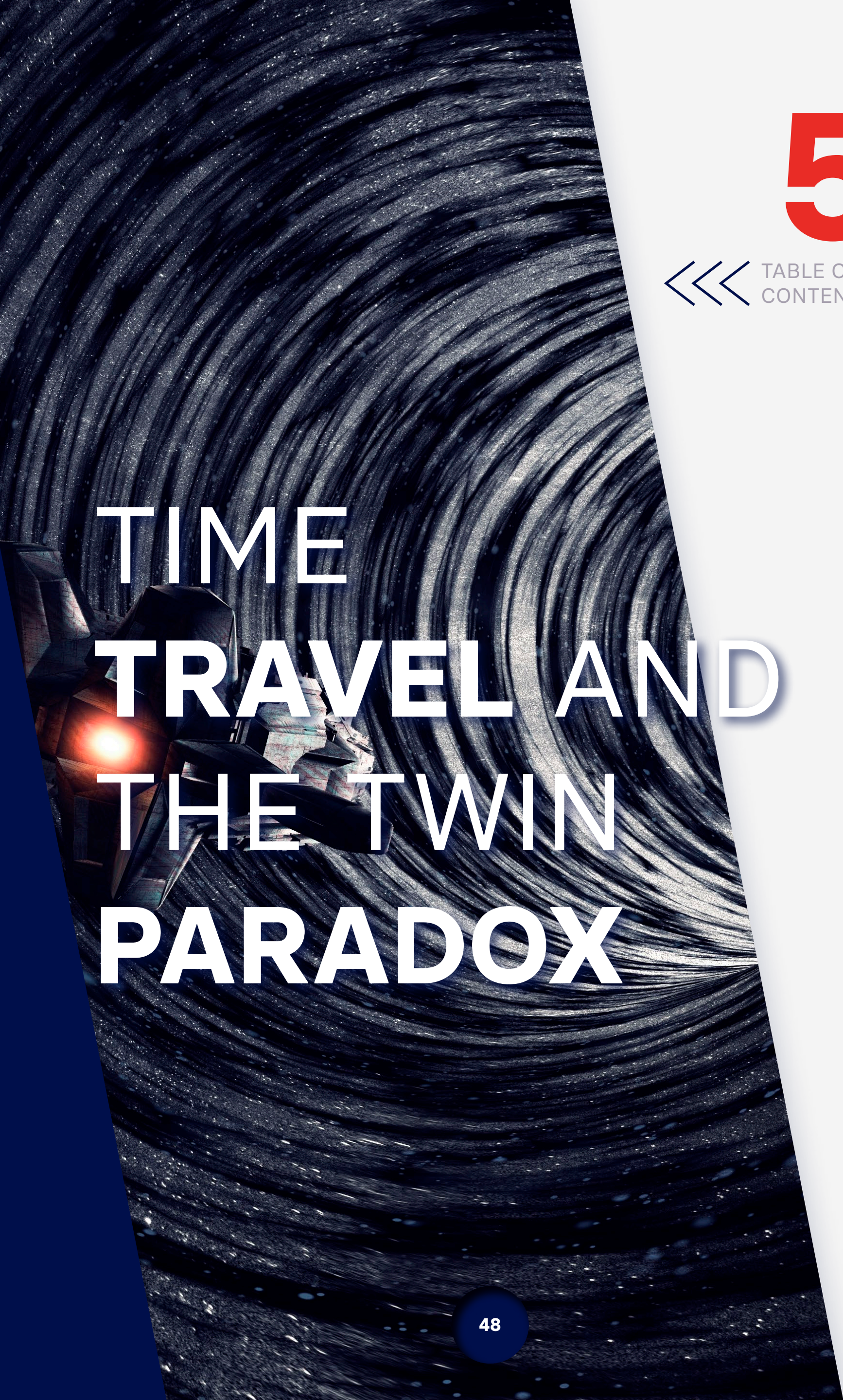
- Remarkably, relative to the nucleus, the atom obeys the standard time-dependent equation of quantum mechanics. A function of space plays the role of time. Even though the system as a whole is timeless, the individual pieces aren't. Hidden in the timeless equation for the total system is a time for the subsystem.

- Much the same works for quantum gravity, as Claus Kiefer of the University of Cologne argued in his Foundational Questions Institute essay. The universe may be timeless, but if one imagines breaking it into pieces, some of the pieces can serve as clocks for the others. Time emerges from timelessness. We perceive time because each of us is, by our very nature, one of those pieces.

- As interesting and startling as this idea is, it leaves us wanting more. The universe can't always be broken up into pieces that serve as clocks, and in those cases, the theory makes no probabilistic predictions. Handling such situations demands a full quantum theory of gravity and a deeper rethinking of time.

ABOUT THIS LESSON

This lesson was adapted from the articles "A Hole at the Heart of Physics" by George Musser, a science writer and contributing editor for *Scientific American*, and "Is Time an Illusion?" by Craig Callender, a philosophy professor at the University of California, San Diego.



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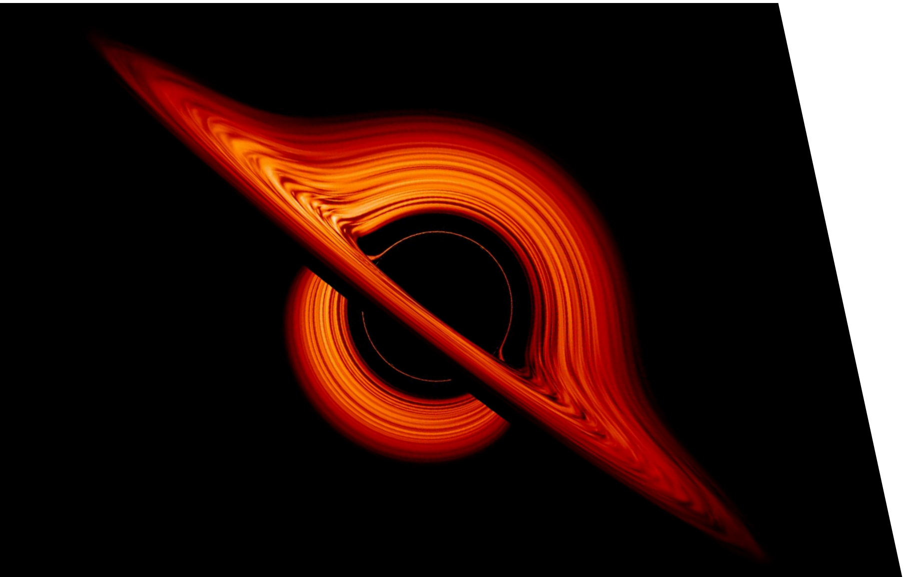
TIME TRAVEL AND THE TWIN PARADOX

To look at the topic of time travel, this lesson explores the roles of speed and gravity. Additionally, the lesson speculates on wormholes as a tool for time travel as well as paradoxes presented by time travel, including the famous twin paradox.



GRAVITY

- In his general theory of relativity, Einstein predicted that gravity slows time. This means that clocks run faster in space than they do on the ground. The effect is minuscule, but it has been directly measured using accurate clocks. In fact, these time-warping effects have to be taken into account in the Global Positioning System.

- At the surface of a neutron star, gravity is so strong that time is slowed down by about 30% relative to Earth time. Viewed from such a star, events on Earth would look like a fast-forwarded video.

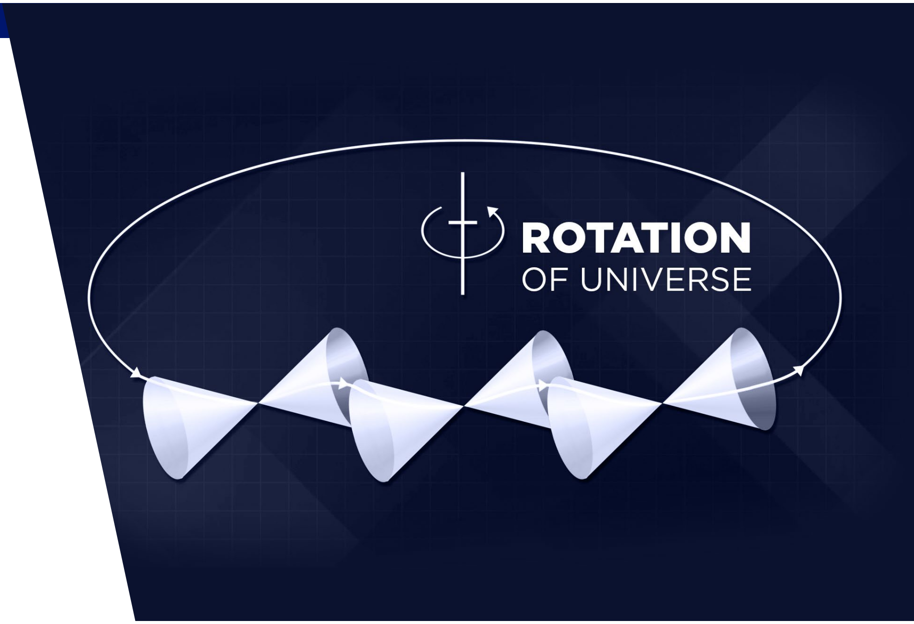
- A black hole represents the ultimate time warp. At the surface of the hole, time stands still relative to Earth. This means that if an astronaut fell into a black hole from nearby, in the brief interval it took her to reach the surface, all of eternity would pass by in the wider universe. However, if an astronaut could zoom very close to a black hole and return unscathed—admittedly a fanciful and foolhardy prospect—she could leap far into the future.

GOING BACKWARD

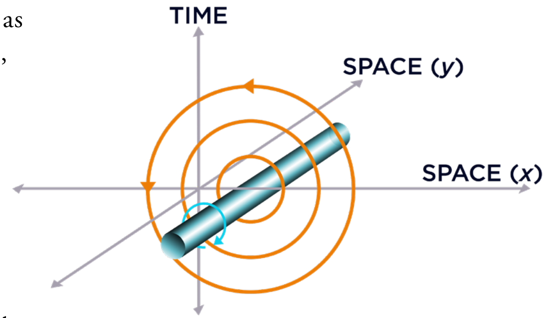
- Going backward in time is much more problematic. In 1948, Kurt Gödel of the Institute for Advanced Study produced a solution of Einstein's gravitational field equations that described a rotating universe. In this universe, an astronaut could travel through space so as to reach his own past.

- This is because of the way gravity affects light. The rotation of the universe would drag light around with it, allowing a material object to travel in a closed loop in space that's also a closed loop in time, without at any point exceeding the speed of light in the immediate neighborhood of the particle.

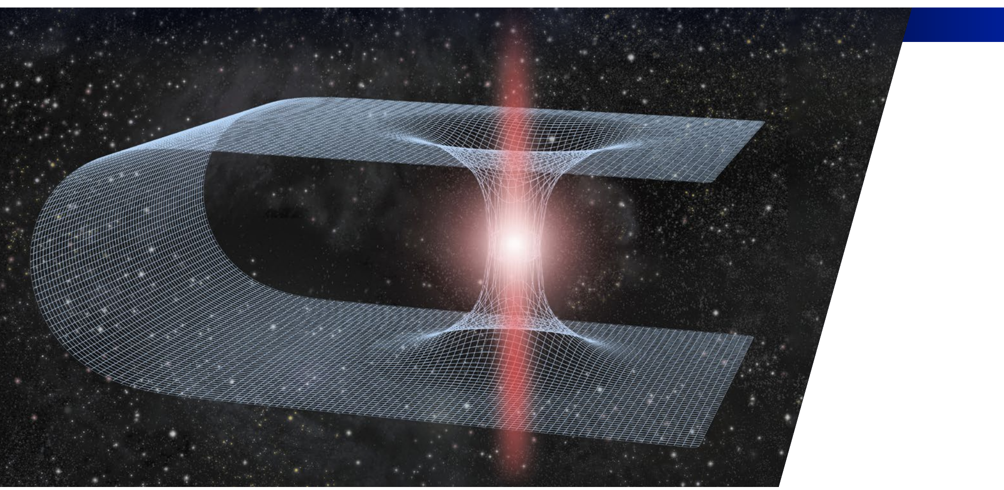
- Gödel's solution was shrugged off as a mathematical curiosity. Still, his result demonstrated that going back in time isn't forbidden by the theory of relativity.



- Other scenarios have been found to permit travel into the past as well. For example, in 1974, Frank J. Tipler of Tulane University calculated that a massive, infinitely long cylinder spinning on its axis at near the speed of light could let astronauts visit their own past, again by dragging light around the cylinder into a loop.



- In the mid-1980s, the most realistic scenario for a time machine emerged. This one was based on the concept of a wormhole. Because they offer a shortcut between two widely separated points in space, in science fiction, wormholes are sometimes called stargates. An astronaut going through a hypothetical wormhole might come out moments later on the other side of the galaxy.



- Wormholes fit into the general theory of relativity, which says gravity warps not only time but also space. The theory allows the analogue of alternative road and tunnel routes connecting two points in space. Mathematicians refer to such a space as multiply connected. Just as a tunnel passing through a hill can be shorter than the street along the surface of the hill, a wormhole may be shorter than the usual route through ordinary space.

- After Carl Sagan used the wormhole as a fictional device in his novel *Contact*, Kip Thorne and his colleagues at the California Institute of Technology set out to discover whether wormholes were consistent with known physics. Their starting point was the idea that a wormhole, like a black hole, would be an object with fearsome gravity. Yet unlike a black hole, which offers a one-way journey to nowhere, a wormhole would have an exit as well as an entrance.

- For the wormhole to be traversable, though, it must contain what Thorne called "exotic matter." In effect, this is something that will generate antigravity to combat the natural tendency of a massive system to implode into a black hole under its own intense weight.

- Antigravity, or gravitational repulsion, can be generated by negative energy or pressure. Negative-energy states are known to exist in certain quantum systems, which suggests that Thorne's exotic matter isn't ruled out by the laws of physics. However, it's unclear whether enough antigravitating stuff can be assembled to stabilize a wormhole.

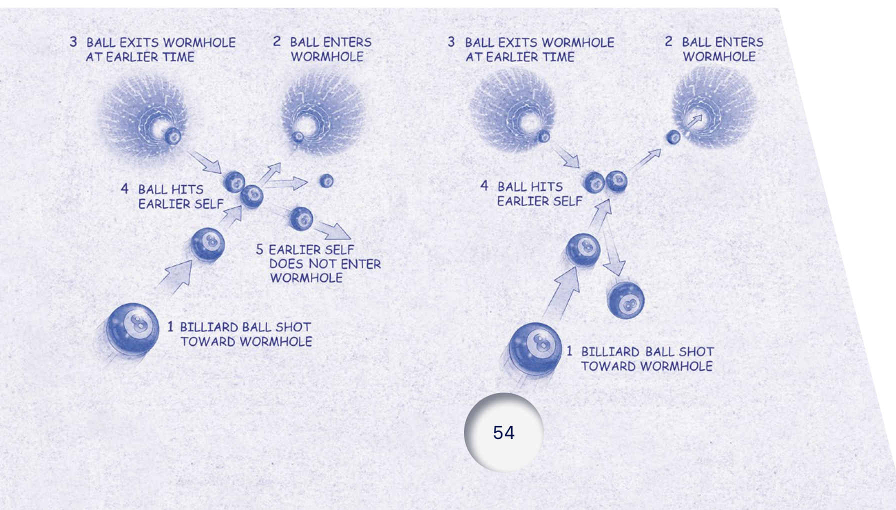
- Soon Thorne and his colleagues realized that if a stable wormhole could be created, then it could readily be turned into a time machine. An astronaut who passed through one might come out not only somewhere else in the universe but at another time, too—in either the future or the past.

- A formidable problem that stands in the way of making a wormhole time machine is the creation of the wormhole in the first place. Possibly space is threaded with such structures naturally—relics of the big bang. If so, a supercivilization might commandeer one.

- Alternatively, wormholes might naturally come into existence on tiny scales, the so-called Planck length. In principle, such a minute wormhole could be stabilized by a pulse of energy and then somehow inflated to usable dimensions.

TIME TRAVEL **STRANGENESS**

- Assuming the engineering problems could be overcome, the production of a time machine would open up a Pandora's box of paradoxes. Consider, for example, this one: A billiard ball passes through a wormhole time machine. When it emerges, it hits its earlier self, thereby preventing it from ever entering the wormhole.



- Resolution of the paradox proceeds from a simple realization: The billiard ball can't do anything that's inconsistent with logic or with the laws of physics. It can't pass through the wormhole in such a way that will prevent it from passing through the wormhole. Yet nothing stops it from passing through the wormhole in an infinity of other ways.

- Even if time travel isn't strictly paradoxical, it certainly is strange. Consider a time traveler who leaps ahead a year and reads about a new mathematical theorem in a future edition of *Scientific American*. She notes the details, returns to her own time, and teaches the theorem to a student, who then writes it up for *Scientific American*. The article is, of course, the very one that the time traveler read.

- The question then arises: Where did the information about the theorem come from? Not from the time traveler, because she read it. But it did not come from the student either, who learned it from the time traveler. The information seems to come into existence from nowhere, without reason.

- The bizarre consequences of time travel have led some scientists to reject the notion altogether. Stephen Hawking of the University of Cambridge proposed a "chronology protection conjecture," which would outlaw causal loops.

- Because the theory of relativity is known to permit causal loops, chronology protection would require some other factor to intercede to prevent travel into the past. What might this factor be? One suggestion is that quantum processes will come to the rescue.

- The existence of a time machine would allow particles to loop into their own past. Calculations hint that the ensuing disturbance would become self-reinforcing, creating a runaway surge of energy that would wreck the wormhole. Chronology protection is still just a conjecture, so time travel remains a possibility.

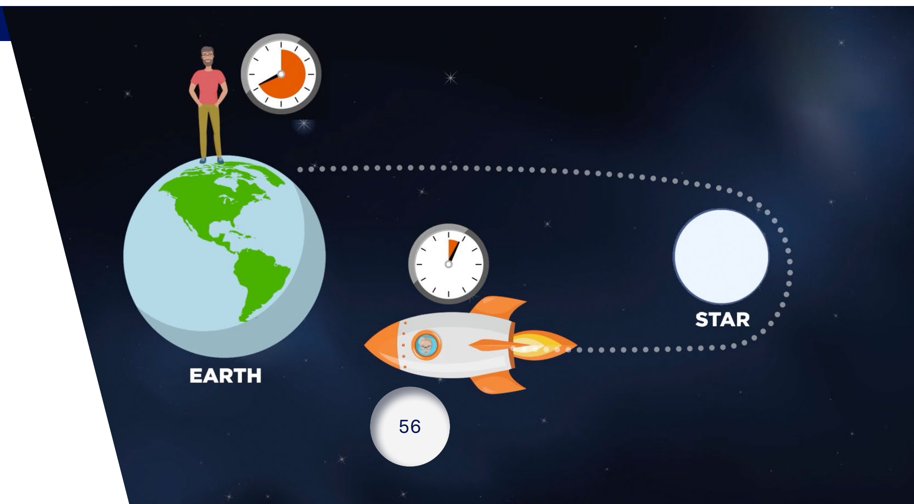
TIME AND THE TWIN PARADOX

- In his special theory of relativity, Albert Einstein proposed that the measured interval between two events depends on how the observer is moving. Crucially, two observers who move differently will experience different durations between the same two events.

- The term *time dilation* was coined to describe the slowing of time caused by motion. To illustrate the effect of time dilation, Einstein proposed an example—the twin paradox—that is arguably the most famous thought experiment in relativity theory.

- To illustrate the paradox: One of two twins travels at near the speed of light to a distant star and returns to Earth. Relativity dictates that when the sister comes back, she's younger than her brother. The paradox lies in the question: Why is the traveling twin younger?

- Special relativity tells us that an observed clock, traveling at high speed past an observer, appears to run more slowly—that is, it experiences time dilation. Since special relativity says there's no absolute motion, wouldn't the sister traveling to the star also see her brother's clock on Earth move more slowly? If this were the case, wouldn't they both be the same age?



- This paradox is typically explained by saying that the twin who feels the acceleration is the one who's younger at the end of the trip; hence, the sister who travels to the star is younger. Although the result is correct, the explanation is misleading.

- Some people may incorrectly assume that the acceleration causes the age difference. But the acceleration incurred by the traveler is incidental, and the paradox can be unraveled by special relativity.

UNRAVELING THE PARADOX

- Assume that the twins, nicknamed the traveler and the homebody, live in Hanover, New Hampshire. They share a common desire to build a spacecraft that can achieve 0.6 times the speed of light (0.6 c). After working on the spacecraft for years, they're ready to launch it, piloted by the traveler, toward a star six light-years away. Her vehicle will quickly accelerate to 0.6 c.

- The traveler uses the length-contraction equation of special relativity to measure distance. The star six light-years away to the homebody appears to be only 4.8 light-years away to the traveler at a speed of 0.6 c. Thus, to the traveler, the trip to the star takes only eight years (derived by dividing 4.8 by 0.6), whereas the homebody calculates it taking 10 years (derived by dividing 6.0 by 0.6).

- Assume each twin has a very powerful telescope that permits observation of the other. Both the traveler and the homebody set their clocks at zero when the traveler leaves Earth for the star. When the traveler reaches the star, her clock reads eight years. But when the homebody sees the traveler reach the star, the homebody's clock reads 16 years.

- The reason is this: To the homebody, the craft takes 10 years to make it to the star, and the light takes six additional years to come back to Earth, showing the traveler at the star. Viewed through the homebody's telescope, the traveler's clock appears to be running at half the speed of his clock.

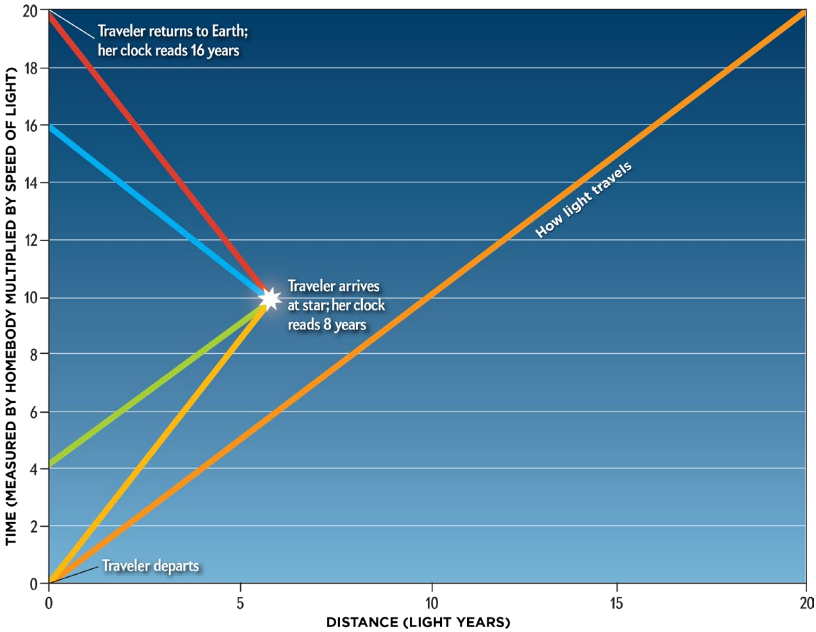
- As the traveler reaches the star, she reads her clock at eight years as mentioned, but she sees the homebody's clock as it was six years ago (the amount of time it takes for the light from Earth to reach her). She sees it as four years (10 minus 6). The traveler also views the homebody's clock as running at half the speed of her clock (derived by dividing 4 by 8).

- On the trip back, the homebody views the traveler's clock going from eight years to 16 years in only four years' time because his clock was at 16 years when he saw the traveler leave the star, and it will be at 20 years when the traveler arrives back home. The homebody sees the traveler's clock advance eight years in four years of his time; it's now running twice as fast as his clock.

- As the traveler returns home, she sees the homebody's clock advance from four to 20 years in eight years of his time. She also sees her brother's clock advancing at twice the speed of her own. They both agree, however, that at the end of the trip the traveler's clock reads 16 years and the homebody's 20 years. Therefore, the traveler is four years younger.

- The asymmetry in the paradox is that the traveler leaves Earth's reference frame and comes back, whereas the homebody never leaves Earth. It's also an asymmetry that the traveler and the homebody agree with the reading on the traveler's clock at each event but that they don't agree about the reading on the homebody's clock at each event. The traveler's actions define the events.

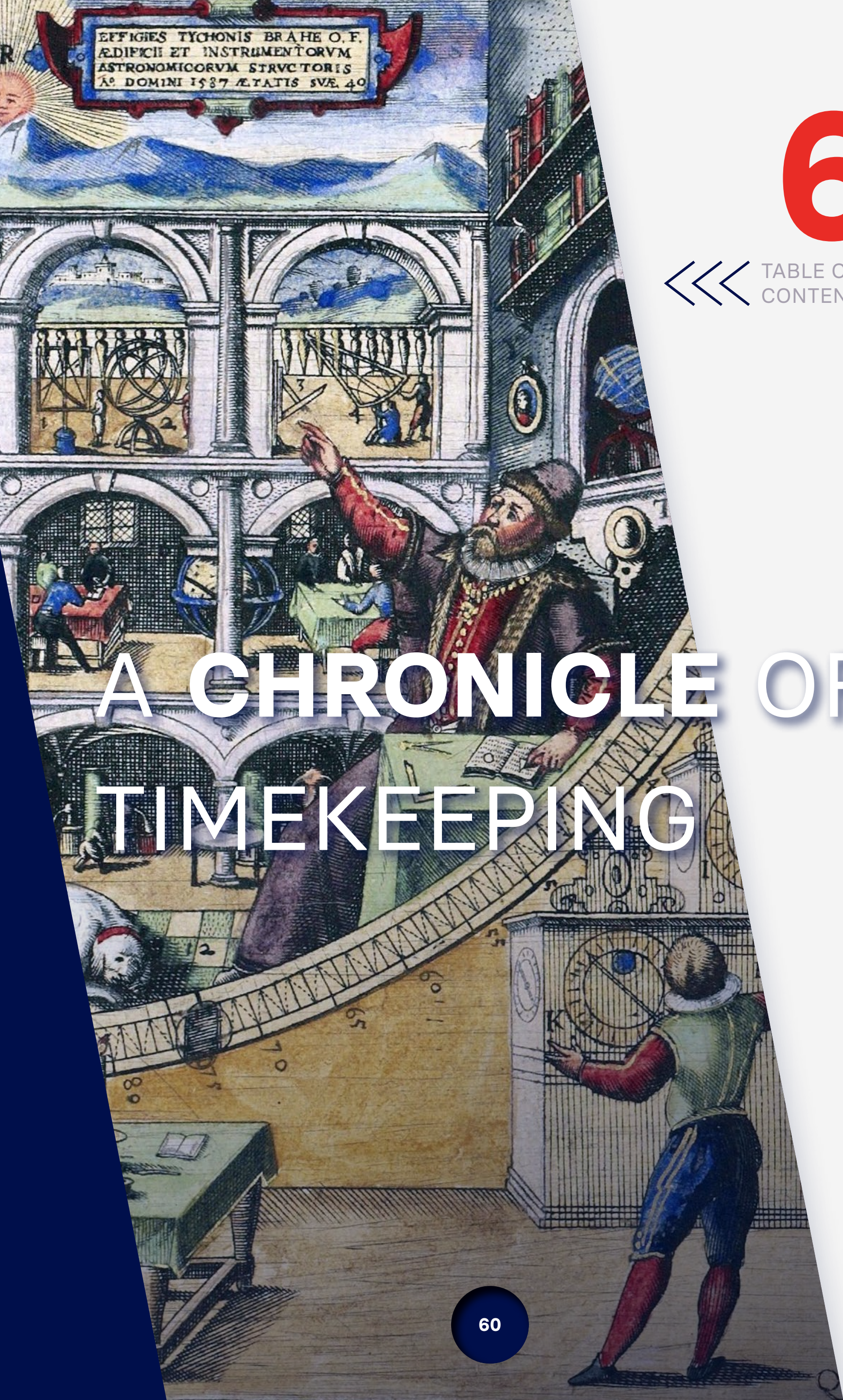
- The Doppler effect and relativity together explain this effect mathematically at any instant. Note, too, that the speed at which an observed clock appears to run depends on whether it's traveling away from or toward the observer.



The fundamentals of this explanation have been exhaustively confirmed experimentally. The twin paradox today is more than just a theory.

ABOUT THIS LESSON

This lesson was adapted from the articles "How to Build a Time Machine" by Paul Davies, a theoretical physicist and cosmologist at Arizona State University, and "Time and the Twin Paradox" by Ronald C. Lasky, an instructional professor at Dartmouth College and a senior technologist at Indium Corporation.



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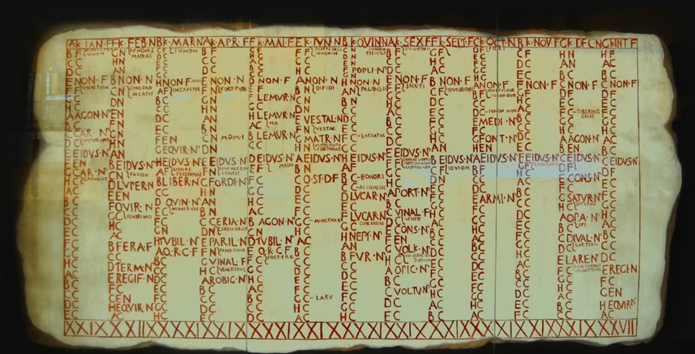
A CHRONICLE OF TIMEKEEPING

Today, highly accurate timekeeping instruments set the beat for most of our electronic devices. Nearly all computers, for example, contain a quartz-crystal clock to regulate their operation. Such time-based technologies have become so integral to our daily lives that we recognize our dependency on them only when they fail to work. This lesson takes a look at their timekeeping predecessors and development.



EARLY **CALENDARS**

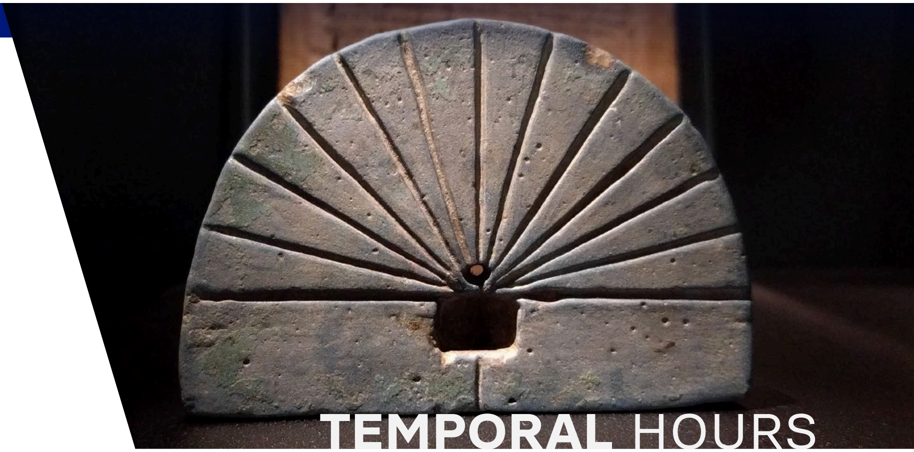
- According to archaeological evidence, at least 5,000 years ago, the Babylonians, Egyptians, and other early civilizations began introducing calendars to organize and coordinate communal activities and public events, to schedule the shipment of goods, and, in particular, to regulate cycles of planting and harvesting.

- They based their calendars on three natural cycles: the solar day, marked by the successive periods of light and darkness as the Earth rotates on its axis; the lunar month, following the phases of the Moon as it orbits the Earth; and the solar year, defined by the changing seasons that accompany our planet's revolution around the Sun.

- Before the invention of artificial light, the Moon had greater social impact. Especially for those living near the equator, its waxing and waning was more conspicuous than the passing of the seasons. For this reason, calendars developed at lower latitudes were influenced more by the lunar cycle than by the solar year.

- In more northern climes, however, where seasonal agriculture was important, the solar year became more crucial. As the Roman Empire expanded northward, it organized its calendar for the most part around the solar year. Today's Gregorian calendar derives from the Babylonian, Egyptian, Jewish, and Roman calendars.

- The Egyptians formulated a civil calendar having 12 months of 30 days, with five days added to approximate the solar year. Each period of 10 days was marked by the appearance of special constellations called decans. At the rise of the star Sirius just before sunrise, which occurred around the all-important annual flooding of the Nile, 12 decans could be seen spanning the heavens.



TEMPORAL HOURS

- The cosmic significance the Egyptians saw in the 12 decans led them to develop a system in which each interval of darkness (and later, each interval of daylight) was divided into a dozen equal parts. These periods became known as temporal hours because their duration varied according to the changing length of days and nights with the passing of the seasons. Summer hours were long, and winter ones were short; only at the spring and autumn equinoxes were the hours of daylight and darkness equal.

- Temporal hours were adopted by the Greeks and then the Romans (who spread them throughout Europe). They remained in use for more than 2,500 years.

- To track temporal hours during the day, inventors devised sundials. The water clock was then designed to measure temporal hours at night. Although these devices performed well enough around the Mediterranean, they couldn't always be depended on in the cloudy and often freezing weather of northern Europe.

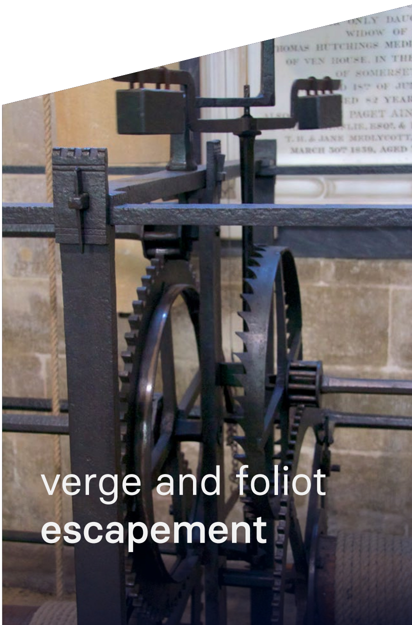
water clocks

WEIGHT-DRIVEN **MECHANICAL** CLOCKS

- The earliest recorded weight-driven mechanical clock was installed in 1283 at Dunstable Priory in Bedfordshire, England. It's not surprising that the Roman Catholic Church should've played a major role in the invention and development of clock technology: The strict observance of prayer times by monastic orders demanded a more reliable instrument of time measurement.

- By 1300, artisans were building clocks for churches and cathedrals in France and Italy. Because these early devices indicated the time by striking a bell (thereby alerting the surrounding community to its daily duties), they took their name from the Latin meaning "bell," *clocca*.

- The revolutionary aspect of this new type of timekeeper was neither the descending weight that provided its motive force nor the gear wheels that transferred the power. Instead, it was the part called the escapement. This device controlled the wheels' rotation and transmitted the power required to maintain the motion of the oscillator, the part that regulated the speed at which the timekeeper operated. The inventor of the clock escapement is unknown.



verge and foliot **escapement**

COUNTING HOURS

- In the early 14th century, a number of systems evolved governing the counting of hours. The schemes that divided the day into 24 equal parts varied according to the start of the count: Italian hours began at sunset and Babylonian hours at sunrise. Astronomical hours began at midday and “great clock” hours (used for some large public clocks in Germany) at midnight.

- Eventually, these and competing systems were superseded by “small clock,” or French, hours. These split the day, as we currently do, into two 12-hour periods commencing at midnight. Minutes and seconds derive from the sexagesimal partitions of the degree introduced by Babylonian astronomers.

PORTABLE CLOCKS

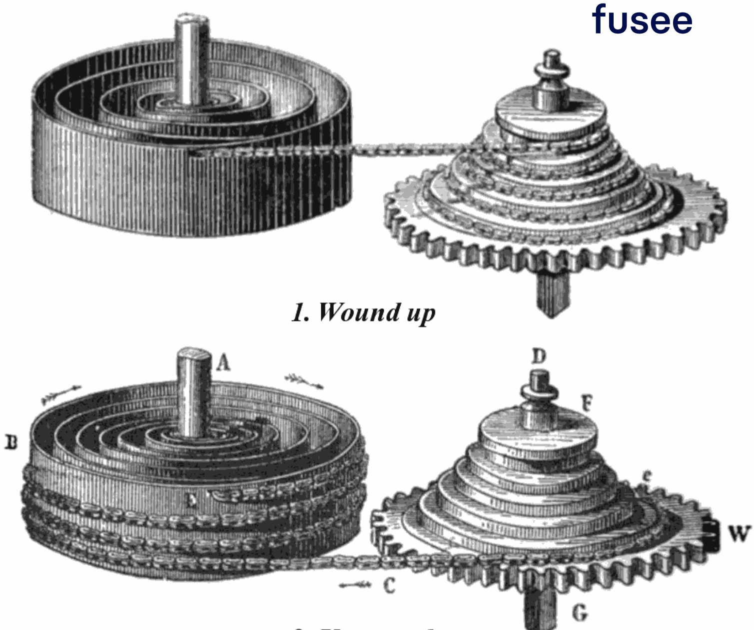
- By the 15th century, a growing number of clocks were being made for domestic use. Those who could afford the luxury of owning a clock found it convenient to have one that could be moved from place to place.

- Innovators achieved portability by replacing the weight with a coiled spring. But the tension of a spring is greater after it’s wound. To overcome this problem, the fusee (from *fusus*, the Latin term for “spindle”) was invented by an unknown mechanical genius probably between 1400 and 1450.

- This cone-shaped device was connected by a cord to the barrel housing the spring. When the clock was wound, drawing the cord from the barrel onto the fusee, the diminishing diameter of the spiral of the fusee compensated for the increasing pull of the spring. Thus, the fusee equalized the force of the spring on the wheels of the timekeeper.

- The fusee allowed for the development of the portable clock as well as the subsequent evolution of the pocket watch. Many high-grade, spring-driven timepieces, such as marine chronometers, continued to incorporate this device until after World War II.

fusee



1. Wound up

2. Unwound

PENDULUM CLOCKS

- In the 16th century, Danish astronomer Tycho Brahe and his contemporaries tried to use clocks for scientific purposes. But even the best ones were still too unreliable. Astronomers in particular needed a better tool to time the transit of stars and create more accurate maps of the heavens.

- The pendulum proved to be the key to boosting the accuracy and dependability of timekeepers. The 27-year-old Dutch astronomer and mathematician Christiaan Huygens devised the first pendulum clock on Christmas Day in 1656.

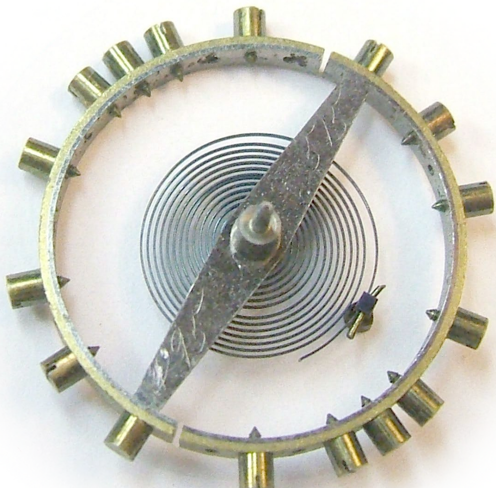
- Pendulum clocks were about 100 times as accurate as their predecessors, reducing a typical gain or loss of 15 minutes a day to about a minute a week. Huygens immediately recognized both the commercial and scientific significance of his invention.

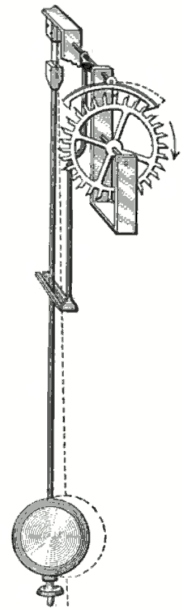
- Within six months, a local maker in the Hague had been granted a license to manufacture pendulum clocks. News of the invention spread rapidly, and by 1660, English and French artisans were developing their own versions of this new timekeeper.

THE SPIRAL BALANCE SPRING AND **NEW ESCAPEMENTS**

- Huygens devoted much of his time to improving the device both for astronomical use and for solving the problem of finding longitude at sea. In 1675, he devised another fundamental improvement: the spiral balance spring.

- The spiral balance spring revolutionized the accuracy of watches, enabling them to keep time to within a minute a day. This advance sparked an almost immediate expansion of the market for watches, which were now typically carried in a pocket. This development also increased the demand for portable sundials by which watches could be set.





- At about the same time, Huygens heard news of an important English invention called the anchor escapement. Unlike the verge escapement he had been using in his pendulum clocks, the anchor escapement allowed the pendulum to swing in such a small arc that maintaining a cycloidal pathway became unnecessary.

- This escapement made the use of a long, seconds-beating pendulum more practical and thus led to the development of a new case design. The longcase clock began to emerge as one of the most popular English styles. Since 1876, these have been commonly called grandfather clocks (after a song by American Henry Clay Work). Longcase clocks with anchor escapements and long pendulums can keep time to within a few seconds a week.

- The celebrated English clockmaker Thomas Tompion—and his successor, George Graham—later modified the anchor escapement to operate without recoil. This enhanced design, called the deadbeat escapement, became the most widely used type in precision timekeeping for the next 150 years.

anchor escapement

FINDING **LONGITUDE**

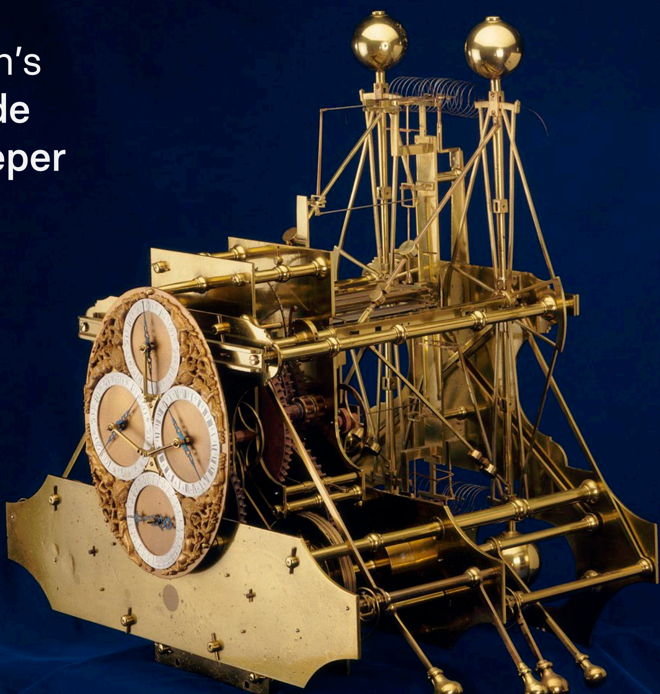
- When the Royal Observatory in Greenwich was founded in 1675, part of its charter was to find "the so-much-desired longitude of places." While navigators could determine their latitude at sea (their position north or south of the equator) by measuring the altitude of the sun or the polestar above the horizon, the heavens didn't provide such a straightforward solution for finding longitude.

- Storms and currents often confounded attempts to keep track of distance and direction traveled across oceans. The resulting navigational errors cost seafaring nations dearly, not just in prolonged voyages but also in loss of lives, ships, and cargo.

- The severity of this predicament was brought home to the British government in 1707, when an admiral of the fleet and more than 1,600 sailors perished in the wrecks of four Royal Navy ships off the coast of the Isles of Scilly. Thus, in 1714, through an act of Parliament, Britain offered substantial prizes for practical solutions to finding longitude at sea.

- The largest prize, £20,000, would be given to the inventor of an instrument that could determine a ship's longitude to within half a degree, or 30 nautical miles, when reckoned at the end of a voyage to a port in the West Indies, whose longitude could be accurately ascertained using proved land-based methods. The great reward attracted a deluge of harebrained schemes. Hence, the Board of Longitude, the committee appointed to review promising ideas, held no meetings for more than 20 years.

- In 1737, the Board of Longitude finally met for the first time to discuss the work of a most unlikely candidate, a Yorkshire carpenter named John Harrison. Harrison's large and rather cumbersome longitude timekeeper had been used on a voyage to Lisbon and on the return trip had proved its worth by correcting the navigator's dead reckoning of the ship's longitude by 68 miles.



Harrison's **longitude timekeeper**

- But Harrison wasn't satisfied. Instead of asking the board for a West Indies trial, he requested and received financial support to construct an improved machine. After two years of work, still displeased with his second effort, Harrison embarked on a third design, laboring on it for 19 years. By the time it was ready for testing, he realized that his fourth marine timekeeper, a five-inch-diameter watch he had been developing simultaneously, was better.

- On a voyage to Jamaica in 1761, Harrison's oversize watch performed well enough to win the prize. But the board refused to give him his due without further proof. A second sea trial in 1764 confirmed his success. Harrison was reluctantly granted £10,000. Only when King George III intervened in 1773 did he receive the remaining prize money.

- Harrison's breakthrough inspired further developments. By 1790, the marine chronometer was so refined that its fundamental design never needed to be changed.

fourth attempt

THE TURN OF THE CENTURY

- At the turn of the 19th century, clocks and watches were relatively accurate, but they were still expensive. Recognizing the potential market for a low-cost timekeeper, two investors in Waterbury, Connecticut, took action.

- In 1807, they gave Eli Terry, a clockmaker in nearby Plymouth, a three-year contract to manufacture 4,000 longcase clock movements from wood. A substantial down payment allowed Terry to devote the first year to fabricating machinery for mass production. By manufacturing interchangeable parts, he completed the work within the terms of the contract.

- A few years later, Terry designed a wooden-movement shelf clock using the same volume-production techniques. For the relatively modest sum of $15, many average people could now afford a clock. This achievement helped establish what would become the renowned Connecticut clockmaking industry.

TIME ZONES

- Eventually, America's expanding railroad network required a uniform time standard for all the stations along the line. Astronomical observatories began distributing precise times to the railroad companies by telegraph.

- The first public time service, introduced in 1851, was based on clock beats wired from the Harvard College Observatory in Cambridge, Massachusetts. The Royal Observatory introduced its own time service the following year, creating a single standard time for Britain.

- The US established four time zones in 1883. By the next year, the governments of all nations had recognized the benefits of a worldwide standard of time for navigation and trade. At the 1884 International Meridian Conference in Washington DC, the globe was divided into 24 time zones. Delegates chose the Royal Observatory as the prime meridian (zero degrees longitude, the line from which all other longitudes are measured) in part because two-thirds of the world's shipping already used Greenwich time for navigation.

MASS **PRODUCTION**

- Many clockmakers of this era realized that the market for watches would far exceed that for clocks if production costs could be reduced. In Maine, a watchmaker named Aaron L. Dennison worried that American watchmakers seemed unable to compete against Europe, which controlled the market in the late 1840s.

- He met with Edward Howard, who had established a successful clock- and scale-making business in Roxbury, Massachusetts, to discuss mass-production methods for watches. Their efforts eventually led to the emergence of the American Waltham Watch Company.

- Their company benefited greatly from a huge demand for watches during the Civil War, when Union Army forces used them to synchronize operations. Improvements in fabrication techniques further boosted output and reduced prices significantly.

- Meanwhile, other US companies formed in the hope of capturing part of the burgeoning trade. Even some of the lower-grade American watches could keep reasonably good time. The watch was at last accessible to the masses. Later, self-winding mechanical wristwatches made their appearance during the 1920s.

LATER DEVELOPMENTS


Riefler clock

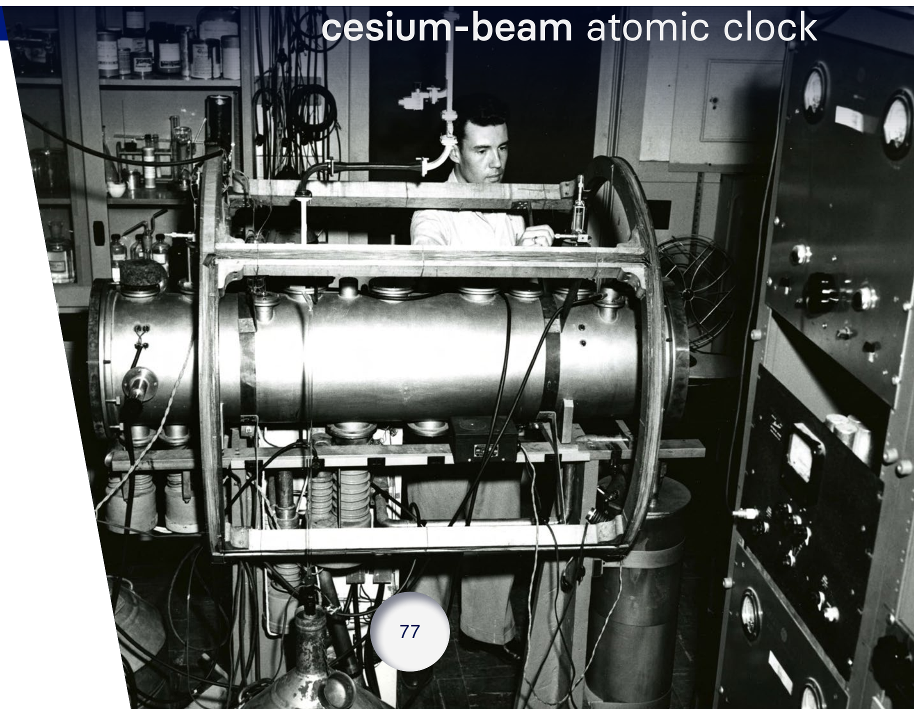
- At the end of the 19th century, Sigmund Riefler of Munich designed a radical new regulator—a highly accurate timekeeper that served as a standard for controlling others. Riefler's regulators attained an accuracy of a tenth of a second a day and were thus adopted by nearly every astronomical observatory.

- In 1928, Warren A. Marrison, an engineer at Bell Laboratories, then in New York City, discovered an extremely uniform and reliable frequency source that was as revolutionary for timekeeping as the pendulum had been 272 years earlier. Originally developed for use in radio broadcasting, the quartz crystal vibrates at a highly regular rate when excited by an electric current.

- The first quartz clocks installed at the Royal Observatory in 1939 varied by only two thousandths of a second a day. By the end of World War II, this accuracy had improved to the equivalent of a second every 30 years.

- Quartz-crystal technology didn't remain the premier frequency standard for long either, however. By 1948, Harold Lyons and his associates at the National Bureau of Standards in Washington DC had based the first atomic clock on a far more precise and stable source of timekeeping: an atom's natural resonant frequency, the periodic oscillation between two of its energy states.

- Subsequent experiments in both the US and England in the 1950s led to the development of the cesium-beam atomic clock. Today, the averaged times of cesium clocks in various parts of the world provide the standard frequency for Coordinated Universal Time, which has an accuracy of better than one nanosecond a day.



ABOUT THIS LESSON

This lesson was adapted from the article "A Chronicle of Timekeeping" by William J. H. Andrewes, a specialist in the field of time measurement who has worked at the Royal Observatory Greenwich, The Time Museum, and Harvard University.

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ATOMIC CLOCKS

Einstein's general theory of relativity predicts that clocks experiencing different gravitational pulls will tick at different rates. A clock at higher elevation will tick faster than will a clock closer to Earth's center. Einstein's special theory of relativity predicts a similar effect for clocks in motion. A stationary clock will tick faster than a moving clock. This lesson looks at efforts to observe those time dilation effects as well as advances in high-precision timekeeping.

OBSERVING TIME DILATION

- Both of the aforementioned time dilation effects have been verified in a number of experiments throughout the decades, which have traditionally depended on large scales of distance or velocity. In one landmark test, in 1971, Joseph Hafele of Washington University in St. Louis and Richard Keating of the US Naval Observatory flew cesium atomic clocks around the world on commercial jet flights, then compared the clocks with reference clocks on the ground to find that they had diverged, as predicted by relativity.

- Yet even at the speed and altitude of jet aircraft, the effects of time dilation are tiny. In the Hafele-Keating experiment, the atomic clocks differed after their journeys by just tens to hundreds of nanoseconds.

- Thanks to improved timekeeping, similar demonstrations can now take place at more mundane scales in the laboratory. In a series of experiments described in *Science* magazine, researchers at the National Institute of Standards and Technology, or NIST, registered differences in the passage of time between two high-precision optical atomic clocks when one was elevated by just a third of a meter or when one was set in motion at speeds of less than 10 meters per second.

cesium atomic clock used in **Hafele-Keating experiment**

- Again, the effects are minuscule: It would take the elevated clock hundreds of millions of years to log one more second than its counterpart, and a clock moving a few meters per second would need to run about as long to lag one second behind the stationary clock. But the development of optical clocks based on aluminum ions, which can keep time to within one second in roughly 3.7 billion years, allows researchers to expose those tiny relativistic effects.

ULTIMATE CLOCKS

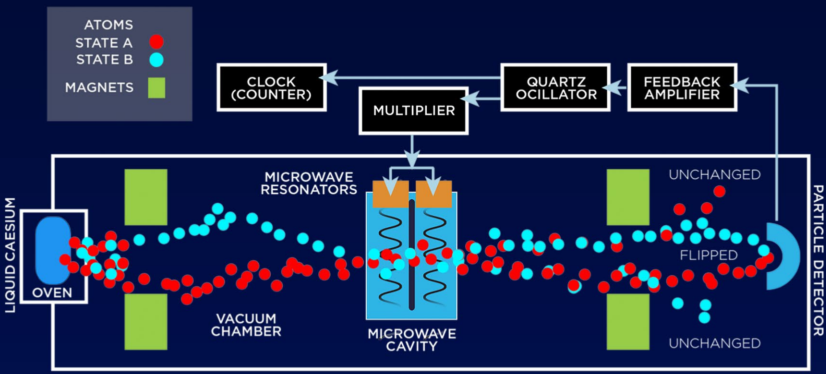
- Thanks to major technical advances, the art of ultraprecise timekeeping has been progressing with a speed not seen for decades. These days, a good cesium beam clock will tick off seconds true to about a microsecond a month, its frequency accurate to five parts in 10^{13}.

- The primary time standard for the US, a cesium fountain clock installed in 2014 by the NIST at its Boulder, Colorado, laboratory, is good to three parts in 10^{16}. That's 2,000 times the accuracy of NIST's best clock in 1975. Successful prototypes of new clock designs—devices that extract time from aluminum or mercury ions instead of cesium—have recently attained accuracy in the 10^{-18} power range, a 100-fold improvement in a decade.

- The second was defined in 1967 by international fiat to be "the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium 133 atom." Under that standard, to measure a second, one has to look at cesium. The best clocks now don't, so, strictly speaking, they don't measure seconds. That's one predicament the clockmakers face.

THE ADVANTAGE OF ATOMIC CLOCKS

Every clock has at least two basic components: an oscillator and a counter. An atomic clock is so accurate because it includes a third element: a feedback system that periodically checks an atomic reference to keep the oscillator ticking with nearly perfect regularity. In a state-of-the-art optical ion clock, an ultraviolet probe laser serves as the oscillator. Pulses of infrared laser light yield a counter. One electron orbiting a single, nearly motionless mercury atom functions as the ultimate reference.



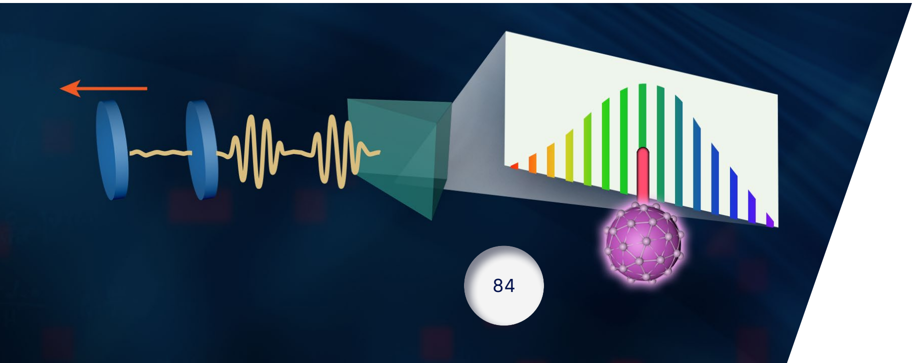
- Further down the road lies a more fundamental limitation: As Albert Einstein theorized and as experiment has confirmed, time isn't absolute. The rate of any clock slows down when gravity gets stronger or when the clock moves quickly relative to its observer. By putting ultraprecise clocks on the International Space Station, scientists hope to put relativity theory through its toughest tests yet.

- Clocks with a precision of 10^{-18} represent proportions that correspond to a deviation of less than half a second over the age of the universe. That means the effects of relativity are starting to test the scientists. No technology exists that can synchronize clocks around the world with such exactness.

FOUNTAIN CLOCKS

- The ticker in a cesium clock is neither mechanical (like a pendulum) nor electromechanical (like a quartz crystal). It's quantum-mechanical: A photon of light is absorbed by the cesium atom's outermost electron, causing the electron to flip its magnetic field upside down.

- All cesium atoms are identical. Each will flip the spin of its outer electron when hit with microwaves at the frequency of exactly 9,192,631,770 cycles per second. To measure seconds, the clock locks its microwave generator onto the spot in the spectrum where the most cesium atoms react. Then it starts counting cycles.



- Complicating matters is the Heisenberg indeterminacy principle, which puts strict limits on how precisely one can measure the frequency of a single photon. The best clocks now scan a one-hertz-wide sweet spot to find its exact center, plus or minus one millihertz, in every single measurement—despite the Heisenberg limits.

- "The reason we can do it is that we look at more than a million atoms each time," explained physicist Kurt Gibble. "Because it isn't really just one measurement, it doesn't violate the laws of quantum mechanics." However, that solution creates other problems.

- At room temperature, cesium is a soft, silvery metal. It would melt in a person's palm to a golden puddle, and it reacts violently with water.

- Inside a cesium beam clock, an oven heats the metal until atoms boil off. These hot particles can zip through the microwave cavity at various speeds and angles. Some move so fast that, because of relativity, they behave as if time has slowed. Because of Doppler shifting to other atoms, the microwaves appear to be higher or lower in frequency than they are.

- The atoms no longer behave identically, so the ticks grow less distinct. Heisenberg would probably have suggested slowing the atoms down, and that's what clockmakers have done. Several clocks around the world—at NIST; the US Naval Observatory; and the standards institutes in Paris; Teddington, England; and Brunswick, Germany—toss supercooled balls of cesium atoms in a fountainlike arc through a microwave.

- To condense the hot cesium gas into a ball, six intersecting laser beams decelerate the atoms to less than two microkelvins—almost a complete ultracold standstill. The low temperature all but eliminates relativistic and Doppler shifts, and it gives a two-meter-tall fountain clock half a second to flip the atoms' spins.

CLOCKS IN SPACE

- Introduced in 1996, fountain clocks rapidly knocked 90% off the uncertainty of international atomic time. However, fountain clocks still rush the job. "We would have to quadruple the height of the tower to double the observation time," said Donald Sullivan, former chief of the time and frequency division at NIST.

- Sullivan led one of three projects to put fountainlike clocks on the International Space Station. Per Sullivan, "In space, we can launch a ball of atoms at 15 centimeters per second through a 74-centimeter cavity." That provides "5 to 10 seconds to observe them," he explains.

- The $25-million Primary Atomic Reference Clock in Space (PARCS) project he worked on was designed to turn out seconds good to five parts in 10^{17}. PARCS was canceled in 2004, when NASA shifted funding from the space station.

- However, a device from the European Space Agency called ACES (Atomic Clock Ensemble in Space) is scheduled to launch in 2021. It aims to measure with 99.99997% accuracy how much the microgravity of low Earth orbit slows time compared with measurements made on the ground.

One of two atomic clocks developed for ACES mission.

RACE

- Efforts to make a third space-faring clock, called RACE (Rubidium Atomic Clock Experiment), helped to refine a newer approach that replaces cesium with a different alkali element. The project was cancelled along with PARCS, but the following is a look at how it could work. "In the best cesium fountains, the largest source of error are so-called cold collisions," explained Gibble, who directed the RACE project.

- At temperatures near absolute zero, quantum physics takes over, and atoms start to behave like waves. "They appear hundreds of times bigger than normal," Gibble continued, "so they collide much more often. At a microkelvin, cesium has nearly the maximum possible cross section."

- However, "the effective size for rubidium atoms is 50 times smaller." That enables rubidium clocks to reach one fifth the uncertainty of ACES. Rubidium clocks offer another advantage as well: the opportunity to look for fluctuations in the fine-structure constant, alpha (α).

- Alpha is a fundamental physical constant that determines the strength of electromagnetic interactions in atoms and molecules. Its value is very nearly 1⁄137, a unitless number that falls out of the equations for the Standard Model of physics. It is a very important number—change α very much, and the universe couldn't support life as we know it.

- In the Standard Model, the fine-structure constant is immutable throughout eternity. However, in some competing theories (such as certain string theories), α could waver slightly or grow as time goes by.

ION CLOCKS

- The development of ion clocks in some ways has surpassed clocks based on fountains of atoms. In 2001, Scott A. Diddams and his colleagues at NIST reported an initial trial run of an optical atomic clock based on a single mercury atom.

- It may seem like a natural idea to graduate from microwaves, at frequencies of gigahertz, to visible light, well into the terahertz part of the spectrum. Optical photons pack enough energy to bump electrons clear into the next orbital shell, removing the need to deal with subtleties like spin. But although the ticker still works at terahertz frequencies, the counter breaks.

- The problem was that "nobody knows how to count 10 to the 16 power cycles per second," observed Eric A. Burt of NASA's Jet Propulsion Laboratory. "We needed a bridge to the microwave regime, where we do have electronic counters."

- That is where optical rulers come in. In 1999, researchers at the Max Planck Institute for Quantum Optics in Garching, Germany, figured out a way to measure optical frequencies directly, using a reference laser that pulses at a rate of one gigahertz.

- Each pulse of light is just a couple of dozen femtoseconds long. (A femtosecond is a very, very small amount of time. More femtoseconds elapse in each second than there have been hours since the big bang.)

- A laser puts out a continuous beam of only one color, but pulsing that laser produces a mixture of colors in each flash. The spectrum of a femtosecond pulse is a bizarre thing to see: millions of sharp lines spanning the rainbow, each line spaced exactly the same distance from its neighbors.

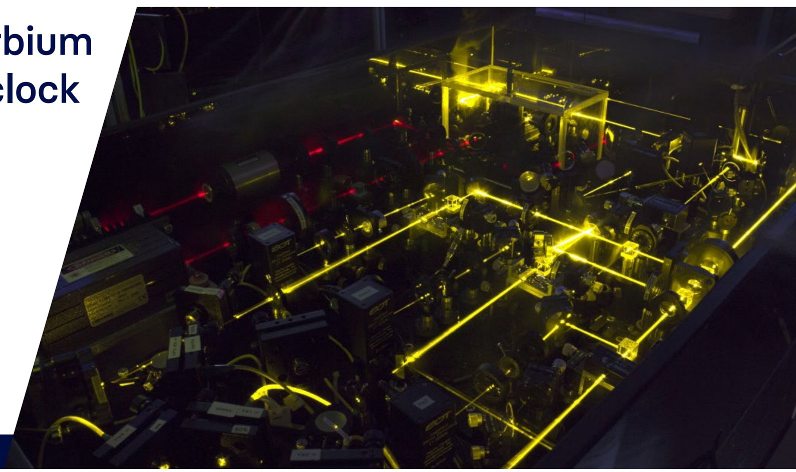
LOOKING **FORWARD**

- Diddams's group at NIST has built a rudimentary optical clockwork around mercury ions, which they immobilize in an electromagnetic trap. Because each atom is missing an electron, the ions carry a positive charge. They repel one another, so collisions are not a problem. The device is stable to better than six parts in 10^{16} over the course of a second.

- Groups at the Federal Institute of Physics and Metrology in Brunswick, Germany, and elsewhere are experimenting with uncharged calcium atoms. Because neutral atoms can be crammed more densely into the trap than ions can, the signal soars higher over the noise.

- In 2015, a NIST-led team reported the successful demonstration of an optical lattice clock based on atoms of strontium 87; the uncertainty was pegged at two parts in 10^{18}. A German research group reported in 2016 on a precision almost as good, of 3.2 parts in 10^{18}, from a system based on a single ion of ytterbium 171. The NIST group also used ytterbium for a lattice clock that achieved an accuracy of 1.6 parts in 10^{18}.

ytterbium lattice clock



- However, note that the word *accuracy* keeps appearing. These new clocks "move away from the atomic definition of the second, which is based on the properties of cesium," Sullivan points out. For the newest and best clocks to be strictly accurate as keepers of the time to which we set our watches, that definition will have to change.

ABOUT THIS LESSON

This lesson was adapted from the articles "How Time Flies" by John Matson, a former reporter and editor for *Scientific American* who has written extensively about astronomy and physics, and "Ultimate Clocks" by W. Wayt Gibbs, a contributing editor for *Scientific American*.

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TIMES OF OUR LIVES

This lesson looks at how humans experience and are affected by the passage of time. Neurologists and other researchers have begun to answer some of the most pressing questions raised by human experience in the fourth dimension. Examples of such questions include: Why does a watched pot never boil? Why does time fly when we're having fun? Why do people live longer than, for instance, hamsters?

INTERVAL TIMING

- The biopsychologist John Gibbon called time the "primordial context": a fact of life that has been felt by all organisms in every era. In human bodies, biological clocks keep track of seconds, minutes, days, months, and years.

- When humans watch something that intrigues them, the time spent doing so seems to pass quickly, but when humans are bored, time drags. That's a quirk of a "stopwatch" in the brain—the so-called interval timer—that marks time spans of seconds to hours. As an example of this in action, the interval timer helps a baseball player figure out how fast he has to run to catch a baseball.

IMPRECISION

The precision of interval timers has been found to range from 5% to 60%. They don't work very well when a person is distracted or tense. Timing errors become worse as an interval gets longer. That's why we rely on cell phones and wristwatches to tell time.

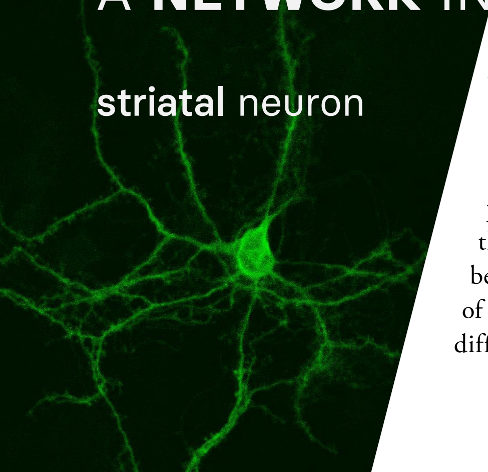
- Interval timing enlists the higher cognitive powers of the cerebral cortex, the part of the brain that governs perception, memory, and conscious thought. When a driver approaches a yellow traffic light, for example, the driver might time how long it has been yellow and compare that with a memory of how long yellow lights usually last.

- After that, the driver "has to make a judgment about whether to put on the brakes or keep driving," according to the Cleveland Clinic's Stephen M. Rao. Rao's studies with functional magnetic resonance imaging (fMRI) have pointed to the parts of the brain engaged in each of those stages.

- Inside the fMRI machine, volunteers listen to two pairs of tones and decide whether the interval between the second pair is shorter or longer than the interval between the first pair. The brain structures that are involved in the task consume more oxygen than those that are not involved, and the fMRI scan records changes in blood flow and oxygenation once every 250 milliseconds.

- Rao says that "the very first structures that are activated are the basal ganglia." Long associated with movement, this collection of brain regions has become a prime suspect in the search for the interval-timing mechanism as well.

A NETWORK IN THE BRAIN



- One area of the basal ganglia, the striatum, hosts a population of conspicuously well-connected nerve cells that receive signals from other parts of the brain. The long arms of these striatal cells are covered with between 10,000 and 30,000 spines, each of which gathers information from a different neuron in another location.

- If the brain acts like a network, then the striatal spiny neurons are critical nodes. "This is one of only a few places in the brain where you see thousands of neurons converge on a single neuron," according to Warren H. Meck of Duke University.

- Striatal spiny neurons are central to an interval-timing theory Meck developed with Gibbon. The theory posits a collection of neural oscillators in the cerebral cortex: nerve cells firing at different rates, without regard to their neighbors' tempos.

- In fact, many cortical cells are known to fire at rates between 10 and 40 cycles per second without external provocation. "All these neurons are oscillating on their own schedules," per Meck, "like people talking in a crowd. None of them are synchronized."

- The cortical oscillators connect to the striatum via millions of signal-carrying arms, so the striatal spiny neurons can eavesdrop on all those haphazard "conversations." Then something—like a yellow traffic light, for instance—gets the cortical cells' attention.

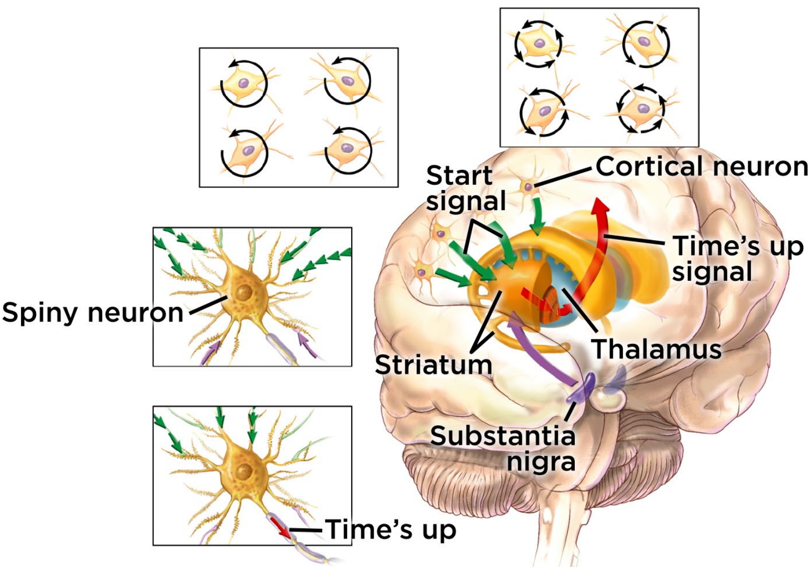
- The stimulation prompts all the neurons in the cortex to fire simultaneously, causing a characteristic spike in electrical output some 300 milliseconds later. This attentional spike acts like a starting gun, after which the cortical cells resume their disorderly oscillations.

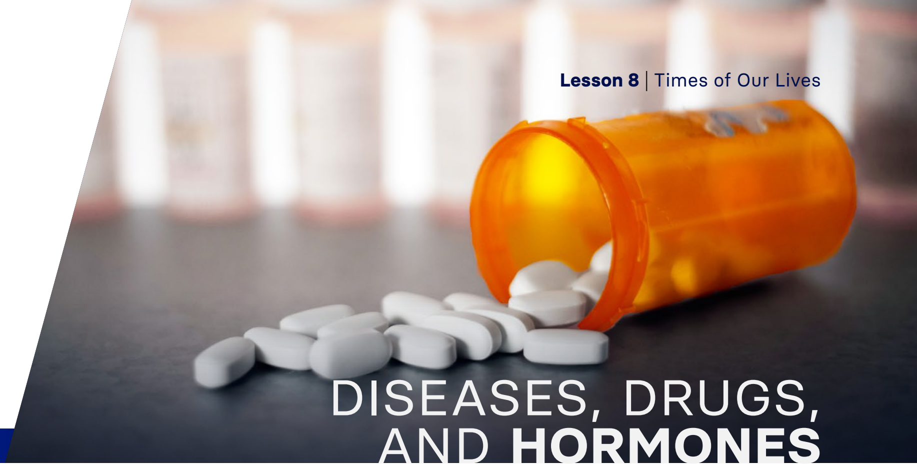
- But because they've begun simultaneously, the cycles now make a distinct, reproducible pattern of nerve activation from moment to moment. The spiny neurons monitor those patterns, which help them to "count" elapsed time.

- At the end of a specified interval—when the traffic light turns red, for example—a part of the basal ganglia called the substantia nigra sends a burst of the neurotransmitter dopamine to the striatum. The dopamine burst induces the spiny neurons to record the pattern of cortical oscillations they receive at that instant, like a flashbulb exposing the interval's cortical signature on the spiny neurons' film.

- According to Meck, "There's a unique time stamp for every interval" imaginable. Once a spiny neuron has learned the time stamp of the interval for a given event, subsequent occurrences of the event prompt both the "firing" of the cortical starting gun and a burst of dopamine at the beginning of the interval. The dopamine burst now tells the spiny neurons to start tracking the patterns of cortical impulses that follow.

- When the spiny neurons recognize the time stamp marking the end of the interval, they send an electrical pulse from the striatum to another brain center, called the thalamus. The thalamus, in turn, communicates with the cortex, and the higher cognitive functions—such as memory and decision-making—take over. Hence, the timing mechanism loops from the cortex to the striatum to the thalamus and back to the cortex again.

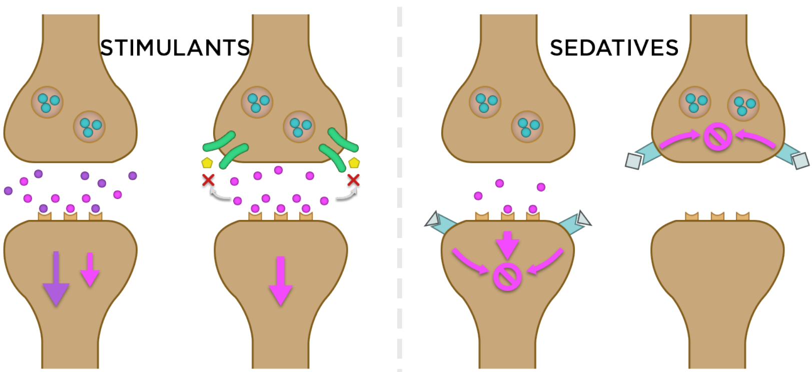




DISEASES, DRUGS, AND **HORMONES**

- If dopamine bursts play an important role in framing a time interval, then diseases and drugs that affect dopamine levels should also disrupt that loop. That is what Meck and others have found.

- Patients with untreated Parkinson's disease, for example, release less dopamine into the striatum, and their clocks run slow. Marijuana also lowers dopamine availability and slows time. Recreational stimulants such as cocaine and methamphetamine increase the availability of dopamine and make the interval clock speed up, so that time seems to expand.



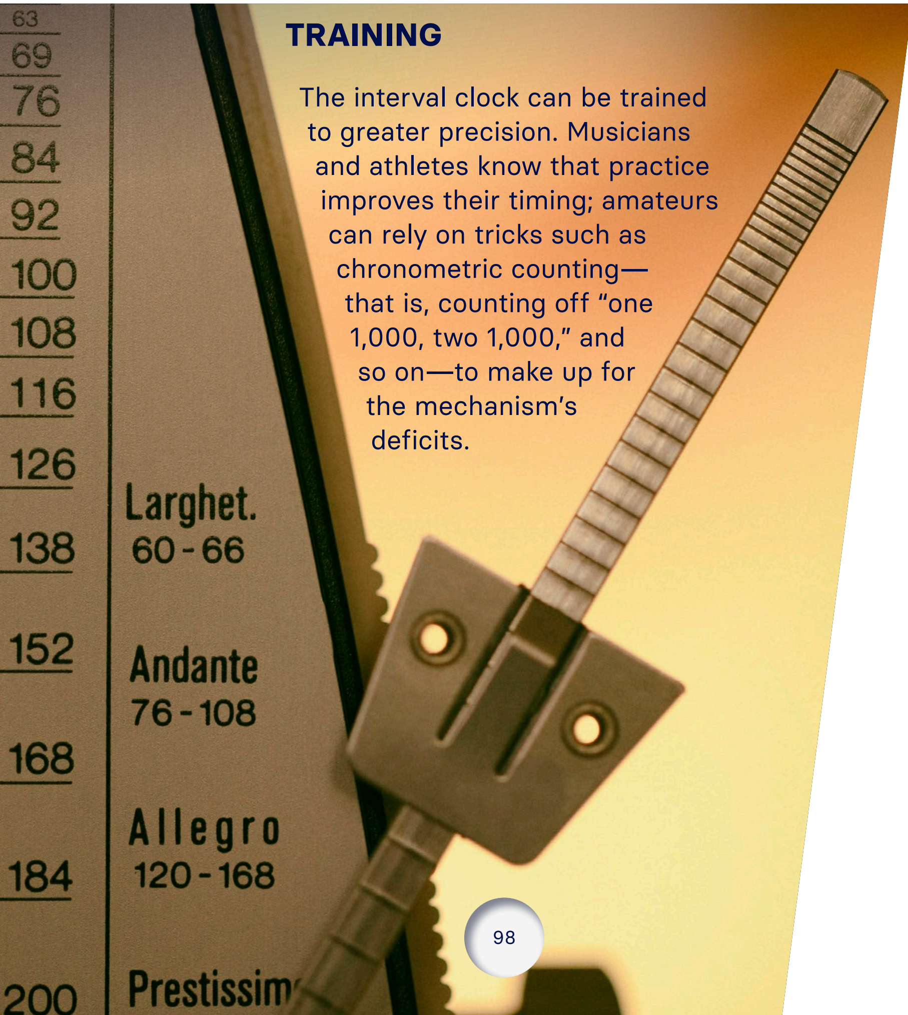
Nicotine ●
Mimics the action of the neurotransmitter acetylcholine

Cocaine/ecstasy ⬟
Increases release and blocks reuptake of dopamine and 5-HT

Benzodiazepines △
Binds to GABA receptors, causing hyperpolarization (postsynaptic)

THC/cannabis □
Binds cannabinoid receptors, causing hyperpolarization (presynaptic)

- Adrenaline and other stress hormones make the clock speed up, too, which may be why a second can feel like an hour during unpleasant situations. States of deep concentration or extreme emotion may flood the system or bypass it altogether; in such cases, time may seem to stand still or not to exist at all.



TRAINING

The interval clock can be trained to greater precision. Musicians and athletes know that practice improves their timing; amateurs can rely on tricks such as chronometric counting—that is, counting off "one 1,000, two 1,000," and so on—to make up for the mechanism's deficits.

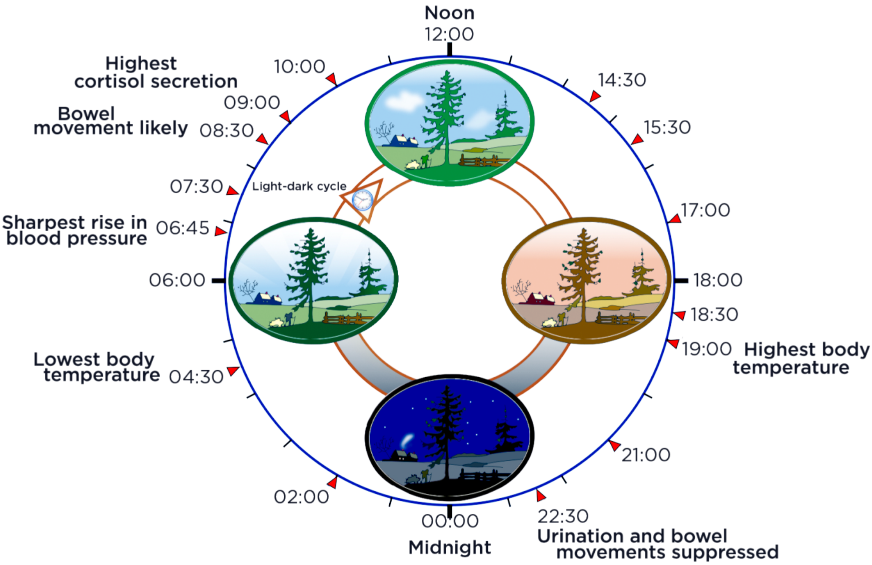
THE **CIRCADIAN** CLOCK

- A more rigorous timepiece chimes in at intervals of 24 hours. The circadian clock tunes our bodies to the cycles of sunlight and darkness that are caused by the Earth's rotation. It helps to program the daily habit of sleeping at night and waking in the morning. Its influence extends much further, however.

- Body temperature regularly peaks in the late afternoon or early evening and bottoms out a few hours before we rise in the morning. Blood pressure typically starts to surge between 6:00 and 7:00 am. Secretion of the stress hormone cortisol is 10 to 20 times higher in the morning than at night. Urination and bowel movements are generally suppressed at night and then pick up again in the morning.

- The circadian timepiece is more like a clock than a stopwatch because it runs without the need for a stimulus from the external environment. Studies of volunteers who live in caves for prolonged studies and other human guinea pigs have demonstrated that circadian patterns persist even in the absence of daylight, occupational demands, and caffeine.

- Moreover, they're expressed in every cell of the body. Confined to a petri dish under constant lighting, human cells still follow 24-hour cycles of gene activity, hormone secretion, and energy production. The cycles are hardwired, and they vary by as little as 1%—just minutes a day.



- Light isn't required to establish a circadian cycle, but it is needed to synchronize the phase of the hardwired clock with natural day and night cycles. Like an ordinary clock that runs a few minutes slow or fast each day, the circadian clock needs to be continually reset to stay accurate.

- Jet lag and shift work are exceptional conditions in which the innate circadian clock is abruptly thrown out of phase with the light-dark cycles or sleep-wake cycles. But the same thing can happen every year, albeit less abruptly, when the seasons change.

SEASONAL AFFECTIVE **DISORDER**

- Research shows that although bedtimes may vary, people tend to get up at about the same time in the morning year-round—usually because their dogs, kids, parents, or careers demand it. In the winter, at northern latitudes, that means many people wake up two to three hours before the sun makes an appearance. Their sleep-wake cycle is several time zones away from the cues they get from daylight.

- The mismatch between day length and daily life could explain the syndrome known as seasonal affective disorder, or SAD. In the US, SAD afflicts as many as one in 20 adults with depressive symptoms such as weight gain, apathy, and fatigue between October and March. The condition is 10 times more common in the north than the south.

- Although SAD occurs seasonally, some experts suspect it is actually a circadian problem. The research of Alfred J. Lewy suggests that SAD patients would come out of their depression if they could get up at the natural dawn in the winter. In his view, SAD isn't so much a pathology as evidence of an adaptive, seasonal rhythm in sleep-wake cycles.

BIOLOGY AND MORTALITY

- This lesson now turns to look at aging and mortality. People tend to relate aging to the diseases of aging—cancer, heart disease, osteoporosis, arthritis, and Alzheimer's, to name a few—as if the absence of disease would be enough to confer immortality. Biology suggests otherwise.

- Modern humans in wealthy countries have a life expectancy of more than 70 years. The life expectancy of an average mayfly, in contrast, is a day. Biologists are just beginning to explore why different species have different life expectancies.

- Comparisons within and among animal species, along with research on aging, have challenged many common assumptions about the factors that determine natural life span. The answer cannot lie solely with a species' genes: Worker honeybees, for example, last a few months, whereas queen bees live for years.

- However, genetics are important. This is exemplified by the fact that single-gene mutation in mice can produce a strain that lives up to 50% longer than usual.

- High metabolic rates can shorten life span, yet many species of birds, which have fast metabolisms, live longer than mammals of comparable body size. And big, slow-metabolizing animals don't necessarily outlast the small ones.

- Scientists in search of the limits to human life span have traditionally approached the subject from the cellular level rather than considering whole organisms. So far, the closest thing they have to a terminal timepiece is the so-called mitotic clock. The clock keeps track of cell division, or mitosis, the process by which a single cell splits into two.

- There seems to be a ceiling on how many times normal cells of the human body can divide. In culture, they will undergo 60 to 100 mitotic divisions. Then, they cease to grow, according to John Sedivy of Brown University, who explains, "They respire, they metabolize, they move, but they will never divide again."

- Cultured cells usually reach this state of senescence in a few months. Fortunately, most cells in the body divide much, much more slowly than cultured cells. Eventually—perhaps after 70 years or so—they, too, can end. Per Sedivy, the cells are counting "the number of cell divisions" rather than chronological time.

- Sedivy has shown that he could squeeze 20 to 30 more cycles out of human fibroblasts by mutating a single gene. This gene encodes a protein called p21, which responds to changes in structures called telomeres that cap the ends of chromosomes.

TELOMERES AND AGING

- Telomeres are made of the same stuff that genes are: DNA. They consist of thousands of repetitions of a six-base DNA sequence that doesn't code for any known protein. Each time a cell divides, chunks of its telomeres are lost.
- Young human embryos have telomeres between 18,000 and 20,000 bases long. By the time senescence kicks in, the telomeres are only 6,000 to 8,000 bases long.
- Biologists suspect that cells become senescent when telomeres shrink below some specific length. Titia de Lange has proposed an explanation for this link. In healthy cells, she showed, the chromosome ends are looped back on themselves like a hand tucked in a pocket.
- The "hand" is the last 100 to 200 bases of the telomere, which are single-stranded, not paired like the rest. With the help of more than a dozen specialized proteins, the single-stranded end is inserted into the double strands upstream for protection.
- If telomeres are allowed to shrink enough, "they can no longer do this looping trick," de Lange says. Untucked, a single-stranded telomere end is vulnerable to fusion with other single-stranded ends. The fusion wreaks havoc in a cell by stringing together all the chromosomes. That could be why Sedivy's mutated p21 cells died after they got in their extra rounds of mitosis.

CONCLUSION

- For now, the link between shortened telomeres and aging is tenuous at best. Experts point out that telomere length varies so much among individuals that it can't be used as a reliable indicator of biological age.

- In any case, most cells don't need to keep dividing to do their job—although white blood cells that fight infection are an exception. Many older people do die of infections that a younger body could withstand.

- In any case, telomere loss is just one of the numerous insults cells sustain when they divide, says Judith Campisi, a professor who has studied aging in-depth. For example, DNA is often damaged when it is replicated during cell division, so cells that have split many times are more likely to harbor genetic errors than young cells.

- "Cell division is very risky business," Campisi observes. Therefore, perhaps it's not surprising that the body puts a cap on mitosis. And cheating cell senescence probably wouldn't grant immortality.

ABOUT THIS LESSON

This lesson was adapted from the article "Times of Our Lives" by Karen Wright, an award-winning writer and editor.

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REMEMBERING **WHEN**

In the course of evolution, humans have developed a biological clock set to the alternating rhythm of light and dark brought by day and night. This clock, located in the brain's hypothalamus, governs what neuroscientist Antonio Damasio calls "body time." However, Damasio says there's another kind of time altogether, which he calls "mind time." Mind time has to do with how we experience the passage of time and how we organize chronology, which are the subjects of this lesson.

SUBJECTIVITY OF TIME

- Despite the steady tick of the clock, durations can seem fast or slow, short or long. And this variability can happen on different scales, from decades, seasons, weeks and hours, down to the tiniest intervals of music—the span of a note or the moment of silence between two notes. We also place events in time, deciding when they occurred, in which order, and on what scale.

- How mind time relates to the biological clock of body time is unknown. It's also not clear whether mind time depends on a single timekeeping device or if our experiences of duration and temporal order rely primarily, or even exclusively, on how we process information.

- If the latter alternative is true, mind time must be determined by the attention we give to events and the emotions we feel when they occur. It must also be influenced by the manner in which we record those events and the inferences we make as we perceive and recall them.

TIME IN THE BRAIN

- Damasio says he was first drawn to the problems of time processing through his work with neurological patients. People who sustain damage to regions of the brain involved in learning and recalling new facts develop major disturbances in their ability to place past events in the correct era and sequence. Moreover, these people with amnesia lose the ability to estimate the passage of time accurately at the scale of hours, months, years, and decades.

- Their biological clock, on the other hand, often remains intact, and so can their abilities to sense brief durations lasting a minute or less and to order them properly. At the very least, the experiences of these patients suggest that the processing of time and certain types of memory must share some common neurological pathways.

- The association between amnesia and time can be seen most dramatically in cases of permanent brain damage to the hippocampus, a region of the brain important to memory, and to the nearby temporal lobe, through which the hippocampus maintains its two-way communication with the rest of the cerebral cortex. Damage to the hippocampus prevents the creation of new factual memories, and the ability to form memories is an indispensable part of the construction of a sense of our own chronology.

- The memories that the hippocampus helps to create are distributed across neural networks located in parts of the cerebral cortex related to the material being recorded: areas dedicated to visual impressions, sounds, tactile information, and so forth. These networks must be activated to both lay down and recall a memory; when they're destroyed, patients can't recover long-term memories, a condition known as retrograde amnesia.

- The memories most markedly lost in retrograde amnesia are precisely those that bear a time stamp: recollections of unique events that happened in a particular context on a particular occasion. For instance, the memory of one's wedding bears a time stamp.

- A different but related kind of recollection—for instance, that of the concept of marriage—carries no such date with it. The temporal lobe cortex that surrounds the hippocampus is critical for making and recalling such memories.

- In patients who sustain damage to the temporal lobe cortex, years and even decades of autobiographical memory can be expunged irrevocably. Viral encephalitis, stroke, and Alzheimer's disease are among the neurological insults responsible for the most profound impairments.

AUTOBIOGRAPHICAL TIME LINES

- How the brain assigns an event to a specific time and then puts that event in a chronological sequence—or fails to do so—is still a mystery. We know only that both the memory of facts and the memory of spatial and temporal relations between those facts are involved.

- Damasio and his colleagues Daniel Tranel and Robert Jones decided to investigate how an autobiographical time line is established. By looking at people with different kinds of memory impairment, they hoped to identify what parts of the brain are required to place memories in the correct epoch.

- They selected four groups of participants, 20 people in total. The groups were broken down as such:

    - Patients with amnesia caused by damage in the temporal lobe.

    - Patients with amnesia caused by damage in the basal forebrain, another area relevant for memory.

    - Patients without amnesia who had damage in places other than the temporal lobe or basal forebrain.

    - Control subjects without neurological disease; these individuals had normal memories and were matched to the patients in terms of age and level of education.

- Every participant completed a detailed questionnaire about key events in their life. The investigators asked them about parents, siblings, various other relatives, schools, friendships, and professional activities. The team then verified the answers with relatives and records. They also established what the participants remembered of key public events.

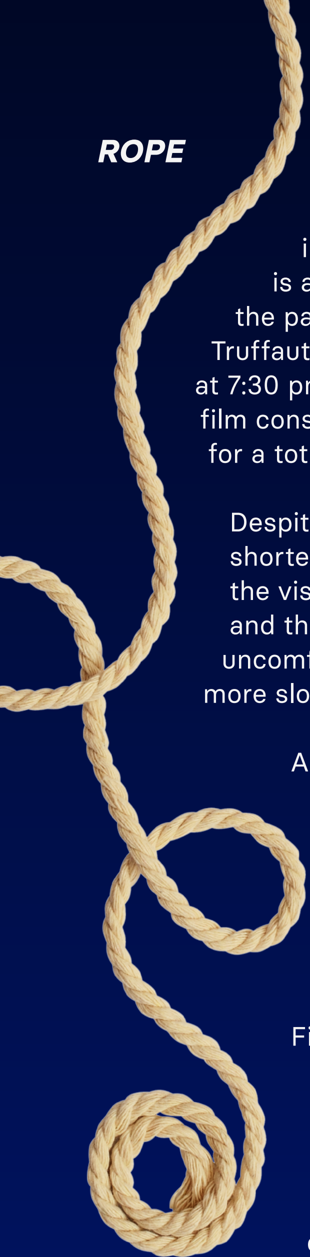
- Then the team had each participant place a customized card that described a specific personal or public event on a board that laid out a year-by-year and decade-by-decade time line for the 1900s. The setup permitted a measurement of the accuracy of time placement.

THE RESULTS

- Predictably, the amnesiac patients differed from the controls. People with normal memory were relatively accurate in their time placements: On average, they were wrong by just 1.9 years.

- Patients with amnesia from basal forebrain damage made far more errors. Although they recalled the event exactly, they were off the mark by an average of 5.2 years. Their recall of events was superior to that of people with amnesia who had temporal lobe damage. However, patients with temporal lobe damage were nonetheless more accurate with regard to time stamping: They were off by an average of only 2.9 years.

- The results suggest that time stamping and event recall are processes that can be separated. More intriguingly, the outcome indicates that the basal forebrain may be critical in helping to establish the context that allows us to place memories in the right era. This notion is in keeping with the clinical observation of basal forebrain patients.



ROPE

Alfred Hitchcock's 1948 film *Rope* was shot in continuous, unedited 10-minute takes, and it is an interesting example of how people perceive the passage of time. In an interview with François Truffaut in 1966, Hitchcock stated that the story begins at 7:30 pm and ends 105 minutes later at 9:15. Yet the film consists of eight reels of 10 minutes each, making for a total of 80 minutes.

Despite the missing 25 minutes, the film never seems shorter than it should. Factors for this may include the visibility of the New York City skyline as night falls and the emotional content of the material: When we're uncomfortable or worried, we often experience time more slowly.

Additionally, a dinner party occurs in the film. The actual time during which food is served is about two reels. But viewers attribute more time to that sequence because we know that neither the hosts nor the guests, who look cool, polite, and unhurried, could swallow down dinner at such speed.

Finally, there are no jump cuts within each 10-minute reel. To join each segment to the next, Hitchcock finished most takes with a close-up on an object. Each interruption may contribute to the elongation of time because we're used to interpreting breaks in the continuity of visual perception as a lapse in the continuity of time.

MENTAL TIME LAG

- Most people don't have to grapple with the large gaps of memory or chronological confusion that many of Antonio Damasio's patients do. However, we all share a strange mental time lag, a phenomenon first brought to light in the 1970s by the neurophysiologist Benjamin Libet of the University of California, San Francisco.

- In one experiment, Libet documented a gap between the time someone was conscious of the decision to flex his finger and the time his brain waves indicated that a flex was imminent. The brain activity occurred a third of a second before the person consciously decided to move his finger.

- Libet performed another experiment in patients undergoing brain surgery. He found that a mild electrical charge to the cortex produced a tingling in a patient's hand a full half a second after the stimulus was applied.

- Although experts disagree how to interpret the findings, it's apparent that a lag exists between the beginning of the neural events leading to awareness and the moment one actually experiences the consequence of those events.

- This finding may seem strange at first glance, and yet the reasons for the delay are fairly obvious. It takes time for the physical signals to modify the sensory detectors of an organ such as the retina. It takes time for the resulting electrochemical modifications to be transmitted as signals to the central nervous system.

- It also takes time to generate a neural pattern in the brain's sensory maps. Finally, it takes time to relate the neural map of the event and the mental image arising from it to the neural map and image of the self—that is, the notion of who we are. This is the last and critical step without which the event will never become conscious.

- This delay covers mere milliseconds, but it is present nonetheless, which raises the question: Why can't we perceive it? One possible explanation is that because we have similar brains and they work similarly, we're all hopelessly late for consciousness and no one notices it.

- But perhaps other reasons apply. At the microtemporal level, the brain manages to "antedate" some events so that delayed processes can appear less delayed and differently delayed processes can appear to have similar delays. This possibility, which Libet contemplated, may explain why we maintain the illusion of continuity of time and space when our eyes move quickly from one target to another.

- We notice neither the blur caused by the eye movement nor the time it takes to get the eyes from one place to the other. Patrick Haggard and John C. Rothwell suggest that the brain predates the perception of the target by as much as 120 milliseconds, thereby giving us the perception of seamless viewing.

- The brain's ability to edit visual experiences and to impart a sense of volition after neurons have already acted is an indication of its exquisite sensitivity to time. Although our understanding of mind time is incomplete, we're gradually coming to know more about why we experience time so variably and about what the brain needs to create a time line.

ABOUT THIS LESSON

This lesson was adapted from the article "Remembering When" by Antonio Damasio, director of the Brain and Creativity Institute at the University of Southern California. He is the author of numerous scientific articles and books, among them *Descartes' Error* and *Self Comes to Mind*.

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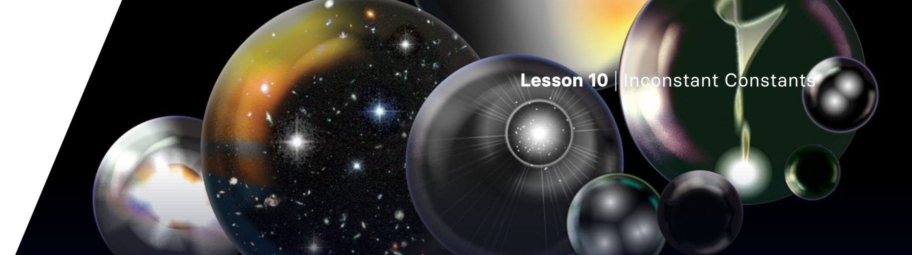
INCONSTANT CONSTANTS

Constants are the topic of this lesson. Such quantities as the velocity of light, *c*, Newton's constant of gravitation, *G*, and the mass of the electron, m_e, are assumed to be the same at all places and times in the universe. They form the framework around which the theories of physics are erected.



TRYING TO EXPLAIN **CONSTANTS**

- It is unclear why constants take the special numerical values that they do. According to the International System of Units, c is 299,792,458; G is 6.673×10^{-11}; and m_e is $9.10938188 \times 10^{-31}$. These are numbers that follow no discernible pattern. The only thread running through the values is that if many of them were even slightly different, complex atomic structures such as living beings would be impossible.

- The desire to explain the constants has been one of the driving forces behind efforts to develop a complete unified description of nature, or "theory of everything." Physicists have hoped such a theory would show that each constant can have only one logically possible value. It would give an underlying order to the seeming arbitrariness of nature.

- In recent years, however, the status of the constants has grown more muddied, not less. Researchers have found that the best candidate for a theory of everything, the variant of string theory called M-theory, is self-consistent only if the universe has more than four dimensions of space and time—as many as seven more.

- One implication is that the constants we observe may not, in fact, be the truly fundamental ones. Those exist in the full higher-dimensional space, and we see only their three-dimensional "shadows."

- Meanwhile, physicists have also come to appreciate that the values of many of the constants may merely be the result of happenstance, acquired during random events and elementary particle processes early in the history of the universe. In fact, string theory allows for a vast number—10^{500}—of possible "worlds" with different self-consistent sets of laws and constants. Thus far, researchers have no idea why our combination exists.

- Continued study may reduce the number of logically possible worlds to just one, but we have to remain open to the unnerving possibility that our known universe is but one of many—a part of a multiverse. Different parts of the multiverse would exhibit different solutions to the theory, making our observed laws of nature just one of many systems of local bylaws.

INCONSTANCY

- The word *constant* itself may be a misnomer. Our constants could vary both in time and in space. If the extra dimensions of space were to change in size, the constants in our three-dimensional world would change with them. If we looked far enough out in space, we might begin to see regions where the so-called constants have settled into different values.

- Ever since the 1930s, researchers have speculated that the constants may not be constant. String theory gives this idea a theoretical plausibility and makes it all the more important for observers to search for deviations from constancy.

- Such experiments are challenging. The first problem is that the laboratory apparatus itself may be sensitive to changes in the constants. The size of all atoms could be increasing, but if the ruler being used to measure them is getting longer, too, it will be impossible to tell.

- Experimenters routinely assume their reference standards—rulers, masses, clocks—are fixed, but they can't do so when testing the constants. They must focus on constants that have no units, so their values are the same irrespective of the units system. An example is the ratio of two masses, such as the proton mass to the electron mass.

- The second experimental problem is that measuring changes in the constants requires high-precision equipment that remains stable long enough to register any changes. Even atomic clocks could detect drifts in the fine-structure constant only over days or, at most, years.

- If α changed by more than four parts in 10^{15} over a three-year period, the best clocks would see it. None have. That may sound like an impressive confirmation of constancy, but three years is a cosmic eyeblink. Slow but substantial changes during the long history of the universe would've gone unnoticed.

- Fortunately, physicists have found other tests. During the 1970s, scientists at the French atomic energy commission noticed something peculiar about the isotopic composition of ore from a uranium mine in Oklo, Gabon: It looked like the waste products of a nuclear reactor. About 2 billion years ago, Oklo must have been the site of a natural reactor.

- In 1976, Alexander Shlyakhter of the Petersburg Nuclear Physics Institute in Russia noticed that the ability of a natural reactor to function depends crucially on the precise energy of a particular state of the samarium nucleus that facilitates the capture of neutrons. That energy depends sensitively on the value of α.

- Therefore, if the fine-structure constant had been slightly different, no chain reaction could have occurred. One did occur, though, which implies the constant hasn't changed by more than one part in 10^8 over the past 2 billion years.

- In 1962, James Peebles and Robert Dicke of Princeton University first applied similar principles to meteorites: The abundance ratios arising from the radioactive decay of different isotopes in these ancient rocks depend on α. The most sensitive constraint involves the beta decay of rhenium into osmium.

- Researchers found that, at the time the rocks formed, α was within two parts in 10^6 of its current value. This result is less precise than the Oklo data but goes back further in time, to the origin of our solar system 4.6 billion years ago.

LOOKING TO THE **STARS**

- To probe possible changes over even longer time spans, researchers must look to the stars. Light takes billions of years to reach our telescopes from distant astronomical sources. It carries a snapshot of the laws and constants of physics at the time when it started its journey or encountered material along the way.

- Astronomy first entered the constants story soon after the discovery of quasars in 1965. The idea was simple. Quasars were identified as bright sources of light located at huge distances from Earth. Because the path of light from a quasar to us is so long, it inevitably intersects the gaseous outskirts of young galaxies. That gas absorbs the quasar light at particular frequencies, imprinting a bar code of narrow lines onto the quasar spectrum.

- Whenever gas absorbs light, electrons within the atoms jump from a low-energy state to a higher one. These energy levels are determined by how tightly the atomic nucleus holds the electrons, which depends on the strength of the electromagnetic force between them—and therefore on the fine-structure constant alpha.

- If the constant was different at the time when the light was absorbed or in the particular region of the universe where it happened, then the energy required to lift the electrons would differ from that required today in lab experiments, and the wavelengths of the transitions seen in the spectra would differ. The way the wavelengths change depends critically on the orbital configuration of the electrons.

- For a given change in α, some wavelengths shrink, whereas others increase. The complex pattern of effects is hard to mimic by data-calibration errors, which makes the test astonishingly powerful.

- John Barrow and John Webb, who wrote the article this lesson is based on, needed some high-precision lab measurements to compare against the quasar spectra. Initial measurements were done by Anne Thorne and Juliet Pickering of Imperial College London, followed by groups at Lund Observatory in Sweden and the National Institute of Standards and Technology.

- A challenge was that previous observers had used so-called alkali-doublet absorption lines—pairs of absorption lines arising from the same gas, such as carbon or silicon. They compared the spacing between these lines in quasar spectra with lab measurements.

- However, this method failed to take advantage of one particular phenomenon: A change in α shifts not just the spacing of atomic energy levels relative to the lowest energy level, or ground state, but also the position of the ground state itself. Consequently, the highest precision observers achieved was only about one part in 10^4.

- In 1999, John Webb and Victor Flambaum of the University of New South Wales in Sydney came up with a method to take both effects into account and achieved 10 times higher sensitivity. Moreover, the method allows different species (for instance, magnesium and iron) to be compared, which allows additional cross-checks. Combined with modern telescopes and detectors, the new approach, known as the many-multiplet method, has enabled Webb and Barrow to test the constancy of α with unprecedented precision.

- When embarking on this project, they anticipated establishing that the value of the fine-structure constant long ago was the same as it is today; their contribution would simply be higher precision. To their surprise, the first results showed small but statistically significant differences.

- Further data confirmed this finding. Based on a total of 128 quasar absorption lines, they found an average increase in α of close to six parts in 1 million over the past 6 to 12 billion years.

NEW DATA

- By 2010, Barrow and Webb completed the analysis of a large amount of new data from the Very Large Telescope, or VLT, operated by the European Southern Observatory. They obtained 153 new measurements.

- All of the data their group had previously analyzed had come from the Keck telescopes on Mauna Kea in Hawaii. For these new VLT data, everything was different: the telescopes, the spectrograph, the detectors, and the software used for the initial stages of the data analysis. These VLT data therefore provided a beautiful cross-check with their results from the Keck telescopes.

- They thought it was possible that the new data would show no change in α at all or that they would show the same effect the Keck data did—with α appearing smaller at higher redshifts. However, the new VLT data showed not a smaller value of α at high redshift but a larger value. It was larger by just about the same amount as the Keck data are smaller.

- The researchers initially suspected they were seeing evidence for systematic problems in both data sets. Add the Keck and VLT samples together, and to a good approximation, the combined sample shows no change in α with redshift. The constants are really constant after all.

- However, if that's the explanation, it requires two different systematic effects, one for each telescope, such that both effects are, independently, of the same magnitude but opposite sign. This isn't impossible, but it's pretty unlikely.

- They did discover another curiosity, though. The Keck data cover a somewhat large portion of the sky in the Northern Hemisphere. It is large enough to ask: Could it be that α changes not with redshift but with position on the sky?

- A simple analysis suggested that might be the case. The VLT is in Chile and, on average, points to a very different part of the universe than the Keck telescopes do. It is possible that that is another coincidence, but that would make for two coincidences.

- When the old Keck and the new VLT samples are merged, the result is positively intriguing: the directional dependence becomes highly significant. Deriving such a result by chance appears to be extremely unlikely. If the result is a fluke, a subset of the data could be generating a rogue result.

- Despite extensive attempts, however, they've yet to find a combination of systematic effects in the data that could mimic a spatial dependence. Alpha appears to change spatially—across, perhaps, the entire observable universe.

- Any change with time is smaller and is currently below their detection sensitivity. In a study in *Science* in 2020, Webb and Barrow and their colleagues used four different measurements of the fine-structure constant going back 13 billion years and concluded that the spatial variation in alpha is real.

CONSEQUENCES

- The consequences of a variable constant are enormous, though only partially explored. Barrow and Webb's theory suggests that varying the fine-structure constant makes objects fall differently.

- Galileo predicted that bodies in a vacuum fall at the same rate no matter what they're made of—an idea known as the weak equivalence principle. But if α varies, that principle no longer holds exactly. The variations generate a force on all charged particles.

- The more protons an atom has in its nucleus, the more strongly it'll feel this force. If Webb and Barrow's quasar observations are correct, then the accelerations of different materials differ by about one part in 10^{14}, which is too small to measure currently.

- Going forward, the main scientific focus is on α, over the other constants of nature, simply because it's possible to build up a statistical sample of measurements, mapping the laws of physics throughout the distant cosmos in greater detail. If α is susceptible to change, however, other constants should vary as well, making the inner workings of nature fickler than scientists ever suspected.

ABOUT THIS LESSON

This lesson was adapted from the article "Inconstant Constants" by John Barrow, a professor of mathematical sciences at the University of Cambridge, and John Webb, a professor at the University of New South Wales.

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ATOMS OF SPACE AND TIME

This lesson's topic is loop quantum gravity—a theory that predicts that space and time are made of discrete pieces. Lee Smolin and his colleagues developed the theory of loop quantum gravity while struggling with a long-standing problem in physics: Is it possible to develop a quantum theory of gravity?

A **CHALLENGING** MERGE

- Formed in the first quarter of the 20th century, quantum theory successfully predicts the properties of atoms and the particles and forces that compose them. The equations of quantum mechanics require that certain quantities, such as the energy of an atom, can come only in specific, discrete units, or quanta.

- In the same decades that quantum mechanics was being formulated, Albert Einstein constructed his general theory of relativity, which is a theory of gravity. In his theory, the gravitational force arises as a consequence of space and time (which together form spacetime) being curved by the presence of matter.

- Quantum theory and Einstein's general theory of relativity have each separately been confirmed by experiment. One problem for merging them is that quantum effects are most prominent at small size scales, whereas general relativistic effects require large masses, so no experiment has been able to combine their domains.

- Along with this hole in the experimental data is a huge conceptual problem: Einstein's general theory of relativity is thoroughly classical, or nonquantum. For physics as a whole to be logically consistent, there has to be a theory that somehow unites quantum mechanics and general relativity.

- This long-sought-after theory is called quantum gravity. Since general relativity deals in the geometry of spacetime, a quantum theory of gravity will also be a quantum theory of spacetime.

- Physicists have developed mathematical procedures for turning a classical theory into a quantum one. Many theoretical physicists and mathematicians have worked on applying those standard techniques to general relativity. Early results were discouraging. Calculations carried out in the 1960s and 1970s seemed to show that quantum theory and general relativity couldn't be combined.

A NEW APPROACH

- In the mid-1980s, Lee Smolin and other theorists decided to reexamine the question of whether quantum mechanics could be combined consistently with general relativity using the standard techniques.

- They knew the negative results from the 1970s had an important loophole. Those calculations assumed that the geometry of space is continuous and smooth. But if this assumption was wrong, the old calculations wouldn't be reliable.

- Smolin and his colleagues began searching for a way to do calculations without assuming that space is smooth and continuous. They kept two key principles of general relativity at the heart of their calculations.

- The first is known as background independence. This principle says that the geometry of spacetime is not fixed. Instead, the geometry is an evolving, dynamic quantity. To find the geometry, one has to solve certain equations that include all the effects of matter and energy.

- The second principle, diffeomorphism invariance, is closely related to background independence. This principle implies that, unlike theories prior to general relativity, one is free to choose any set of coordinates to map spacetime and express the equations. A point in spacetime is defined only by what physically happens at it, not by its location according to some special set of coordinates.

- By combining these two principles with the techniques of quantum mechanics, Smolin and his colleagues developed a mathematical language that allowed them to do a computation to determine whether space is continuous or discrete. That calculation revealed, to their delight, that space is quantized.

- They had laid the foundations of their theory of loop quantum gravity. The term *loop* arises from how some computations in the theory involve small loops marked out in spacetime.

LOOP QUANTUM GRAVITY **IN ACTION**

- Over the years since, the study of loop quantum gravity has grown into a healthy field of research, with many contributors. Their combined efforts give us confidence in the picture of spacetime their theory describes.

- This is a quantum theory of the structure of spacetime at the smallest size scales. To explain how the theory works, it is necessary to consider what it predicts for a small region or volume. In dealing with quantum physics, it's essential to specify precisely what physical quantities are to be measured.

- To do so, consider a region somewhere that's marked out by a boundary, B. The boundary may be defined by some matter, such as a cast-iron shell, or it may be defined by the geometry of spacetime itself, as in the event horizon of a black hole, the boundary where even light can't escape the black hole's gravitational clutches.

- What happens if we measure the volume of the region? What are the possible outcomes allowed by both quantum theory and diffeomorphism invariance? If the geometry of space is continuous, the region could be of any size and the measurement result could be any positive real number; in particular, it could be as close as one wants to zero volume.

- But if the geometry is granular, then the measurement result can come from just a discrete set of numbers, and it can't be smaller than a certain minimum possible volume. The question is like asking how much energy electrons orbiting an atomic nucleus have.

- Classical mechanics predicts that an electron can possess any amount of energy, but quantum mechanics allows only specific energies. The difference is similar to that between the measure of something that flows continuously, like the 19th-century conception of water, and something that can be counted, like the atoms in that water.

- The theory of loop quantum gravity predicts that space is like atoms: There is a discrete set of numbers that the volume-measuring experiment can return. Another quantity we can measure is the area of the boundary B. Again, calculations using the theory return an unambiguous result: The area of the surface is discrete as well. In other words, space is not continuous. It comes only in specific quantum units of area and volume.

THE PLANCK LENGTH

- The possible values of volume and area are measured in units of a quantity called the Planck length. This length is related to the strength of gravity, the size of quanta and the speed of light. It measures the scale at which the geometry of space is no longer continuous.

- The Planck length is very small: 10^{-33} centimeter. The smallest possible nonzero area is about a square Planck length, or 10^{-66} centimeter squared. The smallest nonzero volume is approximately a cube with edges of Planck length, 10^{-99} centimeter cubed.

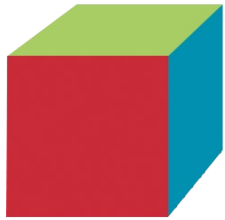
- The theory predicts that there are about 10^{99} atoms of volume in every cubic centimeter of space. The quantum of volume is so tiny that there are more such quanta in a cubic centimeter than there are cubic centimeters in the visible universe.

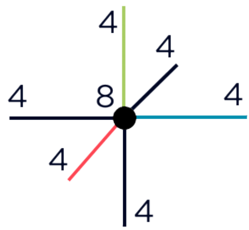
DIAGRAMS

- This lesson turns next to examine what else the theory can tell us about spacetime. To start with, what do these quantum states of volume and area look like? Is space made up of many tiny cubes or spheres?

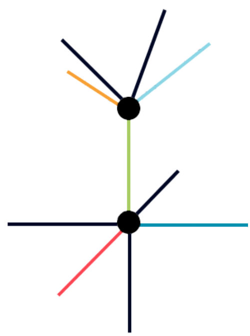
- The answer is no—it's not that simple. However, it is possible to draw diagrams that represent the quantum states of volume and area. To those working in this field, these diagrams are beautiful because of their connection to an elegant branch of mathematics.

- To see how these diagrams work, imagine a lump of space shaped like a cube. In the diagrams, this would be depicted as a dot, which represents the volume, with six lines sticking out, each of which represents one of the cube's faces. A number next to the dot to specifies the quantity of volume, and on each line, a number to specify the area of the face that the line represents.





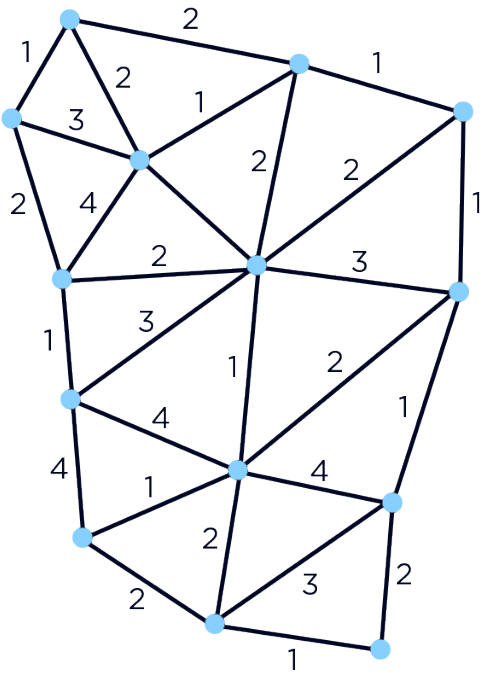
- Next, imagine a pyramid on top of the cube. These two polyhedral shapes, which share a common face, would be depicted as two dots (two volumes) connected by one of the lines (the face that joins the two volumes). The cube has five other faces (five lines sticking out), and the pyramid has four (four lines sticking out).



- More complicated arrangements involving polyhedra other than cubes and pyramids can be depicted with these dot-and-line diagrams: Each polyhedron of volume becomes a dot, or node, and each flat face of a polyhedron becomes a line. The lines join the nodes in the way that the faces join the polyhedra together. Mathematicians call these line diagrams graphs.

- In loop quantum gravity, we throw away the drawings of polyhedra and just keep the graphs. The mathematics that describes the quantum states of volume and area gives us a set of rules for how the nodes and lines can be connected and what numbers can go where in a diagram.

- Every quantum state corresponds to one of these graphs, and every graph that obeys the rules corresponds to a quantum state. The graphs are a convenient shorthand for all the possible quantum states of space.

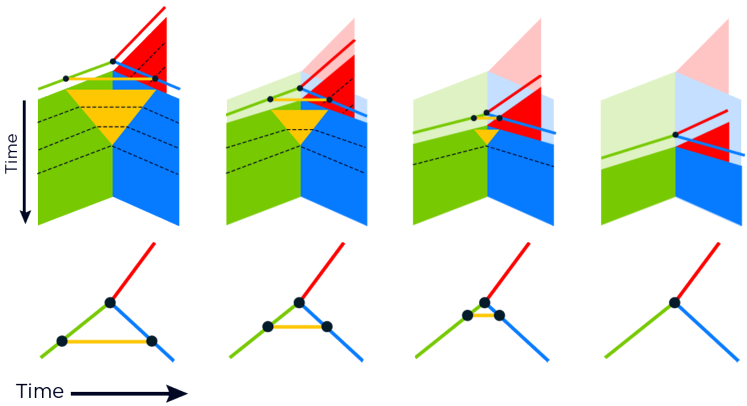


- The graphs are a better representation of the quantum states than the polyhedra are. In particular, some graphs connect in strange ways that can't be converted into a tidy picture of polyhedra. For example, whenever space is curved, the polyhedra will not fit together properly in any drawing we could do, yet we can still draw a graph.

- Indeed, we can take a graph and from it calculate how much space is distorted. Because the distortion of space is what produces gravity, this is how the diagrams form a quantum theory of gravity.

- For simplicity's sake, we often draw the graphs in two dimensions. But it's actually better to imagine them filling three-dimensional space since that's what they represent. Yet there's a conceptual trap here: The lines and nodes of a graph don't live at specific locations in space.

- Each graph is defined only by the way its pieces connect and how they relate to well-defined boundaries such as boundary B. The continuous, three-dimensional space one might imagine the graphs occupying does not exist as a separate entity. All that exist are the lines and nodes; they are space, and the way they connect defines the geometry of space.



SPIN NETWORKS

- These graphs are called spin networks because the numbers on them are related to quantities called spins. Roger Penrose of the University of Oxford first proposed in the early 1970s that spin networks might play a role in theories of quantum gravity. In 1994, Smolin and his colleagues found that precise calculations confirmed Penrose's intuition.

- The individual nodes and edges of the diagrams represent extremely small regions of space: A node is typically a volume of about one cubic Planck length, and a line is typically an area of about one square Planck length. But in principle, nothing limits how big and complicated a spin network can be.

- If we could draw a detailed picture of the quantum state of our universe—the geometry of its space, as curved and warped by the gravitation of galaxies and black holes and everything else—it would be a gargantuan spin network of unimaginable complexity, with approximately 10^{184} nodes.

- These spin networks describe the geometry of space. But how do we represent particles and fields occupying positions and regions of space? Particles such as electrons correspond to certain types of nodes, which are represented by adding more labels on nodes. Fields, such as the electromagnetic field, are represented by additional labels on the lines of the graph.

- We represent particles and fields moving through space by these labels moving in discrete steps on the graphs. Particles and fields aren't the only things that move around, though. According to general relativity, the geometry of space changes in time. The bends and curves of space change as matter and energy move, and waves can pass through it like ripples on a lake.

- In loop quantum gravity, these processes are represented by changes in the graphs. They evolve in time by a succession of certain "moves" in which the connectivity of the graphs changes.

PHENOMENA AND PROBABILITIES

- When physicists describe phenomena quantum-mechanically, they compute probabilities. We do the same when we apply loop quantum gravity theory to describe phenomena, whether it's particles and fields moving on the spin networks or the geometry of space itself evolving in time.

- Work by many people over the past few decades has revealed an elegant set of rules for computing the probabilities of the different moves by which spin networks change in time. These rules express the quantum version of Einstein's equations of general relativity. With them, we have a well-defined procedure for computing the probability of any process that can occur in a world that obeys the rules of our theory.

- To discover the precise rules for computing probabilities, physicists had to follow Einstein in shifting the perspective from space to spacetime. The spin networks that represent space in loop quantum gravity theory accommodate the concept of spacetime by becoming what we call spin foams.

- With the addition of another dimension—time—the lines of the spin networks grow to become two-dimensional surfaces and the nodes grow to become lines. Transitions where the spin networks change are now represented by nodes where the lines meet in the foam.

- In the spacetime way of looking at things, a snapshot at a specific time is like a slice cutting across the spacetime. Taking such a slice through a spin foam produces a spin network.

- But it would be wrong to think of such a slice as moving continuously, like a smooth flow of time. Instead, just as space is defined by a spin network's discrete geometry, time is defined by the sequence of distinct moves that rearrange the network.

- In this way, time also becomes discrete. Time flows not like a river but like the ticking of a clock, with "ticks" that are about as long as the Planck time: 10^{-43} second. More precisely, time in our universe flows by the ticking of innumerable clocks. In a sense, at every location in the spin foam where a quantum "move" takes place, a clock at that location has ticked once.

CONCLUSION

- Loop quantum gravity has opened up a new window on deep cosmological questions such as those relating to the origins of our universe. We can use the theory to study the earliest moments of time just after the big bang.

- General relativity predicts that there was a first moment of time. Models of the very early universe based on loop quantum gravity, however, indicate that the big bang is actually a big bounce. Before the bounce, the universe was rapidly contracting.

- Theorists are now hard at work developing predictions for the early universe that may be testable in future cosmological observations. Perhaps this will lead to evidence of the time before the big bang.

ABOUT THIS LESSON

This lesson was adapted from the article "Atoms of Space and Time" by Lee Smolin of the Perimeter Institute for Theoretical Physics. Smolin's books, including *Time Reborn*, probe philosophical issues raised by research in physics and cosmology.

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COULD TIME **END?**

In our experience, time never really ends. But will that always be the case? Might there come a point sometime in the future when there's no "after"? Some modern physics suggests the answer is yes. All activity would cease, and there would be no renewal or recovery. The end of time would be the end of endings. For now, though, it is the topic of this lesson.

AN UNANTICIPATED PREDICTION

- This prospect was an unanticipated prediction of Albert Einstein's general theory of relativity, which provides our modern understanding of gravity. Before that theory, most physicists and philosophers thought time was a universal drumbeat, a steady rhythm that the cosmos marches to, never varying, wavering, or stopping.

- However, Einstein showed that the universe is more like a big polyrhythmic jam session. Time can slow down, or stretch out, or let it rip. When we feel the force of gravity, we're feeling time's rhythmic improvisation; falling objects are drawn to places where time passes more slowly. Time not only affects what matter does but also responds to what matter is doing. When things get out of hand, though, time can go up in smoke.

- The moments when that happens are known as singularities. A singularity is any boundary of time, be it beginning or end. The best known is the big bang, the instant 13.8 billion years ago when our universe—and, with it, time—burst into existence and began expanding.

- Relativity says time expires inside black holes while carrying on in the universe at large. If a living being fell into one, the being would be torn to shreds, and the remains would eventually hit a singularity at the center of the hole. The being's time line would end. This would be complete death without rebirth.

- It took physicists decades to accept that relativity theory predicts something so unsettling. Singularities are arguably the main reason physicists seek a unified theory of physics that would merge Einstein's brainchild of relativity with quantum mechanics to create a quantum theory of gravity. They do so partly in the hope they might explain singularities away.

THE **ALTERNATIVE** TO TIME ENDING

- Time's end is hard to imagine, but time's not ending may be equally paradoxical. Well before Einstein came along, philosophers through the ages had debated whether time could be mortal.

- Aristotle, for instance, argued that time can't have a beginning or an end. Every moment is both the end of an era and the start of something new; every event is both the outcome of something and the cause of something else.

- The University of Oxford philosopher Richard Swinburne has asserted, "It is not logically possible for time to have an end." But if time cannot end, then the universe must be infinitely long-lived, and all the riddles posed by the notion of infinity come rushing in. Philosophers have thought it absurd that infinity could be anything but a mathematical idealization.

- The triumph of the big bang theory and the discovery of black holes seemed to settle the question. The universe is shot through with singularities and could suffer a distressing variety of temporal cataclysms. But when it comes to figuring out what singularities actually are, the answer's not so clear.

- At the big bang singularity, relativity theory says that the precursors of every single galaxy we see were squashed into a single mathematical point—a true point of zero size.

- Likewise, in a black hole, every single particle of a hapless astronaut is compacted into an infinitesimal point. In both cases, calculating the density means dividing by zero volume, yielding infinity. Other types of singularities don't involve infinite density but an infinite something else.

- Modern physicists take infinity as a sign they've pushed a theory too far. Nearly all physicists presume that cosmic singularities actually have a finite, if high, density. Relativity theory errs because it fails to capture some important aspect of gravity or matter that comes into play near singularities and keeps the density under control.

NEW APPROACHES

- To figure out what goes on will take a more encompassing theory—a quantum theory of gravity. Physicists are still working on such a theory, but they figure that it will incorporate the central insight of quantum mechanics: that matter, like light, has wavelike properties.

- These properties should smear the putative singularity into a small wad, rather than a point, and thereby banish the divide-by-zero error. If so, time may not, in fact, end.

- However, physicists argue it both ways. Some think time does end. The trouble with this option is that the known laws of physics operate within time and describe how things move and evolve. Time's end points would have to be governed not just by a new law of physics but by a new type of law of physics, one that avoids temporal concepts such as motion and change in favor of timeless ones such as geometric elegance.

- A portion of quantum gravity researchers think that time stretches on forever, with no beginning or end. In their view, the big bang was simply a dramatic transition in the eternal life of the universe.

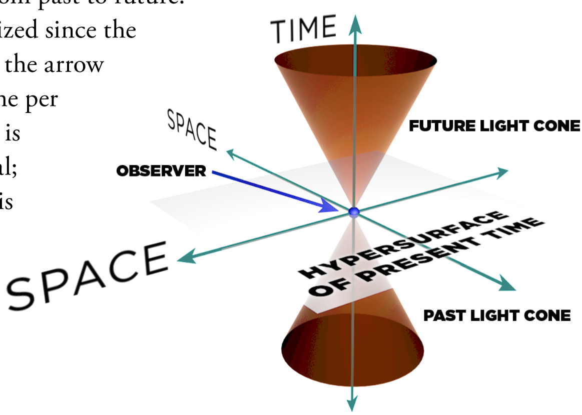
OTHER WAYS OF THINKING

- Some people conclude that science can never resolve whether time ends. For them, the boundaries of time are also the boundaries of reason and empirical observation. Others, however, think figuring out the boundaries of time simply requires some fresh thinking. For example, physicist Gary Horowitz says, “Quantum gravity should be able to provide a definite answer.”

- Just as life emerges out of lifeless molecules that organize themselves, time might emerge from some timeless stuff that brings itself to order. A temporal world is a highly structured one. Time tells us when events occur, for how long, and in what order. Perhaps this structure was not imposed from the outside but arose from within. What can be made can be unmade. When the structure crumbles, time ends.

- By this thinking, time’s demise is no more paradoxical than the disintegration of any other complex system. One by one, time loses its features and passes through the twilight from existence to nonexistence.

- The first to go might be its unidirectionality—its “arrow” pointing from past to future. Physicists have recognized since the mid-19th century that the arrow is a property not of time per se but of matter. Time is inherently bidirectional; the arrow we perceive is simply the natural degeneration of matter from order to chaos.



- If this trend keeps up, the universe will approach a state of equilibrium in which it can't possibly get any messier. Individual particles will continue to reshuffle themselves, but the universe as a whole will cease to change. Any surviving clocks will jiggle in both directions, and the future will become indistinguishable from the past.

- Another feature time might lose could be the concept of duration. Time as we know it comes in amounts such as seconds, days, and years. If it didn't, we'd be able to tell that events occurred in chronological order but not how long they lasted. That scenario is what University of Oxford physicist Roger Penrose presents in his book *Cycles of Time: An Extraordinary New View of the Universe*.

TIME AS A **DIMENSION** OF SPACE

- Even if duration becomes meaningless, time isn't dead quite yet. It still dictates that events unfold in a sequence of cause and effect that is the same for all observers. In this respect, time is different from space.

- Two events that are adjacent within time—like a person typing on a keyboard and letters appearing on their computer screen—are inextricably linked. But two objects that are adjacent within space—the keyboard and a nearby piece of paper—might have nothing to do with each other. Spatial relations simply don't have the same inevitability that temporal ones do.

- Under certain conditions, though, time could lose even this basic ordering function and become just another dimension of space. This idea goes back to the 1980s, when Stephen Hawking and James Hartle sought to explain the big bang as the moment when time and space became differentiated.

THE **HOLOGRAPHIC** PRINCIPLE

- Even if we can't define duration or causal relations, we can still label events by the time they occurred and lay them out on a time line. Several groups have made progress on how time might be stripped of this last remaining feature by studying what happens to it at black hole singularities using one of the most powerful ideas of string theory, known as the holographic principle.

- A hologram is a special type of image that evokes a sense of depth. Though flat, the hologram is patterned to make it look as though a solid object is floating in front of you in three-dimensional space.

- The holographic principle holds that our entire universe is like a holographic projection. A complex system of interacting quantum particles can evoke a sense of depth—that is to say, a spatial dimension that doesn't exist in the original system.

- However, the converse is not true. Not every image is a hologram; it must be patterned in just the right way. If a hologram is scratched, its illusion is spoiled. Likewise, not every particle system gives rise to a universe like ours. The system must be patterned just so.

- If the system initially lacks the necessary regularities and then develops them, the spatial dimension pops into existence. If the system reverts to disorder, the dimension disappears where it came from.

- With that in mind, imagine the collapse of a star to a black hole. The star looks three-dimensional to us but corresponds to a pattern in some two-dimensional particle system. As its gravity intensifies, the corresponding planar system jiggles with increasing fervor. When a singularity forms, order breaks down completely.

- The process is analogous to the melting of an ice cube: The water molecules go from a regular crystalline arrangement to the disordered jumble of a liquid. The third dimension literally melts away. As it goes, so does time.

- If an astronaut falls into a black hole, the time on the astronaut's watch depends on their distance from the center of the hole, which is defined within the melting spatial dimension. As that dimension disintegrates, the watch starts to spin uncontrollably, and it becomes impossible to say that events occur at specific times or objects reside in specific places.

- In practice, this means that space and time no longer give structure to the world. Attempted measurements of the objects' positions will show that they appear to reside in more than one place.

- Spatial separation means nothing to them; they jump from one place to another without crossing the intervening distance. In fact, that's how the imprint of a hapless astronaut who passes the black hole's point of no return, its event horizon, can get back out. "If space and time do not exist near a singularity, the event horizon is no longer well defined," Gary Horowitz says.

- In other words, string theory doesn't just smear out the putative singularity, replacing the errant point with something more palatable while leaving the rest of the universe much the same. Instead, it reveals a broader breakdown of the concepts of space and time, the effects of which persist far from the singularity itself.

The theory still requires a primal notion of time in the particle system. Scientists are still trying to develop a notion of dynamics that doesn't presuppose time at all. Until then, time clings stubbornly to life. It's so deeply ingrained in physics that scientists have yet to imagine its final and total disappearance.

ABOUT THIS LESSON

This lesson was adapted from the article "Could Time End?" by George Musser, a contributing editor for *Scientific American* and author of *Spooky Action at a Distance*. The original article won the 2011 Science Communication Award from the American Institute of Physics.

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