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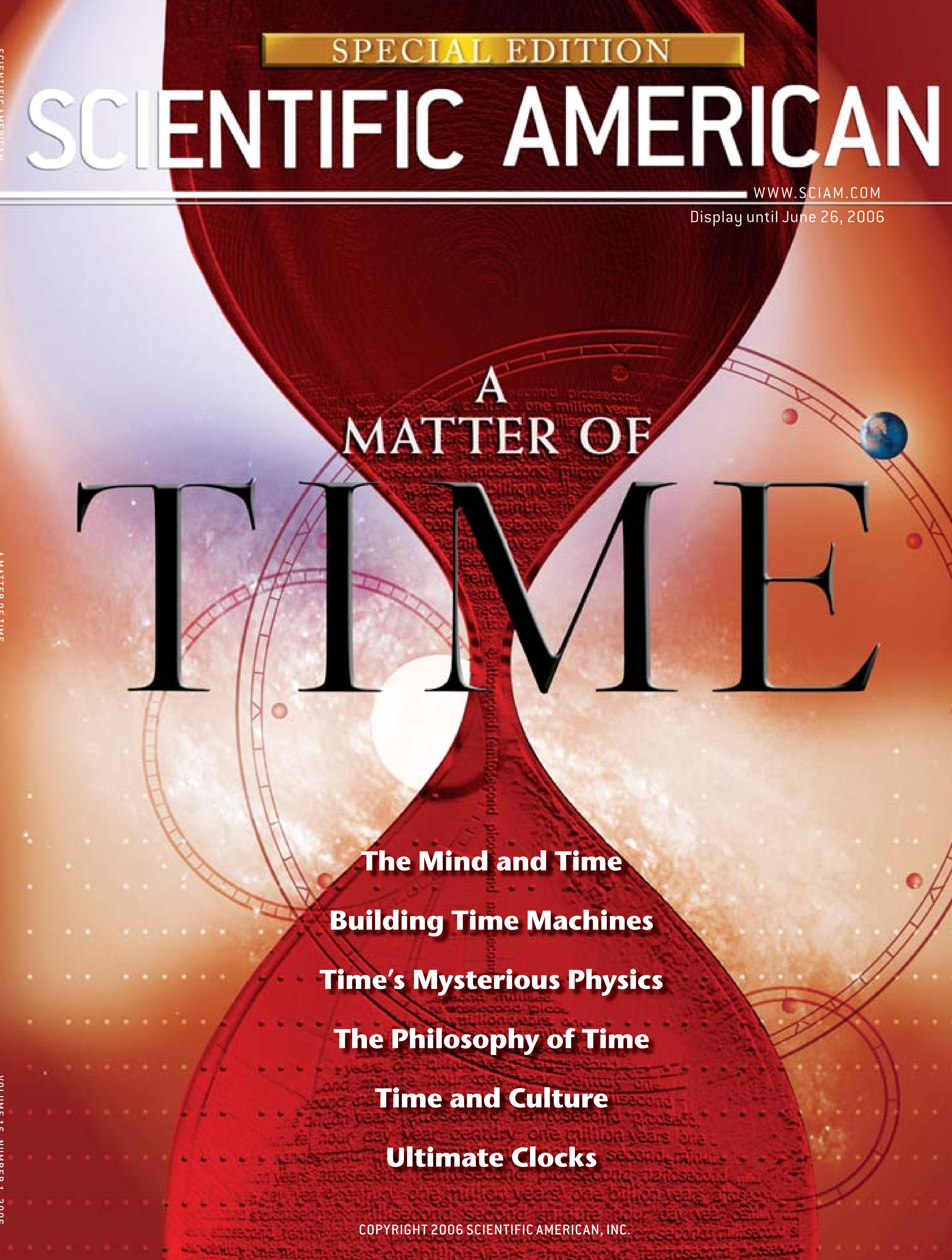

A MATTER OF TIME

The Mind and Time

Building Time Machines

Time's Mysterious Physics

The Philosophy of Time

Time and Culture

Ultimate Clocks

SCIENTIFIC AMERICAN
A MATTER OF TIME
VOLUME 16, NUMBER 1, 2006


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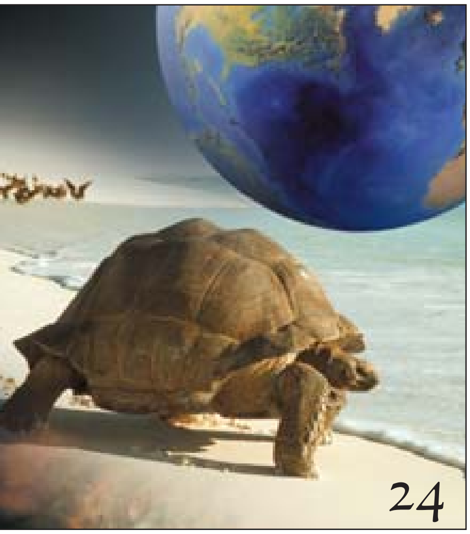
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A MATTER OF TIME

Volume 16, Number 1, 2006

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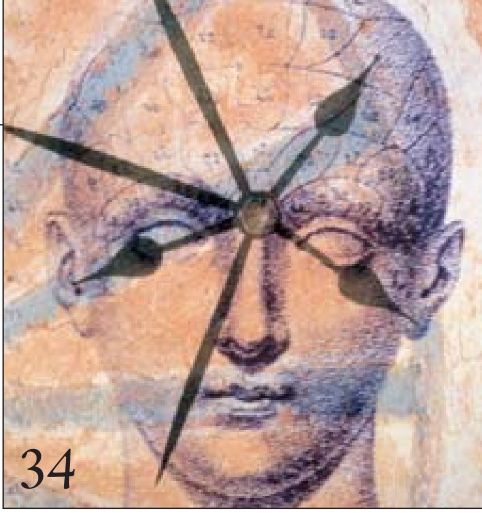

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REAL TIME

The pace of living quickens continuously, yet a full understanding of things temporal still eludes us **By Gary Stix**

More than 200 years ago Benjamin Franklin coined the now famous dictum that equated passing minutes and hours with shillings and pounds. The new millennium—and the decades leading up to it—has given his words their real meaning. 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 and gigabits per second.

An English economics professor even tried to capture the millennial zeitgeist by supplying Franklin's adage with a quantitative underpinning. According to a formula derived by Ian Walker of the University of Warwick, three minutes of brushing one's teeth works out to the equivalent of 45 cents, the compensation (after taxes and Social Security) that the average Briton gives up by doing something besides working. Half an hour of washing a car by hand translates into $4.50.

This reduction of time to money may extend Franklin's observation to an absurd extreme. But the commodification of time is genuine—and results from a radical alteration in how we view the passage of events. Our fundamental human drives have not changed from the Paleolithic era, hundreds of thousands of years ago. Much of what we are about centers on the same impulses to eat, procreate, fight or flee that motivated Fred Flintstone. Despite the constancy of these primal urges, human culture has experienced upheaval after upheaval in the period since our hunter-gatherer forebears roamed the savannas. Perhaps the most profound change in the long transition from Stone Age to information age revolves around our subjective experience of time.

By one definition, time is a continuum in which one event follows another from the past through to the future. Today the number of occurrences packed inside a given interval, whether it be a year or a nanosecond, increases unendingly. The technological age has become a game of one-upmanship in which more is always better. In his book *Faster: The Acceleration of Just About Everything,* James Gleick noted that before Federal Express shipping became commonplace in the 1980s, the exchange of business documents did not usually require a package to be delivered "absolutely positively overnight." At first, FedEx gave its customers an edge. But soon 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."

Simultaneity

THE ADVENT of the Internet eliminated the burden of having to wait until the next day for the FedEx truck. 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 or Dakar. Time has, in essence, triumphed over space. Noting this trend, Swatch, the watchmaker, went so far as to try to abolish the temporal boundaries that separate one place from another. It created a standard for Internet timekeeping that eliminated time zones, dividing the day into 1,000 increments that are the same anywhere on the globe, with the meridian at Biel, Switzerland, the location of Swatch's headquarters.

The digital Internet clock still marches through its paces on the Web and on the Swatch corporate building in Biel. But the prospects for it as a widely adopted universal time standard are about as good as the frustrated aspirations for Esperanto to become the world's lingua franca.

Leaving gimmickry aside, the wired world does erase time barriers.

KAREN BEARD / *Image Bank*

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This achievement relies on an ever progressing ability to measure time more precisely. Over the aeons, the capacity to gauge duration has correlated directly with increasing control over the environment that we inhabit. Keeping time is a practice that may go back more than 20,000 years, when hunters of the ice age notched holes in sticks or bones, possibly to track the days between phases of the moon. And a mere 5,000 years ago or so the Babylonians and Egyptians devised calendars for planting and other time-sensitive activities.

Early chronotechnologists were not precision freaks. They tracked natural cycles: the solar day, the lunar month and the solar year. The sundial could do little more than cast a shadow, when clouds or night did not render it a useless decoration. Beginning in the 13th century, though, the mechanical clock initiated a revolution equivalent to the one engendered by the later invention by Gutenberg of the printing press. Time no longer "flowed," as it did literally in a water clock. Rather it was marked off by a mechanism that could track the beats of an oscillator. When refined, this device let time's passage be counted to fractions of a second.

MEET YOU AT @694 Internet time (5:39 P.M. in Biel, Switzerland). This Swatch-created standard breaks a day up into 1,000 ".beats," observed around the world simultaneously.

The mechanical clock ultimately enabled the miniaturization of the timepiece. Once it was driven by a coiled spring and not a falling weight, it could be carried or worn like jewelry. The technology changed our perception of the way society was organized. It was an instrument that let one person coordinate activities with another. "Punctuality comes from within, not from without," writes Harvard University historian David S. Landes in his book *Revolution in Time: Clocks and the Making of the Modern World*. "It is the mechanical clock that made possible, for better or worse, a civilization attentive to the passage of time, hence to productivity and performance."

Mechanical clocks persisted as the most accurate timekeepers for centuries. But the past 50 years has seen as much progress in the quest for precision as in the previous 700 [see "A Chronicle of Timekeeping," by William J. H. Andrewes, on page 46]. It hasn't been just the Internet that has brought about the conquest of time over space. Time is more accurately measured than any other physical entity. As such, elapsed time is marshaled to size up spatial dimensions. Today standard makers gauge the length of the venerable meter by the distance light in a vacuum travels in 1/299,792,458 of a second.

Atomic clocks, which are used to make such measurements, also play a role in judging location. In some of them, the resonant frequency of cesium atoms remains amazingly stable, becoming a pseudo-pendulum capable of maintaining near nanosecond precision. The Global Positioning System (GPS) satellites continuously broadcast their exact whereabouts as well as the time maintained by onboard atomic clocks. A receiving device processes this information from at least four satellites into exact terrestrial coordinates for the pilot or the hiker, whether in Patagonia or Lapland. The requirements are exacting. A time error of only a millionth of a second from an individual satellite could send a signal to a GPS receiver that would be inaccurate by as much as a fifth of a mile (if it went uncorrected by other satellites).

Advances in precision timekeeping continue apace. In fact, in the next few years clockmakers may outdo themselves. They may create an atomic clock so precise that it will be impossible to synchronize other timepieces to it [see "Ultimate Clocks," by W. Wayt Gibbs, on page 56]. Researchers also continue to press ahead in slicing and dicing the second more finely. The need for speed has become a cornerstone of the infor-

SWATCH

mation age. In the laboratory, transistors can switch faster than a picosecond, a thousandth of a billionth of a second [see "From Instantaneous to Eternal," on page 24].

A team from France and the Netherlands set a new speed record for subdividing the second, reporting in 2001 that a laser strobe light had emitted pulses lasting 250 attoseconds—that is 250 billionths of a billionth of a second. The strobe may one day be fashioned into a camera that can track the movements of single electrons. The modern era has also registered gains in assessing big intervals. Radiometric dating methods, measuring rods of "deep time," indicate how old the earth really is.

The ability to transcend time and space effortlessly—whether on the Internet or piloting a GPS-guided airliner—lets us do things faster. Just how far speed limits can be stretched remains to be tested. Conference sessions and popular books toy with ideas for the ultimate cosmic hot rod, a means of traveling forward or back in time [see "How to Build a Time Machine," by Paul Davies, on page 14]. But despite watchmakers' prowess, neither physicists nor philosophers have come to any agreement about what we mean when we say "tempus fugit."

Perplexity about the nature of time—a tripartite oddity that parses into past, present and future—precedes the industrial era by quite a few centuries. Saint Augustine described the definitional dilemma more eloquently than anyone. "What then, is time?" he asked in his *Confessions*. "If no one asks me, I know; if I want to explain it to someone who does ask me, I do not know." He then went on to attempt to articulate why temporality is so hard to define: "How, then, can these two kinds of time, the past and the future be, when the past no longer is and the future as yet does not be?"

Hard-boiled physicists, unburdened by theistic encumbrances, have also had difficulty grappling with this question. We remark that time "flies" as we hurtle toward our inevitable demise. But what does that mean exactly? Saying that time races along at one second per second has as much scientific weight as the utterance of a Zen koan. One could hypothesize a metric of current flow for time, a form of temporal amperage. But such a measure may simply not exist [see "That Mysterious Flow," by Paul Davies, on page 6]. In fact, one of the hottest themes in theoretical physics is whether time itself is illusory. The confusion is such that physicists have gone as far as to recruit philosophers in their attempt to understand whether a *t* variable should be added to their equations [see "A Hole at the Heart of Physics," by George Musser, on page 12].

The Great Mandala

THE ESSENCE OF TIME is an age-old conundrum that preoccupies not just the physicist and the philosopher but also the anthropologist who studies non-Western cultures that perceive events as proceeding in a cyclical, nonlinear sequence [see "Clocking Cultures," by Carol Ezzell, on page 42]. Yet for most of us, time is not only real, it is the master of everything we do. We are clock-watchers, whether by nature or training.

The distinct feeling we have of being bookended between a past and a future—or, in a traditional culture, being enmeshed in the Great Mandala of recurring natural rhythms—may be related to a basic biological reality. Our bodies are chock-full of living clocks—ones that govern how we connect a ball with a bat, when we feel sleepy and perhaps even when our time is up [see "Times of Our Lives," by Karen Wright, on page 26].

These real biorhythms have now begun to reveal themselves to biologists. Scientists are closing in on areas of the brain that produce the sensation of time flying when we're having fun—the same places that induce the slow-paced torpor of sitting through a monotone lecture on Canadian interest-rate policy. They are also beginning to understand the connections between different kinds of memory and how events are organized and recalled chronologically. Studies of neurological patients with various forms of amnesia, some of whom have lost the ability to judge accurately the passage of hours, months and even entire decades, are helping to pinpoint which areas of the brain are involved in how we experience time [see "Remembering When," by Antonio R. Damasio, on page 34].

Recalling where we fit in the order of things determines who we are. So ultimately, it doesn't matter whether time, in cosmological terms, retains an underlying physical truth. If it is a fantasy, it is one we cling to steadfastly. The reverence we hold for the fourth dimension, the complement of the three spatial ones, has much to do with a deep psychic need to embrace meaningful temporal milestones that we can all share: birthdays, Christmas, the Fourth of July. How else to explain the frenzy of celebration in January 2000 for a date that neither marked a highlight of Christ's life nor, by many tallies, the true millennium?

We will, nonetheless, continue to celebrate the next millennium (if we as a species are still around), and in the meantime, we will fete our parents' golden wedding anniversary and the 20th year of the founding of our local volunteer fire department. Doing so seems to be the only way of imposing hierarchy and structure on a world in which instant messaging, one-hour photo, express checkout and same-day delivery threaten to rob us of any sense of permanence. SA

Gary Stix is special projects editor at Scientific American.

MORE TO EXPLORE

Faster: The Acceleration of Just About Everything. James Gleick. Vintage Books, 1999.

The Story of Time. Edited by Kristen Lippincott. Merrell Holberton, 1999.

Revolution in Time. Revised edition. David S. Landes. Belknap Press of Harvard University Press, 2000.

The Discovery of Time. Edited by Stuart McCready. Sourcebooks, 2001.

From the fixed past to the tangible
present to the undecided future,
it feels as though time flows inexorably on.
But that is an illusion

By Paul Davies

THAT MYSTERIOUS FLOW

OVERVIEW

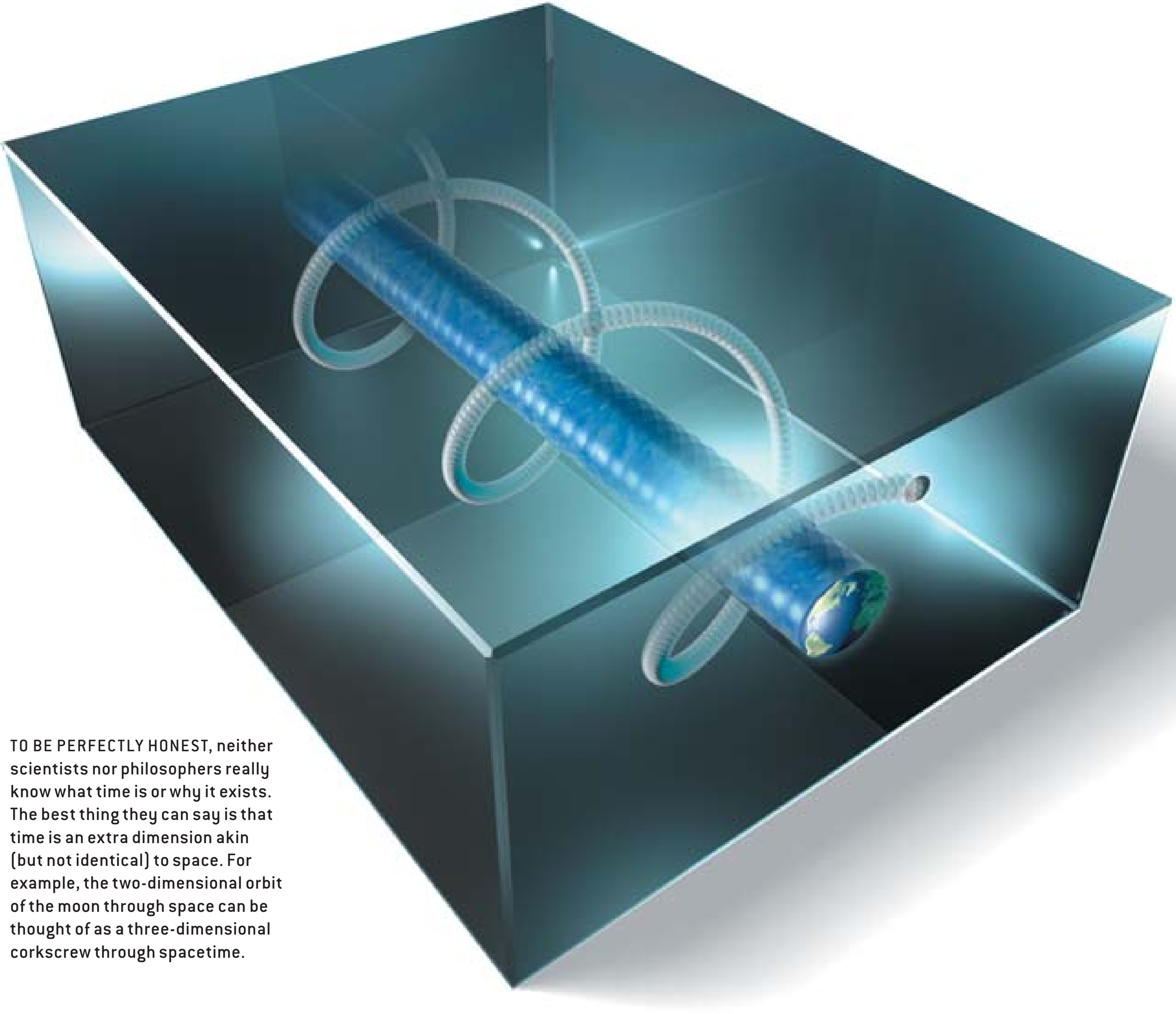
- Our senses tell us that time flows: namely, that the past is fixed, the future undetermined, and reality lives in the present. Yet various physical and philosophical arguments suggest otherwise.
- The passage of time is probably an illusion. Consciousness may involve thermodynamic or quantum processes that lend the impression of living moment by moment.

"Gather ye rosebuds while ye may, / Old Time is still a-flying." So wrote 17th-century English poet Robert Herrick, capturing the universal cliché that time flies. And who could doubt that it does? The passage of time is probably the most basic facet of human perception, for we feel time slipping by in our innermost selves in a manner that is altogether more intimate than our experience of, say, space or mass. The passage of time has been compared to the flight of an arrow and to an ever rolling stream, bearing us inexorably from past to future. Shakespeare wrote of "the whirligig of time," his countryman Andrew Marvell of "Time's winged chariot hurrying near."

Evocative though these images may be, they run afoul of a deep and devastating paradox. Nothing in known physics corresponds to the passage of time. Indeed, 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 and that talk of the river or flux of time is founded on a misconception. How can something so basic to our experience of the physical world turn out to be a case of mistaken identity? Or is there a key quality of time that science has not yet identified?

Time Isn't of the Essence

IN DAILY LIFE we divide time into three parts: past, present and future. The grammatical structure of language revolves around this fundamental distinction. 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,



TO BE PERFECTLY HONEST, neither scientists nor philosophers really know what time is or why it exists. The best thing they can say is that time is an extra dimension akin (but not identical) to space. For example, the two-dimensional orbit of the moon through space can be thought of as a three-dimensional corkscrew through spacetime.

BRYAN CHRISTIE DESIGN

transforming events that were once in the unformed future into the concrete but fleeting reality of the present, and thence relegating them to the fixed past.

Obvious though this commonsense description may seem, it is seriously 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 directly 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.

An innocuous question such as "What is 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 cannot travel faster than light, an Earth-based observer is unable to know the situation on Mars at the same instant. He 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 manned expedition to Mars, mission controllers back on Earth might say, "I wonder what Commander Jones is doing at Alpha Base now." Looking at their clock and seeing that it was 12:00 P.M. on Mars, their answer might be "Eating lunch." But an astronaut zooming past Earth at near the speed of light at the same moment could, on looking at his clock, say that the time on Mars was earlier or later than 12:00, depending on his direction of motion. That astronaut's answer to the question about Commander Jones's activities would be "Cooking lunch" or "Washing dishes" [*see box on page 10*]. 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 you and I were in relative motion, an event that I might judge to be in the as yet undecided future might for you already exist in the fixed past.

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 is a notion sometimes referred to as block time. Completely absent from this description of nature is anything that singles out a privileged special moment as the present or any process that would systematically turn future events into present, then past, events. In short, the time of the physicist does not pass or flow.

> Physicists think of time as laid out in its entirety—a timescape, analogous to a landscape.

How Time Doesn't Fly

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? Relative to what does it move? Whereas other types of motion relate one physical process to another, the putative flow of time relates time to itself. Posing the simple question "How fast does time pass?" exposes the absurdity of the very idea. The trivial answer "One second per second" tells us nothing at all.

NOBODY REALLY KNOWS . . .

What Is Time, Anyway?

Saint Augustine of Hippo, the famous fifth-century theologian, remarked that he knew well what time is—until somebody asked. Then he was at a loss for words. Because we sense time psychologically, definitions of time based on physics seem dry and inadequate. For the physicist, time is simply what (accurate) clocks measure. Mathematically, it is a one-dimensional space, usually assumed to be continuous, although it might be quantized into discrete "chronons," like frames of a movie.

The fact that time may be treated as a fourth dimension does not mean that it is identical to the three dimensions of space. Time and space enter into daily experience and physical theory in distinct ways. For instance, the formula for calculating spacetime distances is not the same as the one for calculating spatial distances. The distinction between space and time underpins the key notion of causality, stopping cause and effect from being hopelessly jumbled. On the other hand, many physicists believe that on the very smallest scale of size and duration, space and time might lose their separate identities. *—P.D.*

Although we find it convenient to refer to time's passage in everyday affairs, the notion imparts no new information that cannot be conveyed without it. Consider the following scenario: 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 this 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, in a manner that omits all reference to time passing or the world changing. Thus, the following cumbersome and rather dry catalogue of facts suffices:

December 24: Alice hopes for a white Christmas.
December 25: There is rain. Alice is disappointed.
December 26: There is snow. 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 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 seems 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, perhaps a rather drastic conclusion. Most physicists would put it less dramatically: the flow of time is unreal, but time itself is as real as space.

Just in Time

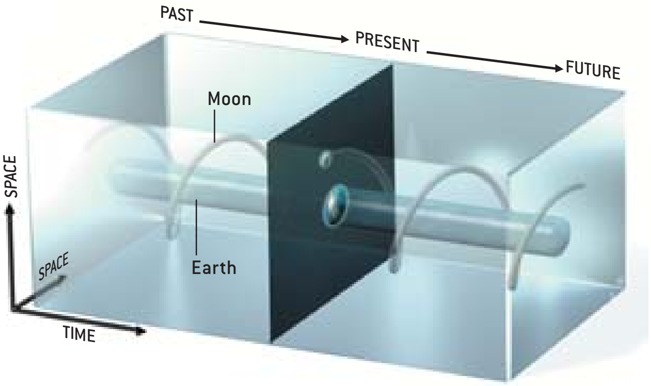
A GREAT SOURCE of confusion in discussions of time's passage stems from its link with the so-called arrow of time. To deny that time flows is not to claim that the designations "past" and "future" are without physical basis. Events in the world undeniably form a unidirectional sequence. For instance, an egg dropped on the floor will smash into pieces, whereas the reverse process—a broken egg spontaneously assembling itself into an intact egg—is never witnessed. This is an example of the second law of thermodynamics, which states that the entropy of a closed system—roughly defined as

BLOCK TIME

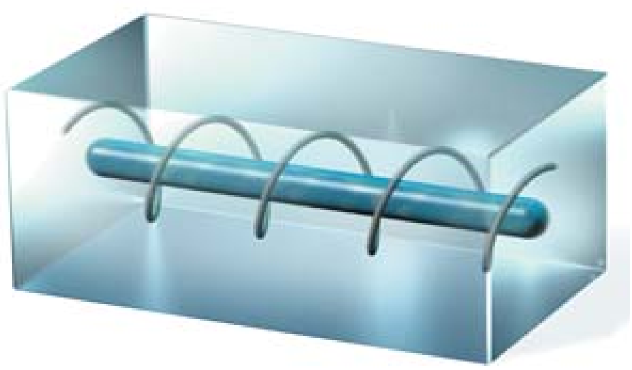
All Time Like the Present

According to conventional wisdom, the present moment has special significance. It is all that is real. As the clock ticks, the moment passes and another comes into existence—a process that we call the flow of time. The moon, for example, is located at only one position in its orbit around Earth. Over time, it ceases to exist at that position and is instead found at a new position.

Researchers who think about such things, however, generally argue that we cannot possibly single out a present moment as special when every moment considers itself to be special. Objectively, past, present and future must be equally real. All of eternity is laid out in a four-dimensional block composed of time and the three spatial dimensions. (This diagram shows only two of these spatial dimensions.) *—P.D.*



CONVENTIONAL VIEW: Only the present is real



BLOCK UNIVERSE: All times are equally real

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, however, 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. The arrow of time denotes an asymmetry of the world in time, not an asymmetry or flux of time. The labels "past" and "future" may legitimately be applied to temporal directions, just as "up" and "down" may be applied to spatial directions, but talk of the past or the future is as meaningless as referring to the up or the down.

The distinction between pastness or futureness and "the" past or "the" future is graphically illustrated by imagining a movie of, say, the egg being dropped on the floor and breaking. If the film were run backward through the projector, everyone would see that the sequence was unreal. Now imagine if the film strip were cut up into frames and the frames shuffled randomly. It would be a straightforward task for someone to rearrange the stack of frames into a correctly ordered sequence, with the broken egg at the top of the stack and the intact egg at the bottom. This vertical stack retains the asymmetry implied by the arrow of time because it forms an ordered sequence in vertical space, proving that time's asymmetry is actually a property of states of the world, not a property of time as such. It is not necessary for the film actually to be run as a movie for the arrow of time to be discerned.

Given that most physical and philosophical analyses of time fail to uncover any sign of a temporal flow, we are left with something of a mystery. To what should we attribute the powerful, universal impression that the world is in a continual state of flux? Some researchers, notably the late Nobel laureate chemist Ilya Prigogine, have contended that the subtle physics of irreversible processes make the flow of time an objective aspect of the world. But I and others argue that it is some sort of illusion.

After all, we do not really observe the passage of time. What we actually observe is that later states of the world differ from earlier states that 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. Nothing other than a conscious observer registers the flow of time. A clock measures durations between events much as a measuring tape

BRYAN CHRISTIE DESIGN

THE AUTHOR

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SIMULTANEITY

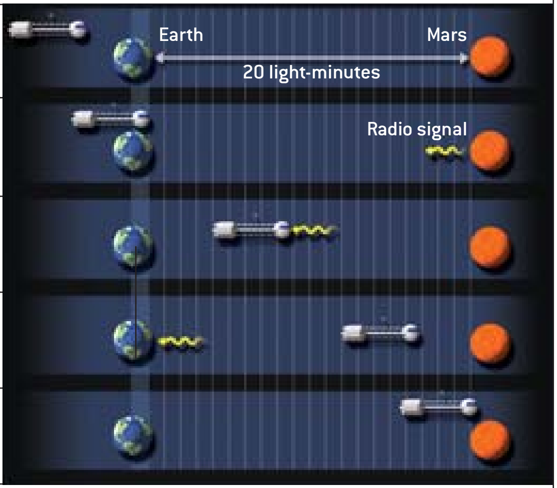
It's All Relative

What is happening on Mars right now? Such a simple question, such a complex answer. The trouble stems from the phrase "right now." Different people, 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 a rocketman crossing the solar system at 80 percent of the speed of light—attempt to answer the question of what is happening on Mars right now. A resident of Mars has agreed to eat lunch when his clock strikes 12:00 P.M. and to transmit a signal at the same time. *—P.D.*

As Seen from Earth

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 percent of the speed of light. The situation looks exactly the same to the Martian.

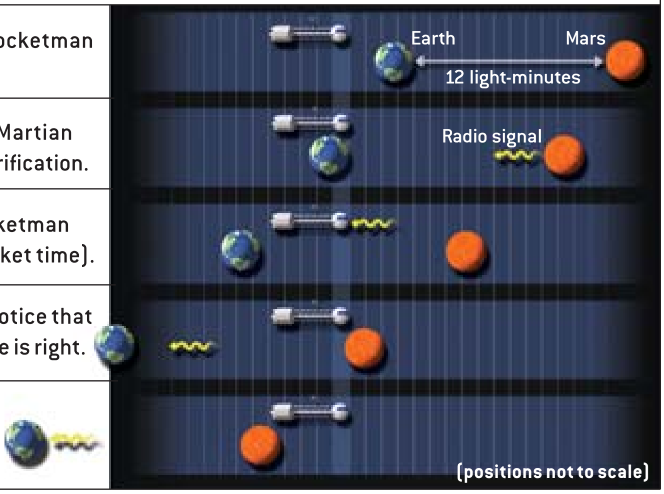
Before noon	By exchanging light signals, the Earthling and Martian measure the distance between them and synchronize their clocks.
12:00 P.M.	The Earthling hypothesizes that the Martian has begun to eat lunch. He prepares to wait 20 minutes for verification.
12:11 P.M.	Knowing the rocket's speed, the Earthling deduces that it encounters the signal while on its way to Mars.
12:20 P.M.	The signal arrives at Earth. The Earthling has confirmed his earlier hypothesis. Noon on Mars is the same as noon on Earth.
12:25 P.M.	The ship arrives at Mars.



As Seen from the Rocket

From the rocketman's perspective, the rocket is standing still. It is the planets that are hurtling through space at 80 percent of the speed of light. His measurements show the two planets to be separated by 12 light-minutes—a different distance than the Earthling inferred. This discrepancy, a well-known 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. (The Earthling and Martian think the ship's clock is slow; the rocketman thinks the planets' are.) As the ship passes Earth, it synchronizes its clock to Earth's.

Before noon	By exchanging light signals with his colleagues, the rocketman measures the distance between the planets.
12:00 P.M.	Passing Earth, the rocketman hypothesizes that the Martian has begun to eat. He prepares to wait 12 minutes for verification.
12:07 P.M.	The signal arrives, disproving the hypothesis. The rocketman infers that the Martian ate sometime before noon (rocket time).
12:15 P.M.	Mars arrives at the ship. The rocketman and Martian notice that their two clocks are out of sync but disagree as to whose is right.
12:33 P.M.	The signal arrives at Earth. The clock discrepancies demonstrate that there is no universal present moment.



(positions not to scale)

BRYAN CHRISTIE DESIGN

measures distances between places; it does not measure the "speed" with which one moment succeeds another. Therefore, it appears that the flow of time is subjective, not objective.

Living in the Present

THIS ILLUSION CRIES OUT for explanation, and that explanation is to be sought in psychology, neurophysiology, and maybe linguistics or culture. 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. If you spin around several times and stop suddenly, you will feel giddy. Subjectively, it seems as if the world is rotating relative to you, but the evidence of your eyes is clear enough: it is not. The apparent movement of your surroundings is an illusion created by the rotation of fluid in the inner ear. Perhaps temporal flux is similar.

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 realized over the past few decades, 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. It was appreciated from the earliest days of the formulation of quantum mechanics 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. Heisenberg's uncertainty principle, according to which 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.

But when a human observer makes a measurement, one and 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 gets projected out from a vast array of possibilities. Within the observer's mind, the possible makes a transition to the actual, the open future to the fixed past—which is precisely what we mean by the flux of time.

There is no agreement among physicists on how this transition from many potential realities into a single actuality takes place. Many physicists have argued that it has something to do with the consciousness of the observer, on the basis that it is the act of observation that prompts nature to make up its mind. A few researchers, such as Roger Penrose of the University of Oxford, maintain that consciousness—including the impression of temporal flux—could be related to quantum processes in the brain.

Although researchers have failed to find evidence for a single "time organ" in the brain, in the manner of, say, the visual cortex, it may be that future work will pin down those brain processes responsible for our sense of temporal passage. It is possible to imagine drugs that could suspend the subject's impression that time is passing. Indeed, some practitioners of meditation claim to be able to achieve such mental states naturally.

And what if science were able to explain away the flow of time? Perhaps we would no longer fret about the future or grieve for the past. Worries about death might become as irrelevant as worries about birth. Expectation and nostalgia might cease to be part of human vocabulary. Above all, the sense of urgency that attaches to so much of human activity might evaporate. No longer would we be slaves to Henry Wadsworth Longfellow's entreaty to "act, act in the living present," for the past, present and future would literally be things of the past. SA

> Modern science has barely begun to consider the question of how we perceive the passage of time.

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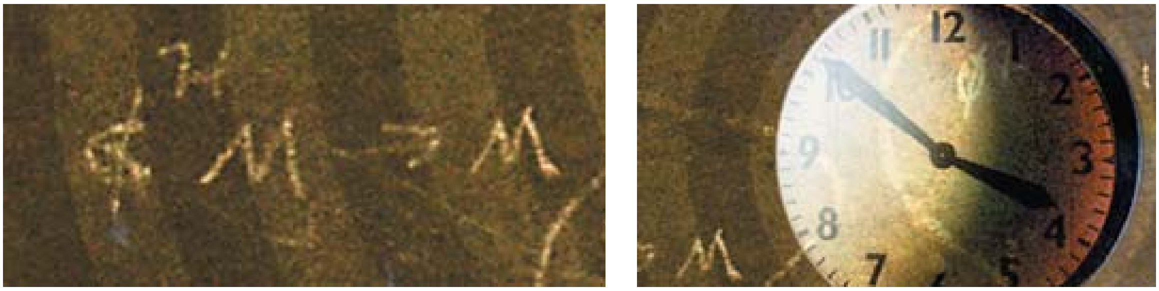


A HOLE AT THE HEART OF PHYSICS

Physicists can't seem to find the time—literally. Can philosophers help? **By George Musser**

For most people, the great mystery of time is that there never seems to be enough of it. If it is any consolation, physicists are having much the same problem. The laws of physics contain a time variable, but it fails to capture key aspects of time as we live it—notably, the distinction between past and future. And as researchers try to formulate more fundamental laws, the little *t* evaporates altogether. Stymied, many physicists have sought help from an unfamiliar source: philosophers.

From philosophers? To most physicists, that sounds rather quaint. The closest some get to philosophy is a late-night conversation over dark beer. Even those who have read serious philosophy generally doubt its usefulness; after a dozen pages of Kant, philosophy begins to seem like the unintelligible in pursuit of the undeterminable. "To tell you the truth, I think most of my colleagues are terrified of talking to philosophers—like being caught coming out of a pornographic cinema," says physicist Max Tegmark of the University of Pennsylvania.

But it wasn't always so. Philosophers played a crucial role in past scientific revolutions, including the development of quantum mechanics and relativity in the early 20th century. Today a new revolution is under way, as physicists struggle to merge those two theories into a theory of quantum gravity—a theory that will have to reconcile two vastly different conceptions of space and time. Carlo Rovelli of the University of Aix-Marseille in France, a leader in this effort, says, "The contributions of philosophers to the new understanding of space and time in quantum gravity will be very important."

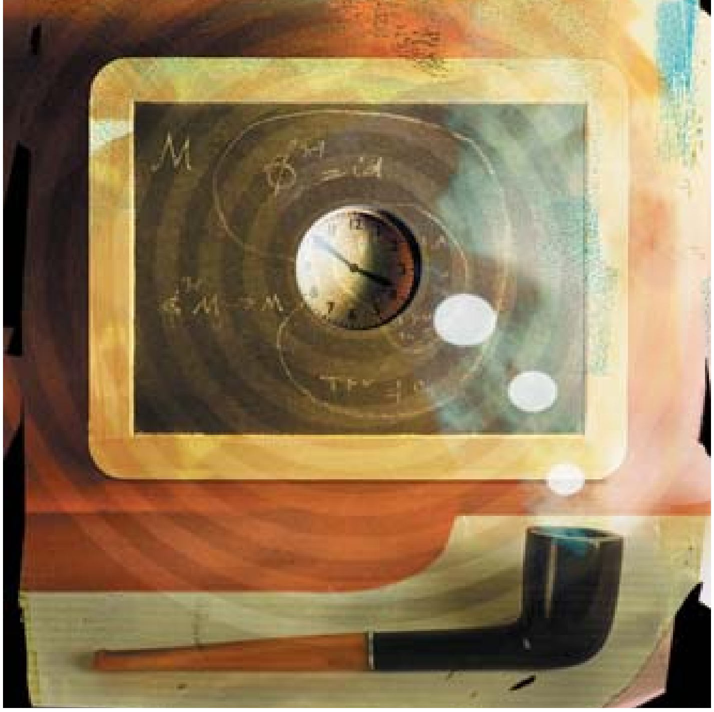
Two examples illustrate how physicists and philosophers have been pooling their resources. The first concerns the "problem of frozen time," also known simply as the "problem of time." It arises when theorists try to turn Albert Einstein's general theory of relativity into a quantum theory using a procedure called canonical quantization. The procedure worked brilliantly when applied to the theory of electromagnetism, but in the case of relativity, it produces an equation—the Wheeler-DeWitt equation—without a time variable. Taken literally, the equation indicates that the universe should be frozen in time, never changing.

Don't Lose Any More Time

THIS UNHAPPY OUTCOME may reflect a flaw in the procedure itself, but some physicists and philosophers argue that it has deeper roots, right down to one of the founding principles of relativity: general covariance, which holds that the laws of physics are the same for all observers. Physicists think of the principle in geometric terms. Two observers will perceive spacetime to have two different shapes, corresponding to their views of who is moving and what forces are acting. Each shape is a smoothly warped version of the other, in the way that a coffee cup is a reshaped doughnut. General covariance says that the difference cannot be meaningful. Therefore, any two such shapes are physically equivalent.

In the late 1980s philosophers John Earman and John D. Norton of the University of Pittsburgh argued that general covariance has startling implications for an old metaphysical question: Do space and time exist independently of stars, gal-

STUART BRADFORD



axies and their other contents (a position known as substantivalism), or are they merely an artificial device to describe how physical objects are related (relationism)? As Norton has written: "Are they like a canvas onto which an artist paints; they exist whether or not the artist paints on them? Or are they akin to parenthood; there is no parenthood until there are parents and children."

He and Earman revisited a long-neglected thought experiment of Einstein's. Consider an empty patch of spacetime. Outside this hole the distribution of matter fixes the geometry of spacetime, per the equations of relativity. Inside, however, general covariance lets spacetime take on any of a variety of shapes. In a sense, spacetime behaves like a canvas tent. The tent poles, which represent matter, force the canvas to assume a certain shape. But if you leave out a pole, creating the equivalent of a hole, part of the tent can sag, or bow out, or ripple unpredictably in the wind.

Leaving aside the nuances, the thought experiment poses a dilemma. If the continuum is a thing in its own right (as substantivalism holds), general relativity must be indeterministic—that is, its description of the world must contain an element of randomness. For the theory to be deterministic, spacetime must be a mere fiction (as relationism holds). At first glance, it looks like a victory for relationism. It helps that other theories, such as electromagnetism, are based on symmetries that resemble relationism.

But relationism has its own troubles. It is the ultimate source of the problem of frozen time: space may morph over time, but if its many shapes are all equivalent, it never truly changes. Moreover, relationism clashes with the substantivalist underpinnings of quantum mechanics. If spacetime has no fixed meaning, how can you make observations at specific places and moments, as quantum mechanics seems to require?

Different resolutions of the dilemma lead to very different theories of quantum gravity. Some physicists, such as Rovelli and Julian Barbour, are trying a relationist approach; they think time does not exist and have searched for ways to explain change as an illusion. Others, including string theorists, lean toward substantivalism.

"It's a good example of the value of philosophy of physics," says philosopher Craig Callender of the University of California, San Diego. "If physicists think the problem of time in canonical quantum gravity is solely a quantum problem, they're hurting their understanding of the problem—for it's been with us for much longer and is more general."

Running on Entropy

A SECOND EXAMPLE of philosophers' contributions concerns the arrow of time—the asymmetry of past and future. Many people assume that the arrow is explained by the second law of thermodynamics, which states that entropy, loosely defined as the amount of disorder within a system, increases with time. Yet no one can really account for the second law.

The leading explanation, put forward by 19th-century Austrian physicist Ludwig Boltzmann, is probabilistic. The basic idea is that there are more ways for a system to be disordered than to be ordered. If the system is fairly ordered now, it will probably be more disordered a moment from now. This reasoning, however, is symmetric in time. The system was probably more disordered a moment ago, too. As Boltzmann recognized, the only way to ensure that entropy will increase into the future is if it starts off with a low value in the past. Thus, the second law is not so much a fundamental truth as historical happenstance, perhaps related to events early in the big bang.

Other theories for the arrow of time are similarly incomplete. Philosopher Huw Price of the University of Sydney argues that almost every attempt to explain time asymmetry suffers from circular reasoning, such as some hidden presumption of time asymmetry. His work is an example of how philosophers can serve, in the words of philosopher Richard Healey of the University of Arizona, as the "intellectual conscience of the practicing physicist." Specially trained in logical rigor, they are experts at tracking down subtle biases.

Life would be boring if we always listened to our conscience, and physicists have often done best when ignoring philosophers. But in the eternal battle against our own leaps of logic, conscience is sometimes all we have to go on. SA

George Musser is a staff editor and writer at Scientific American.

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HOW TO BUILD A TIME MACHINE

It wouldn't be easy, but it might be possible

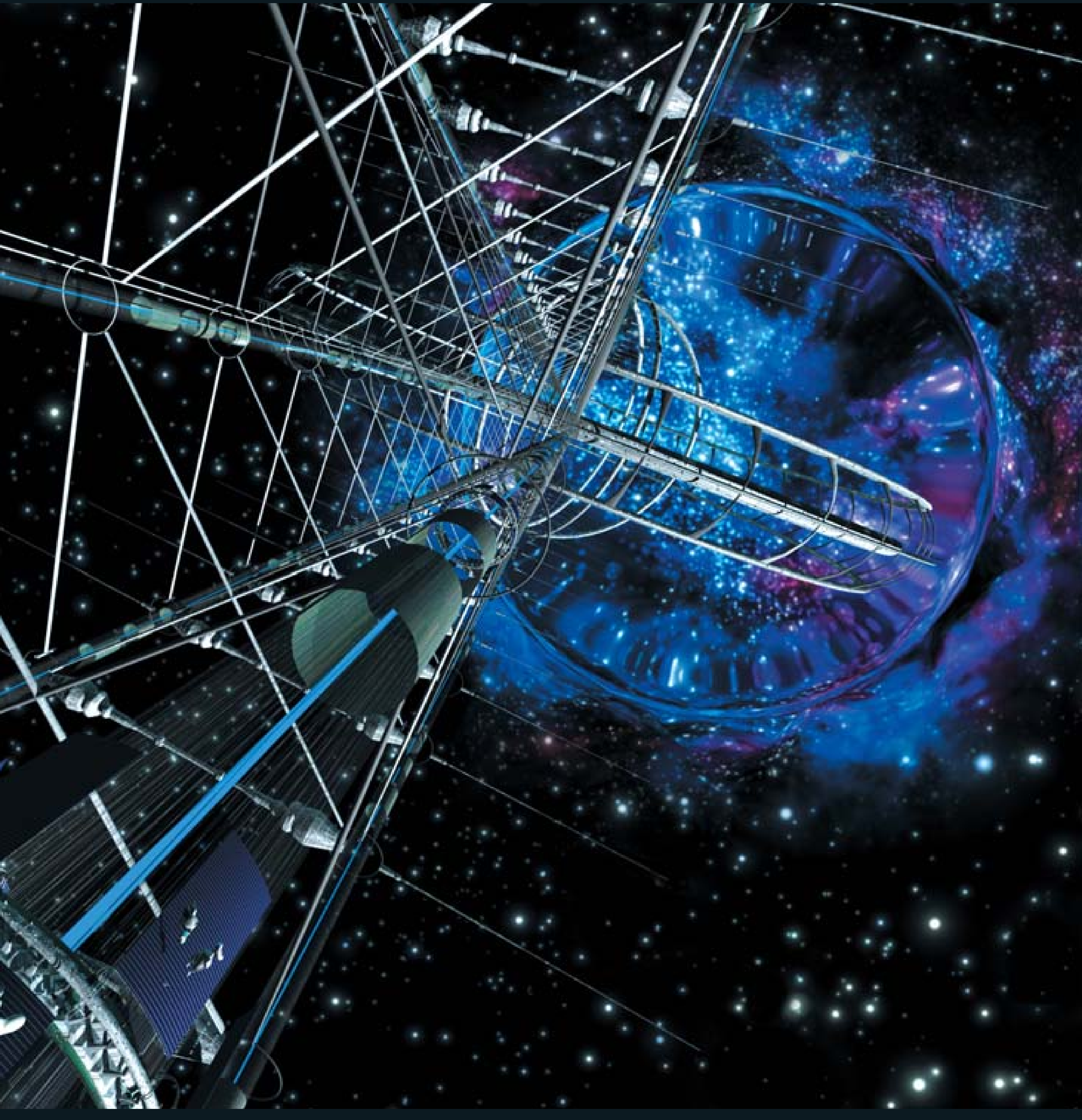
By Paul Davies

OVERVIEW

- Traveling forward in time is easy enough. If you move close to the speed of light or sit in a strong gravitational field, you experience time more slowly than other people do—another way of saying that you travel into their future.
- Traveling into the past is rather trickier. Relativity theory allows it in certain spacetime configurations: a rotating universe, a rotating cylinder and, most famously, a wormhole—a tunnel through space and time.

Time travel has been a popular science-fiction theme since H. G. Wells wrote his celebrated novel *The Time Machine* in 1895. But can it really be done? Is it possible to build a machine that would transport a human being into the past or future?

For decades, time travel lay beyond the fringe of respectable science. In recent years, however, the topic has become something of a cottage industry among theoretical physicists. The motivation has been partly recreational—time travel is fun to think about. But this research has a serious side, too. Understanding the relation between cause and effect is a key part of attempts to construct a unified theory of physics. If unrestricted time travel were possible, even in principle, the nature of such a unified theory could be drastically affected.



WORMHOLE GENERATOR/TOWING MACHINE **is imagined by futurist artist Peter Bollinger. This painting depicts a gigantic space-based particle accelerator that is capable of creating, enlarging and moving wormholes for use as time machines.**

Our best understanding of time comes from Einstein's theories of relativity. Prior to these theories, time was widely regarded as absolute and universal, the same for everyone no matter what their physical circumstances were. In his special theory of relativity, 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 effect is often described using the "twin paradox." Suppose that Sally and Sam are twins. Sally boards a rocket ship and travels at high speed to a nearby star, turns around and flies back to Earth, while Sam stays at home. For Sally the duration of the journey might be, say, one year, but when she returns and steps out of the spaceship, she finds that 10 years have elapsed on Earth. Her brother is now nine years older than she is. Sally and Sam are no longer the same age, despite the fact that they were born on the same day. This example illustrates a limited type of time travel. In effect, Sally has leaped nine years into Earth's future.

The wormhole was used as a fictional device by Carl Sagan in his novel *Contact*.

Jet Lag

THE EFFECT, KNOWN AS time dilation, occurs whenever two observers move relative to each other. In daily life we don't notice weird time warps, because the effect becomes dramatic only when the motion occurs at close to the speed of light. Even at aircraft speeds, the time dilation in a typical journey amounts to just a few nanoseconds—hardly an adventure of Wellsian proportions. Nevertheless, atomic clocks are accurate enough to record the shift and confirm that time really is stretched by motion. So travel into the future is a proved fact, even if it has so far been in rather unexciting amounts.

To observe really dramatic time warps, one has to look beyond the realm of ordinary experience. Subatomic particles can be propelled at nearly the speed of light in large accelerator machines. Some of these particles, such as muons, have a built-in clock because they decay with a definite half-life; in accordance with Einstein's theory, fast-moving muons inside accelerators are observed to decay in slow motion. Some cosmic rays also experience spectacular time warps. These particles move so close to the speed of light that, from their point of view, they cross the galaxy in minutes, even though in Earth's frame of reference they seem to take tens of thousands of years. If time dilation did not occur, those particles would never make it here.

THE AUTHOR

PAUL DAVIES **is a theoretical physicist and professor of natural philosophy at Macquarie University's Australian Center for Astrobiology in Sydney. He is one of the most prolific writers of popular-level books in physics. His scientific research interests include black holes, quantum field theory, the origin of the universe, the nature of consciousness and the origin of life.**

Speed is one way to jump ahead in time. Gravity is another. In his general theory of relativity, Einstein predicted that gravity slows time. Clocks run a bit faster in the attic than in the basement, which is closer to the center of Earth and therefore deeper down in a gravitational field. Similarly, clocks run faster in space than on the ground. Once again the effect is minuscule, but it has been directly measured using accurate clocks. Indeed, these time-warping effects have to be taken into account in the Global Positioning System. If they weren't, sailors, taxi drivers and cruise missiles could find themselves many kilometers off course.

At the surface of a neutron star, gravity is so strong that time is slowed by about 30 percent relative to Earth time. Viewed from such a star, events here would resemble 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 you fell into a black hole from nearby, in the brief interval it took you to reach the surface, all of eternity would pass by in the wider universe. The region within the black hole is therefore beyond the end of time, as far as the outside universe is concerned. If an astronaut could zoom very close to a black hole and return unscathed—admittedly a fanciful, not to mention foolhardy, prospect—he could leap far into the future.

My Head Is Spinning

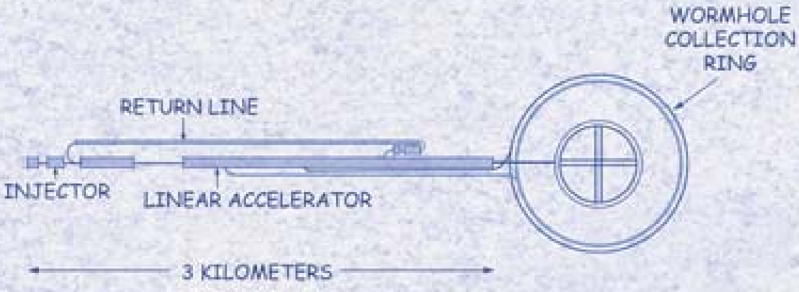
SO FAR I HAVE DISCUSSED travel forward in time. What about going backward? This is much more problematic. In 1948 Kurt Gödel of the Institute for Advanced Study in Princeton, N.J., produced a solution of Einstein's gravitational field equations that described a rotating universe. In this universe, an astronaut could travel through space so as to reach his own past. This comes about because of the way gravity affects light. The rotation of the universe would drag light (and thus the causal relations between objects) around with it, enabling a material object to travel in a closed loop in space that is also a closed loop in time, without at any stage exceeding the speed of light in the immediate neighborhood of the particle. Gödel's solution was shrugged aside as a mathematical curiosity—after all, observations show no sign that the universe as a whole is spinning. His result served nonetheless to demonstrate that going back in time was not forbidden by the

PETER BOLLINGER (*preceding page*); EVERETT COLLECTION (*above*)

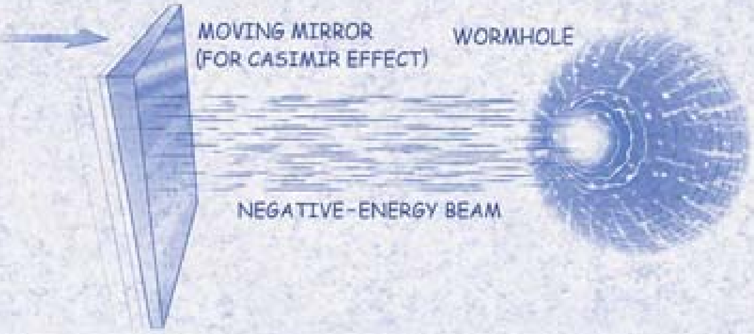
WORMHOLE TRAVEL

A Wormhole Time Machine in Three Not So Easy Steps

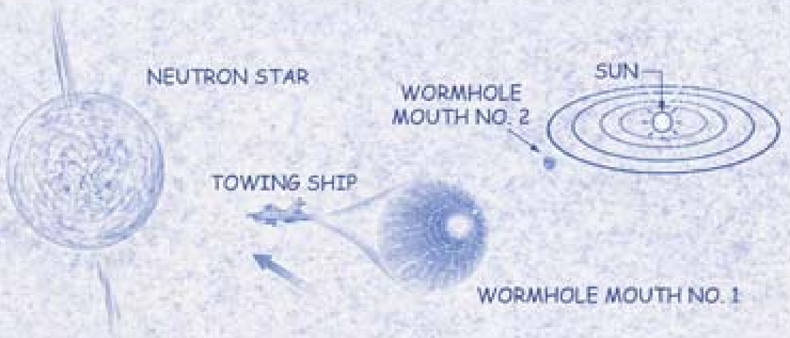
1 FIND OR BUILD A WORMHOLE—a tunnel connecting two different locations in space. Large wormholes might exist naturally in deep space, a relic of the big bang. Otherwise we would have to make do with subatomic wormholes, either natural ones (which are thought to be winking in and out of existence all around us) or artificial ones (produced by particle accelerators, as imagined here). These smaller wormholes would have to be enlarged to useful size, perhaps using energy fields like those that caused space to inflate shortly after the big bang.



2 STABILIZE THE WORMHOLE. An infusion of negative energy, produced by quantum means such as the so-called Casimir effect, would allow a signal or object to pass safely through the wormhole. Negative energy counteracts the tendency of the wormhole to pinch off into a point of infinite or near-infinite density. In other words, it prevents the wormhole from becoming a black hole.



3 TOW THE WORMHOLE. A spaceship, presumably of highly advanced technology, would separate the mouths of the wormhole. One mouth might be positioned near the surface of a neutron star, an extremely dense star with a strong gravitational field. The intense gravity causes time to pass more slowly. Because time passes more quickly at the other wormhole mouth, the two mouths become separated not only in space but also in time.



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theory of relativity. Indeed, Einstein confessed that he was troubled by the thought that his theory might permit travel into the past under some circumstances.

Other scenarios have been found to permit travel into the past. 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 1991 J. Richard Gott of Princeton University predicted that cosmic strings—structures that cosmologists think were created in the early stages of the big bang—could produce similar results. But in the mid-1980s the most realistic scenario for a time machine emerged, based on the concept of a wormhole.

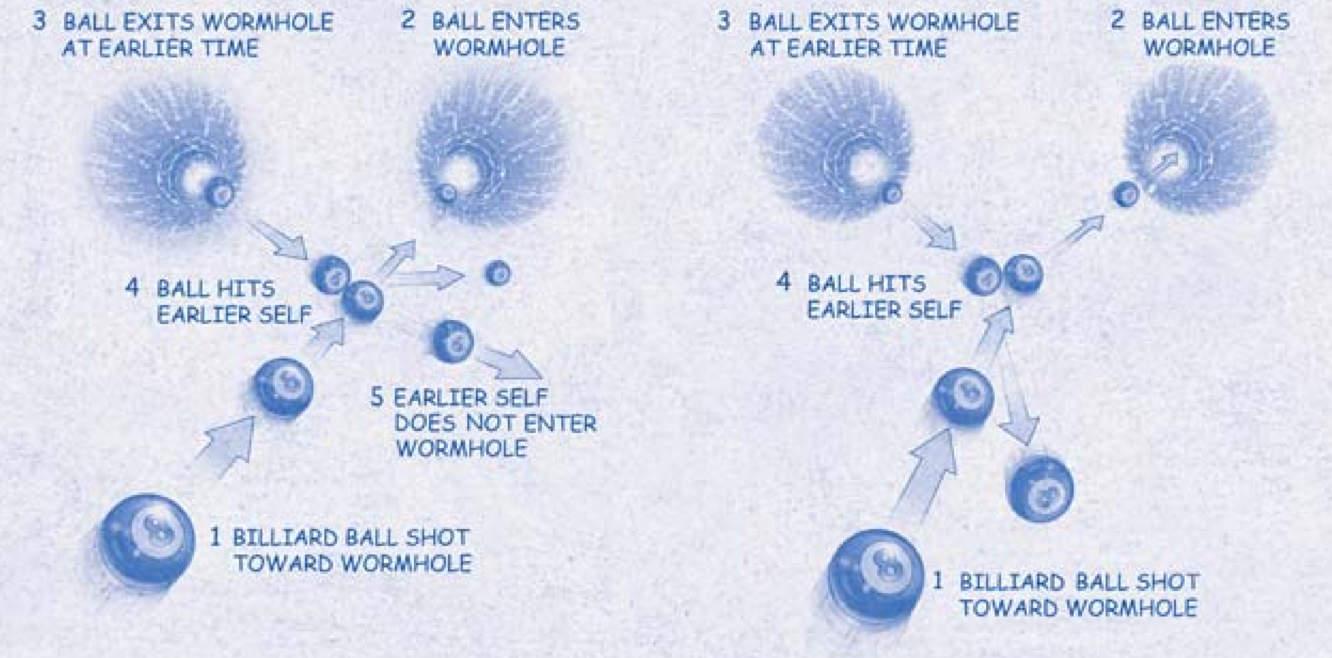
In science fiction, wormholes are sometimes called stargates; they offer a shortcut between two widely separated points in space. Jump through a hypothetical wormhole, and you might come out moments later on the other side of the galaxy. Wormholes naturally fit into the general theory of relativity, whereby gravity warps not only time but also space.

CHANGING THE PAST

Mother of All Paradoxes

THE NOTORIOUS MOTHER PARADOX (sometimes formulated using other familial relationships) arises when people or objects can travel backward in time and alter the past. A simplified version involves billiard balls. A billiard ball passes through a wormhole time machine. Upon emerging, 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 cannot do something that is inconsistent with logic or with the laws of physics. It cannot pass through the wormhole in such a way that will prevent it from passing through the wormhole. But nothing stops it from passing through the wormhole in an infinity of other ways.



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 under a hill can be shorter than the surface street, a wormhole may be shorter than the usual route through ordinary space.

The wormhole was used as a fictional device by Carl Sagan in his 1985 novel *Contact*. Prompted by Sagan, Kip S. Thorne and his co-workers at the California Institute of Technology set out to find whether wormholes were consistent with known physics. Their starting point was that a wormhole would resemble a black hole in being an object with fearsome gravity. But unlike a black hole, which offers a one-way journey to nowhere, a wormhole would have an exit as well as an entrance.

EXISTING FORMS OF FORWARD TIME TRAVEL

SYSTEM	SPECIFICATIONS	CUMULATIVE TIME LAG
Airline flight	920 km per hour for eight hours	10 nanoseconds (relative to inertial reference frame)
Nuclear submarine tour	300 meters' depth for six months	500 nanoseconds (relative to sea level)
Cosmic-ray neutron	10^{18} electron volts	Mean life stretched from 15 minutes to 30,000 years
Neutron star	Redshift 0.2	Time intervals expand 20 percent (relative to deep space)

In the Loop

FOR THE WORMHOLE to be traversable, it must contain what Thorne termed 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 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 is not ruled out by the laws of physics, although it is unclear whether enough antigravitating stuff can be assembled to stabilize a wormhole [see "Negative Energy, Wormholes and Warp Drive," by Lawrence H. Ford and Thomas A. Roman; SCIENTIFIC AMERICAN, January 2000].

Soon Thorne and his colleagues realized that if a stable wormhole could be created, then it could readily be turned

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into a time machine. An astronaut who passed through one might come out not only somewhere else in the universe but somewhen else, too—in either the future or the past.

To adapt the wormhole for time travel, one of its mouths could be towed to a neutron star and placed close to its surface. The gravity of the star would slow time near that wormhole mouth, so that a time difference between the ends of the wormhole would gradually accumulate. If both mouths were then parked at a convenient place in space, this time difference would remain frozen in.

Suppose the difference were 10 years. An astronaut passing through the wormhole in one direction would jump 10 years into the future, whereas an astronaut passing in the other direction would jump 10 years into the past. By returning to his starting point at high speed across ordinary space, the second astronaut might get back home before he left. In other words, a closed loop in space could become a loop in time as well. The one restriction is that the astronaut could not return to a time before the wormhole was first built.

> It is conceivable that the next generation of particle accelerators will be able to create subatomic wormholes.

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, about 20 factors of 10 as small as an atomic nucleus. In principle, such a minute wormhole could be stabilized by a pulse of energy and then somehow inflated to usable dimensions.

Censored!

ASSUMING THAT the engineering problems could be overcome, the production of a time machine could open up a Pandora's box of causal paradoxes. Consider, for example, the time traveler who visits the past and murders his mother when she was a young girl. How do we make sense of this? If the girl dies, she cannot become the time traveler's mother. But if the time traveler was never born, he could not go back and murder his mother.

Paradoxes of this kind arise when the time traveler tries to change the past, which is obviously impossible. But that does not prevent someone from being a part of the past. Suppose the time traveler goes back and rescues a young girl from murder, and this girl grows up to become his mother. The causal loop is now self-consistent and no longer paradoxical. Causal consistency might impose restrictions on what a time traveler is able to do, but it does not rule out time travel per se.

Even if time travel isn't strictly paradoxical, it is certainly weird. Consider the time traveler who leaps ahead a year and reads about a new mathematical theorem in a future edition of *Scientific American*. He notes the details, returns to his 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 he read it, but not from the student either, who learned it from the time traveler. The information seemingly came into existence from nowhere, reasonlessly.

The bizarre consequences of time travel have led some scientists to reject the notion outright. Stephen W. Hawking of the University of Cambridge has 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.

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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. A final resolution of the matter may have to await the successful union of quantum mechanics and gravitation, perhaps through a theory such as string theory or its extension, so-called M-theory. It is even conceivable that the next generation of particle accelerators will be able to create subatomic wormholes that survive long enough for nearby particles to execute fleeting causal loops. This would be a far cry from Wells's vision of a time machine, but it would forever change our picture of physical reality.

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TIME and the TWIN PARADOX

Time must never be thought of as preexisting in any sense; it is a manufactured quantity. —Hermann Bondi

By Ronald C. Lasky

As maxims go, "Time is relative" may not be quite as famous as "Time is money." But the notion that time speeds up or slows down depending on how fast one object is traveling relative to another surely ranks as one of Albert Einstein's most inspired insights.

The term "time dilation" was coined to describe the slowing of time caused by motion. And to illustrate the effect of time dilation, he proposed an example—the twin paradox—that is arguably the most famous thought experiment in relativity theory. In this supposed paradox, one of two twins travels at near the speed of light to a distant star and returns to Earth. Relativity dictates that when he comes back, he is younger than his identical twin [see "How to Build a Time Machine," by Paul Davies, on page 6].

OVERVIEW

- We take for granted that time ticks by at the same rate for everyone. But Einstein's theory of relativity shows that this assumption is not strictly true.
- The classic case of time disparity involves twins—one of whom leaves Earth and travels round-trip to a star at nearly the speed of light, arriving back much younger than his brother. This aging difference is noticeable only when long distances are traveled at speeds approximating the speed of light.

MICHAEL BARLEY *Corbis*

The paradox lies in the question "Why is the traveling brother 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. (Many of us solved this traveling-clock problem in sophomore physics, to demonstrate one effect of the absolute nature of the speed of light.) Because special relativity says that there is no absolute motion, wouldn't the brother traveling to the star also see his brother's clock on Earth move more slowly? If this were the case, wouldn't they both be the same age?

This paradox is discussed in many books but solved in very few. It is typically explained by saying that the one who feels the acceleration is the one who is younger at the end of the trip; hence, the brother who travels to the star is younger. Although the result is correct, the explanation is misleading. Some people may falsely assume that the acceleration causes the age difference and that the general theory of relativity, which deals with noninertial or accelerating reference frames, is required to explain the paradox. But the acceleration incurred by the traveler is incidental, and the paradox can be unraveled by special relativity alone.

A Long, Strange Space Trip

LET US ASSUME that twin brothers, nicknamed the traveler and the homebody, live in Hanover, N.H. They differ in their wanderlust but 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 are ready to launch it, manned by the traveler, toward a star six light-years away.

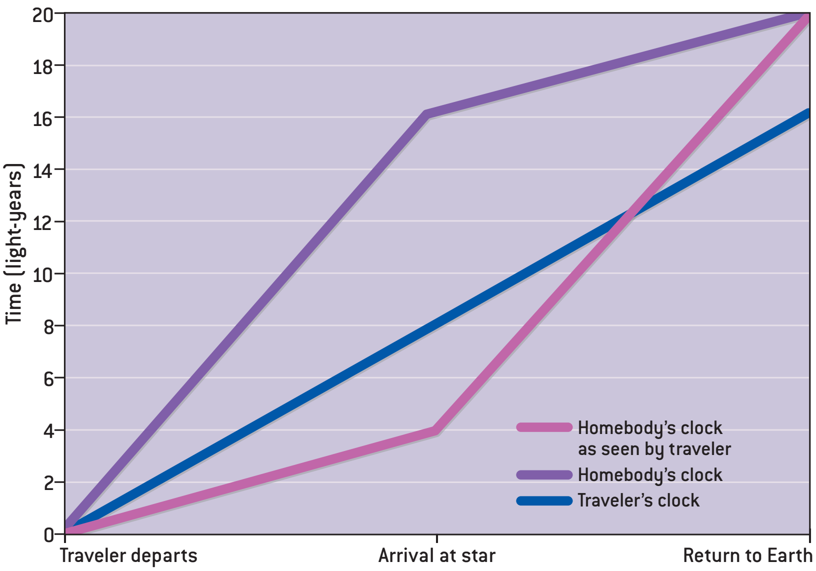
His craft will quickly accelerate to 0.6 *c*. To reach that speed, it would take a little more than 100 days at an acceleration of two g's. Two g's is two times the acceleration of gravity, about what one experiences on a sharp loop on a roller coaster. If, however, the traveler were an electron, he could be accelerated to 0.6 *c* in a tiny fraction of a second. Hence, the time to reach 0.6 *c* is not central to the argument.

The traveler uses the length-contraction equation of special relativity to measure distance. So 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*. Therefore, to the traveler, the trip to the star takes only eight years ($^{4.8}/_{0.6}$), whereas the homebody calculates it taking 10 years ($^{6.0}/_{0.6}$). To solve the twin paradox, we need to consider how each twin would view his and the other's clocks during the trip. Let us assume that each twin has a very powerful telescope that permits such observation. Surprisingly, by focusing on the time it takes light to travel between the two, the paradox can be explained.

Both the traveler and homebody set their clocks at zero when the traveler leaves Earth for the star [*see box at left*]. When the traveler reaches the star, his clock reads eight years. But when the homebody sees the traveler reach the star, the homebody's clock reads 16 years. Why 16 years? Because, 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. So, viewed through the homebody's telescope, the traveler's clock appears to be running at half the speed of his clock ($^{8}/_{16}$).

As the traveler reaches the star, he reads his clock at eight years as mentioned, but he sees the homebody's clock as it was six years ago (the amount of time it takes for the light from Earth to reach him), or at four years (10 – 6). So the traveler also views the homebody's clock as running at half the speed of his clock ($^{4}/_{8}$).

COMPARING CLOCKS



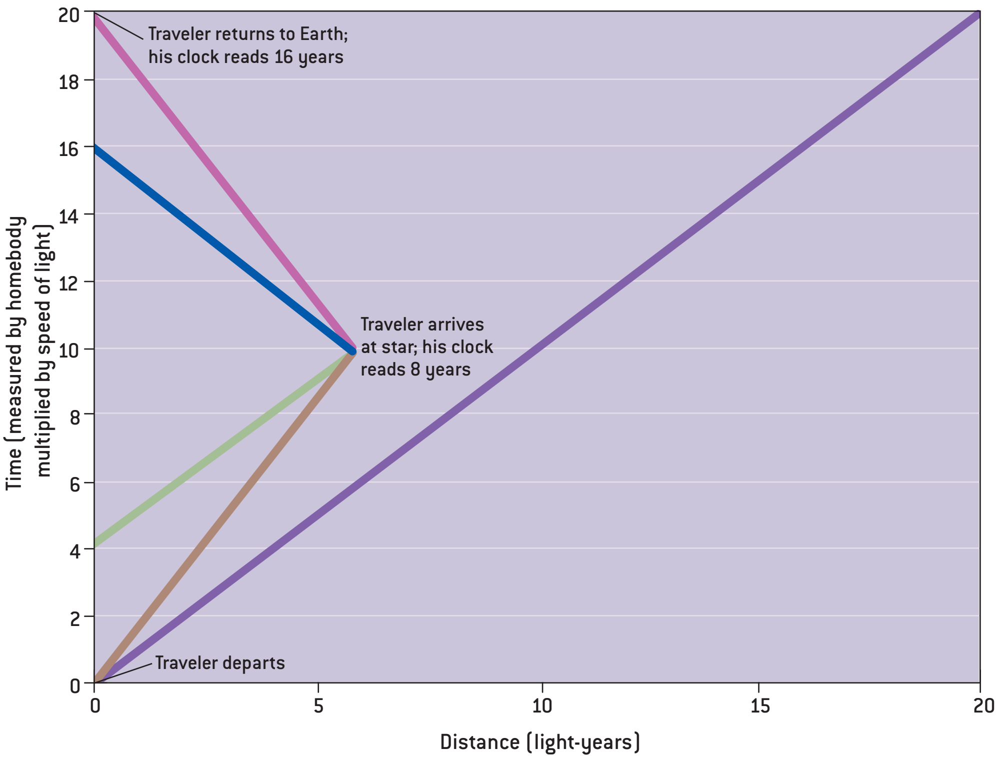
Time passage differs for two twins: a traveler who makes a near-light-speed round trip to a distant star and a homebody who waits for his return on Earth. At each event—the traveler's departure, his arrival at the star and his return to Earth—both the homebody and the traveler see the same reading on the traveler's clock but different readings on the homebody's clock.

LUCY READING-IKKANDA

THE AUTHOR

RONALD C. LASKY is a visiting professor at Dartmouth College and a senior technologist at Indium Corporation. He has edited several books on electronic packaging and optoelectronics and written numerous technical papers and patent disclosures. One of his hobbies is studying the subtleties of relativity and quantum theory so that he can explain it to laypeople.

GO FAR, YOUNGER MAN



After a 20-year round trip to a star at near light speeds, the traveling twin ends up four years younger than the homebody because of the effects of Doppler time dilation. It takes the traveler eight years to reach the star on the trip out (*gold*). When he looks back to Earth he sees the homebody's clock reading only four years (*green*). But when the homebody sees the traveler at the star, the homebody's clock reads 16 years (*blue*). On the traveler's arrival back on Earth (*red*) they both agree that the homebody's clock reads 20 years and the traveler's clock reads 16 years. Hence, the traveler is four years younger. (The purple line shows how light travels over 20 years.)

LUCY READING-IKKANDA

From Twin to Younger Brother

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 will be at 20 years when the traveler arrives back home. So the homebody now sees the traveler's clock advance eight years in four years of his time; it is now twice as fast as his clock.

As the traveler returns home, he sees the homebody's clock advance from four to 20 years in eight years of his time. Therefore, he also sees his brother's clock advancing at twice the speed of his. They both agree, however, that at the end of the trip the traveler's clock reads 16 years and the homebody's 20 years. So 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 is also an asymmetry that the traveler and the homebody agree with the reading on the traveler's clock at each event, but 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. The reader should also note that the speed that an observed clock appears to run depends on whether it is traveling away from or toward the observer.

Finally, we should point out that the twin paradox today is more than a theory, because its fundamentals have been exhaustively confirmed experimentally. In one such experiment, the lifetime of muon decay verifies the existence of time dilation. Stationary muons have a lifetime of about 2.2 microseconds. When traveling past an observer at 0.9994 *c*, their lifetime stretches to 63.5 microseconds, just as predicted by special relativity. Experiments in which atomic clocks are transported at varying speeds have also produced results that confirm both special relativity and the twin paradox. SA

MORE TO EXPLORE

The Story of Time. Edited by Kristen Lippincott. Merrell, 1999.

Revolution in Time. Revised edition. David S. Landes. Belknap Press of Harvard University Press, 2000.

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About Time: Einstein's Unfinished Revolution. Paul Davies. Gardners Books, 2004.

Fundamentals of Physics. Seventh edition. David Halliday et al. Wiley, 2004.

For those with a little more formal physics background, supporting calculations for the Doppler effect on the observed time are available at **www.sciam.com/lasky**

From INSTANTANEOUS

The units of time range from the infinitesimally brief to the interminably long. The descriptions given here attempt to convey a sense of this vast chronological span.

ONE ATTOSECOND (a billionth of a billionth of a second)
The most fleeting events that scientists can clock are measured in attoseconds. Researchers have created pulses of light lasting just 250 attoseconds using sophisticated high-speed lasers. Although the interval seems unimaginably brief, it is an aeon compared with the Planck time—about 10^{-43} second—which is believed to be the shortest possible duration.

ONE FEMTOSECOND (a millionth of a billionth of a second)
An atom in a molecule typically completes a single vibration in 10 to 100 femtoseconds. Even fast chemical reactions generally take hundreds of femtoseconds to complete. The interaction of light with pigments in the retina—the process that allows vision—takes about 200 femtoseconds.

ONE PICOSECOND (a thousandth of a billionth of a second)
The fastest transistors operate in picoseconds. 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.

ONE NANOSECOND (a billionth of a second)
A beam of light shining through a vacuum will travel only 30 centimeters (not quite one foot) in this time. The microprocessor inside a personal computer will typically take two to four nanoseconds to execute a single instruction, such as adding two numbers. The K meson, another rare subatomic particle, has a lifetime of 12 nanoseconds.

ONE MICROSECOND (a millionth of a second)
That beam of light will now have traveled 300 meters, about the length of three football fields, but a sound wave at sea level will have propagated only one third of a millimeter. The flash of a high-speed commercial stroboscope lasts about one microsecond. It takes 24 microseconds for a stick of dynamite to explode after its fuse has burned down.

ONE MILLISECOND (a thousandth of a second)
The shortest exposure time in a typical camera. A housefly flaps its wings once every three milliseconds; a honeybee does the same once every five milliseconds. The moon travels around Earth two milliseconds more slowly each year as its orbit gradually widens. In computer science, an interval of 10 milliseconds is known as a jiffy.

ONE TENTH OF A SECOND
The duration of the fabled "blink of an eye." The human ear needs this much time to discriminate an echo from the original sound. Voyager 1, a spacecraft speeding out of the solar system, travels about two kilometers farther away from the sun during this time frame. A hummingbird can beat its wings seven times. A tuning fork pitched to A above middle C vibrates four times.

ONE SECOND
A healthy person's heartbeat lasts about this long. On average, Americans eat 350 slices of pizza during this time. Earth travels 30 kilometers around the sun, while the sun zips 274 kilometers on its trek through the galaxy. It is not quite enough time for moonlight to reach Earth (1.3 seconds). Traditionally, the second was the 60th part of the 60th part of the 24th part of a day, but science has given it a more precise definition: it is the duration of 9,192,631,770 cycles of one type of radiation produced by a cesium 133 atom.

TOM DRAPER DESIGN; MICHAEL W. DAVIDSON (*microprocessor*), BSIP (*eye*), G. C. KELLEY (*hummingbird*) AND SCOTT CAMAZINE (*chest x-ray*) *Photo Researchers, Inc.*

to ETERNAL

ONE MINUTE

The brain of a newborn baby grows one to two milligrams in this time. A shrew's fluttering heart beats 1,000 times. The average person can speak about 150 words or read about 250 words. Light from the sun reaches Earth in about eight minutes; when Mars is closest to Earth, sunlight reflected off the Red Planet's surface reaches us in about four minutes.

ONE HOUR

Reproducing cells generally take about this long to divide into two. One hour and 16 minutes is the average time between eruptions of the Old Faithful geyser in Yellowstone National Park. Light from Pluto, the most distant planet in our solar system, reaches Earth in five hours and 20 minutes.

ONE DAY

For humans, this is perhaps the most natural unit of time, the duration of Earth's rotation. 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, while the lungs inhale about 11,000 liters of air. In the same amount of time, an infant blue whale adds another 200 pounds to its bulk.

ONE YEAR

Earth makes one circuit around the sun and spins on its axis 365.26 times. The mean level of the oceans rises between one and 2.5 millimeters, and North America moves about three centimeters away from Europe. It takes 4.3 years for light from Proxima Centauri, the closest star, to reach Earth—approximately the same amount of time that ocean-surface currents take to circumnavigate the globe.

ONE CENTURY

The moon recedes from Earth by another 3.8 meters. Standard compact discs and CD-ROMs are expected to degrade in this time. Baby boomers have only a one-in-26 chance of living to the age of 100, but giant tortoises can live as long as 177 years. The most advanced recordable CDs may last more than 200 years.

ONE MILLION YEARS

After traveling for a million years, a spaceship moving at the speed of light would not yet be at the halfway point on a journey to the Andromeda galaxy (2.3 million light-years away). The most massive stars, blue supergiants that are millions of times brighter than the sun, burn out in about this much time. 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.

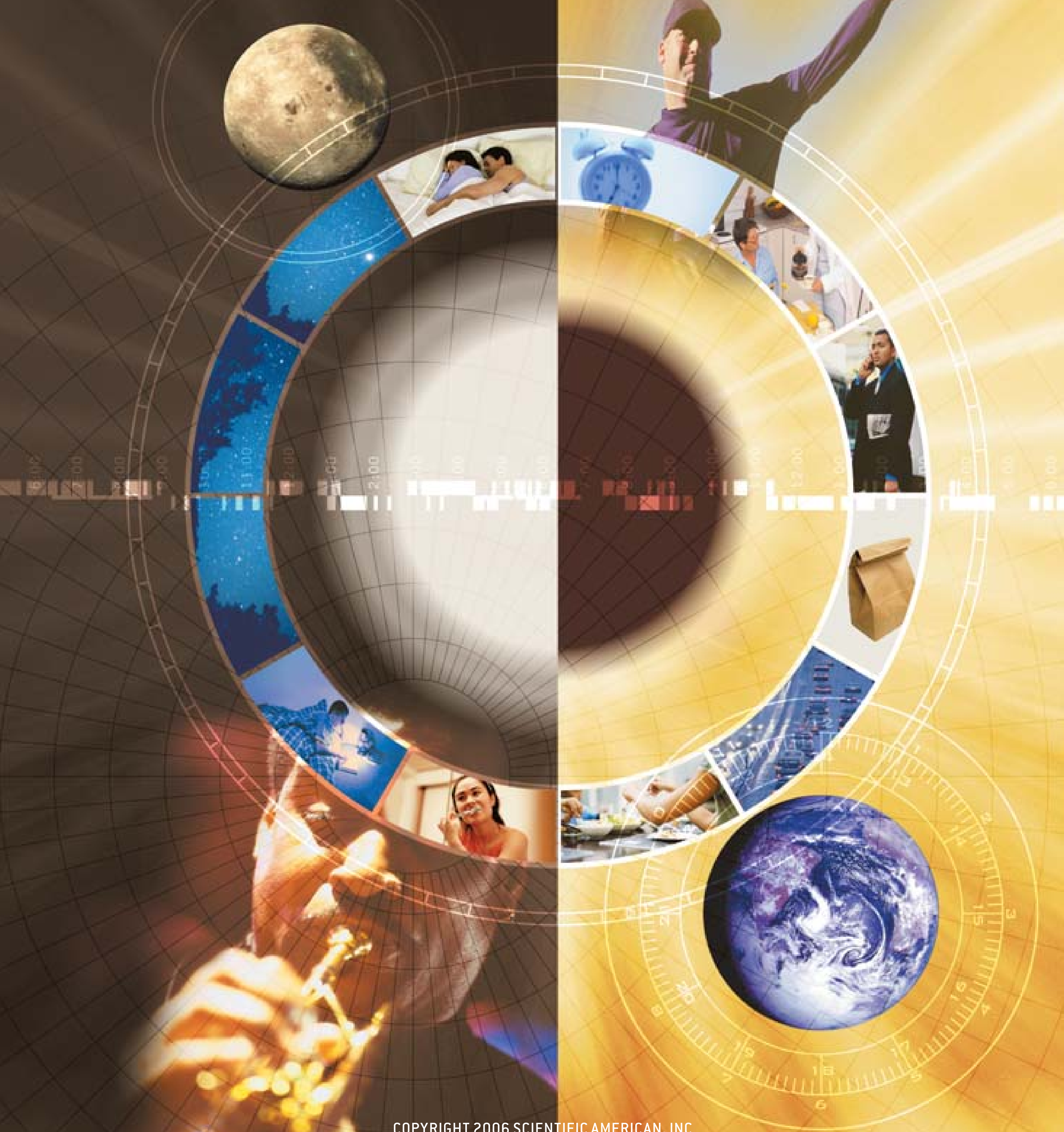
ONE BILLION YEARS

It took approximately this long 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. Meanwhile the sun orbited four times around the center of the galaxy. Because the universe is 12 billion to 14 billion years old, units of time beyond a billion years aren't used very often. But cosmologists believe that the universe will probably keep expanding indefinitely, until long after the last star dies (100 trillion years from now) and the last black hole evaporates (10^{100} years from now). Our future stretches ahead much farther than our past trails behind.

David Labrador, freelance writer and researcher, assembled this list.

SIMON FRASER (*newborn*) AND DAVID HALPERN (*Old Faithful*) *Photo Researchers, Inc.*; NASA/NSSDC (*moon and Orion nebula*); WOLFGANG KAEHLER *Corbis* (*tortoise*)

TIMES



OF OUR LIVES

Whether they're counting minutes, months or years,
biological clocks help to keep our brains
and bodies running on schedule **By Karen Wright**

The late biopsychologist John Gibbon called time the "primordial context": a fact of life that has been felt by all organisms in every era. For the morning glory that spreads its petals at dawn, for geese flying south in autumn, for locusts swarming every 17 years and even for lowly slime molds sporing in daily cycles, timing is everything. In human bodies, biological clocks keep track of seconds, minutes, days, months and years. They govern the split-second moves of a tennis serve and account for the trauma of jet lag, monthly surges of menstrual hormones and bouts of wintertime blues. Cellular chronometers may even decide when your time is up. Life ticks, then you die.

The pacemakers involved are as different as stopwatches and sundials. Some are accurate and inflexible, others less reliable but subject to conscious control. Some are set by planetary cycles, others by molecular ones. They are essential to the most sophisticated tasks the brain and body perform. And timing mechanisms offer insights into aging and disease. Cancer, Parkinson's disease, seasonal depression and attention-deficit disorder have all been linked to defects in biological clocks.

The physiology of these timepieces is not completely understood. But neurologists and other clock researchers have begun to answer some of the most pressing questions raised by human experience in the fourth dimension. Why, for example, a watched pot never boils. Why time flies when you're having fun. Why all-nighters can give you indigestion, and why people live longer than hamsters. It's only a matter of time before clock studies resolve even more profound quandaries of temporal existence.

The Psychoactive Stopwatch

IF THIS ARTICLE intrigues you, the time you spend reading it will pass quickly. It'll drag if you get bored. That's a quirk of a "stopwatch" in the brain—the so-called interval timer—that marks time spans of seconds to hours. The interval timer helps you figure out how fast you have to run to catch a baseball. It tells you when to clap to your favorite song. It lets you sense how long you can lounge in bed after the alarm goes off.

Interval timing enlists the higher cognitive powers of the cerebral cortex, the brain center that governs perception, memory and conscious thought. When you approach a yellow traffic light, for example, you time how long it has been yellow and compare that with a memory of how long yellow lights usually last. "Then you have to make a judgment about whether to put on the brakes or keep driving," says Stephen M. Rao of the Medical College of Wisconsin.

Rao's studies with functional magnetic resonance imaging (fMRI) have pointed to the parts of the brain engaged in each of those stages. In the fMRI machine, subjects 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. The brain structures that are involved in the task consume more

OVERVIEW

- In the brain, a "stopwatch" can track seconds, minutes and hours.
- Another timepiece in the brain, more a clock than a stopwatch, synchronizes many bodily functions with day and night. This same clock may account for seasonal affective disorder.
- A molecular hourglass that governs the number of times a cell can divide might put a limit on longevity.

oxygen than those that are not involved, and the fMRI scan records changes in blood flow and oxygenation once every 250 milliseconds. “When we do this, the very first structures that are activated are the basal ganglia,” Rao says.

Long associated with movement, this collection of brain regions has become a prime suspect in the search for the interval-timing mechanism as well. 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 locale. 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,” says Warren H. Meck of Duke University.

> “There’s a **unique time stamp** for every interval you can imagine.” *—Warren H. Meck, Duke University*

Striatal spiny neurons are central to an interval-timing theory Meck developed over the past decade with Gibbon, who worked at Columbia University until his death in 2001. The theory posits a collection of neural oscillators in the cerebral cortex: nerves 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,” Meck says, “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—a yellow traffic light, say—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 have 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, for example, the traffic light turns red—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. “There’s a unique time stamp for every interval you can imagine,” Meck says.

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 [*see top illustration in box on opposite page*]. 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.

If Meck is right and dopamine bursts play an important role in framing a time interval, then diseases and drugs that affect dopamine levels should also disrupt that loop. So far 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. In trials these patients consistently underestimate the duration of time intervals. 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. 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 exist at all. Because an attentional spike initiates the timing process, Meck thinks people with attention-deficit hyperactivity disorder might also have problems gauging the true length of intervals.

The interval clock can also be trained to greater precision. Musicians and athletes know that practice improves their timing; ordinary folk can rely on tricks such as chronometric counting (“one one-thousand”) to make up for the mechanism’s deficits. Rao forbids his subjects from counting in experiments because it could activate brain centers related to language as well as timing. But counting works, he says—well enough to expose cheaters. “The effect is so dramatic that we can tell whether they’re counting or timing based just on the accuracy of their responses.”

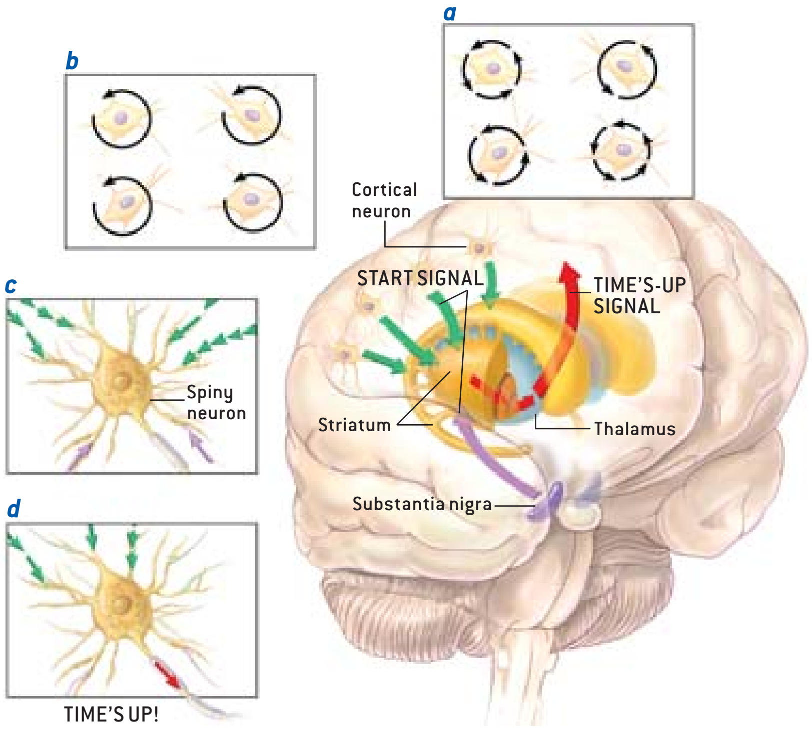
The Somatic Sundial

ONE OF THE VIRTUES of the interval-timing stopwatch is its flexibility. You can start and stop it at will or ignore it completely. It can work subliminally or submit to conscious control.

PAGE 26: TOM DRAPER DESIGN; NASA/NSSDC (*Earth and moon*); CORBIS (*baseball pitcher and horn player*); TOMMY FLYNN *Photonica* (*alarm clock*); CORBIS (*breakfast*); JOHN TERRENCE TURNER *Getty Images* (*highway*); ROBERT DALY *Stone* (*dinner table*); ERICA McCONNELL *Getty Images* (*brushing teeth*); GEOFF MANASSE *Aurora* (*child reading*); YOSHINORI WATABE *Photonica* (*night sky*)

Clocks in the Brain

Scientists are uncovering the workings of two neural timepieces: an interval timer (*top*), which measures intervals lasting up to hours, and a circadian clock (*bottom*), which causes certain body processes to peak and ebb on 24-hour cycles. —*K.W.*

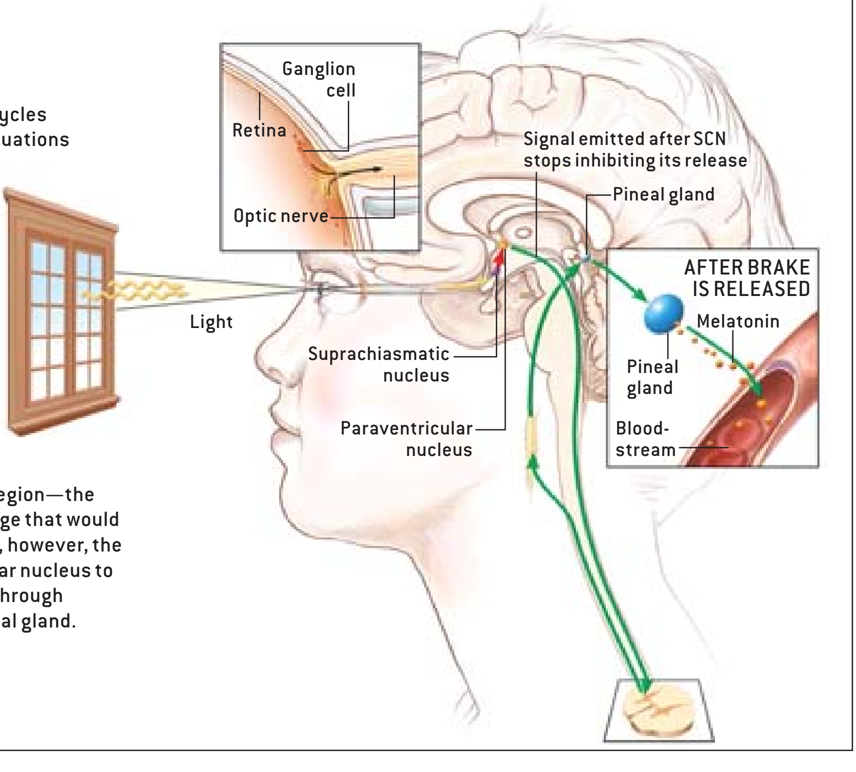


The Interval Timer

According to one model, the onset of an event lasting a familiar amount of time (such as the switching on of a four-second yellow traffic light) activates the "start button" of the interval timer by evoking two brain responses. It induces a particular subset of cortical nerve cells that fire at different rates (*a*) to momentarily act together (*b* and *green arrows on brain*), and it prompts neurons of the substantia nigra to release a burst of the signaling chemical dopamine (*purple arrow*). Both signals impinge on spiny cells of the striatum (*c*), which proceed to monitor the overall patterns of impulses coming from the cortical cells after those neurons resume their various firing rates. Because the cortical cells act in synchrony at the start of the interval, the subsequent patterns occur in the same sequence every time and take a unique form when the end of the familiar interval is reached (*d*). At that point, the striatum sends a "time's up" signal (*red arrows*) through other parts of the brain to the decision-making cortex.

The Circadian Clock

Daily cycles of light and dark dictate when many physiological processes that operate on 24-hour cycles will be most and least active. The brain tracks fluctuations in light with the help of ganglion calls in the retina of the eye. A pigment in some of the cells—melanopsin—probably detects light, leading the retinal ganglion cells to send information about its brightness and duration to the suprachiasmatic nucleus (SCN) of the brain. Then the SCN dispatches the information to the parts of the brain and body that control circadian processes. Researchers best understand the events leading the pineal gland to secrete melatonin, sometimes called the sleep hormone (*diagram*). In response to daylight, the SCN emits signals (*red arrow*) that stop another brain region—the paraventricular nucleus—from producing a message that would ultimately result in melatonin's release. After dark, however, the SCN releases the brake, allowing the paraventricular nucleus to relay a "secrete melatonin" signal (*green arrows*) through neurons in the upper spine and the neck to the pineal gland.



TERESE WINSLOW

But it won't win any prizes for accuracy. The precision of interval timers has been found to range from 5 to 60 percent. They don't work too well if you're distracted or tense. And timing errors get worse as an interval gets longer. "Hence the instruments we all wear on our wrists," Rao notes.

Fortunately, a more rigorous timepiece chimes in at intervals of 24 hours. The circadian clock—from the Latin *circa* ("about") and *diem* ("a day")—tunes our bodies to the cycles of sunlight and darkness caused by the earth's rotation. It helps to program the daily habit of sleeping at night and waking in the morning. But its influence extends much further. 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 A.M. 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 pick up again in the morning.

A virtue of the interval-timing stopwatch is its flexibility. You can start and stop it at will.

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 volunteer cave dwellers and other human guinea pigs have demonstrated that circadian patterns persist even in the absence of daylight, occupational demands and caffeine. And they are 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 percent: just minutes a day.

But if light isn't required to establish a circadian cycle, 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. Neurologists have made great progress in understanding how daylight sets the clock. Two clusters of 10,000 nerve cells in the hypothalamus of the brain have long been considered the clock's locus. Decades of animal studies have demonstrated that these centers, each called a suprachiasmatic nucleus (SCN), drive daily fluctuations in blood pressure, body temperature, activity level and alertness. The SCN also tells the brain's pineal gland when to release melatonin, which promotes sleep in humans and is secreted only at night.

In 2002 separate teams of researchers proved that dedicated cells in the retina of the eye transmit information about light levels to the SCN. These cells—a subset of those known as ganglion cells—operate completely independently of the rods and cones that mediate vision, and they are far less responsive to sudden changes in light. That sluggishness befits a circadian system. It would be no good if watching fireworks or going to a movie matinee tripped the mechanism.

But the SCN's role in circadian rhythms is being reevaluated in view of other findings. Scientists had assumed that the SCN somehow coordinated all the individual cellular clocks in the body's organs and tissues. Then, in the mid-1990s, researchers discovered four critical genes that govern circadian cycles in flies, mice and humans. These genes turned up not just in the SCN but everywhere else, too. "These clock genes are expressed throughout the whole body, in every tissue," says Joseph Takahashi of Northwestern University. "We didn't expect that."

And in 2002 researchers at Harvard University reported that the expression of more than 1,000 genes in the heart and liver tissue of mice varied in regular 24-hour periods. But the genes that showed these circadian cycles differed in the two tissues, and their expression peaked in the heart at different hours than in the liver. "They're all over the map," says Michael Menaker of the University of Virginia. "Some are peaking at night, some in the morning and some in the daytime."

Menaker has shown that specific feeding schedules can shift the phase of the liver's circadian clock, overriding the light-dark rhythm followed by the SCN. When lab rats that usually ate at will were fed just once a day, for example, peak expression of a clock gene in the liver shifted by 12 hours, whereas the same clock gene in the SCN stayed locked in sync with light schedules. It makes sense that daily rhythms in feeding would affect the liver, given its role in digestion. Researchers think circadian clocks in other organs and tissues may respond to other external cues—including stress, exercise, and temperature changes—that occur regularly every 24 hours. No one is ready to dethrone the SCN: its authority over body temperature, blood pressure and other core rhythms is still secure. But this brain center is no longer thought to rule the peripheral clocks with an iron fist. "We have oscillators in our organs that can function independently of our oscillators in our brain," Takahashi says.

The autonomy of the peripheral clocks makes a phenomenon such as jet lag far more comprehensible. Whereas the interval timer, like a stopwatch, can be reset in an instant, circadian rhythms take days and sometimes weeks to adjust to a sudden shift in day length or time zone. A new schedule of light will slowly reset the SCN clock. But the other clocks may not follow its lead. The body is not only lagging; it's lagging at a dozen different paces.

Jet lag doesn't last, presumably because all those different drummers are able to eventually sync up again. But shift workers, party animals, college students and other night owls face a worse chronodilemma. They may be leading a kind of physiological double life. Even if they get plenty of shut-eye by day, their core rhythms are still ruled by the SCN—hence, the core functions continue "sleeping" at night. "You can will your sleep cycle earlier or later," says Alfred J. Lewy of the Oregon Health & Science University. "But you can't will your melatonin levels earlier or later, or your cortisol levels, or your body temperature."

Meanwhile their schedules for eating and exercising could be setting their peripheral clocks to entirely different phases from either the sleep-wake cycle or the light-dark cycle. With their bodies living in so many time zones at once, it's no wonder shift workers have an increased incidence of heart disease, gastrointestinal complaints and, of course, sleep disorders.

A Clock for All Seasons

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. 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 dawn. Their sleep-wake cycle is several time zones away from the cues they get from daylight.

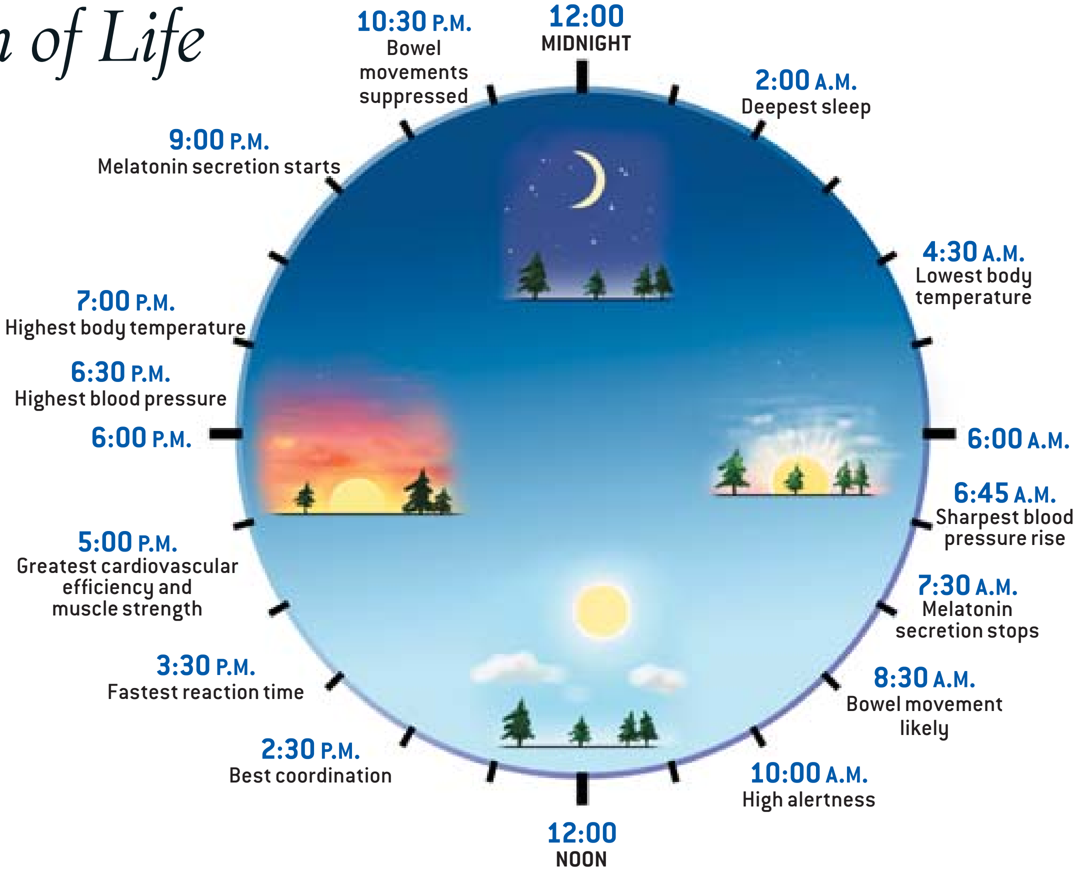
The mismatch between day length and daily life could explain the syndrome known as seasonal affective disorder, or SAD. In the U.S., SAD afflicts as many as one in 20 adults with depressive symptoms such as weight gain, apathy and fatigue between October and March. The condition is 10 times more common in the north than the south. Although SAD occurs seasonally, some experts suspect it is actually a circadian problem. Lewy's work 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 is not so much a pathology as evidence of an adaptive, seasonal rhythm in sleep-wake cycles. "If we adjusted our daily schedules according to the seasons, we might not have seasonal depression," Lewy says. "We got into trouble when we stopped going to bed at dusk and getting up at dawn."

If modern civilization doesn't honor seasonal rhythms, it's partly because

CYCLIC EVENTS

Rhythm of Life

The circadian clock affects the daily rhythms of many physiological processes. The diagram at the right depicts the circadian patterns typical of someone who rises early in the morning, eats lunch around noon and sleeps at night. Although circadian rhythms tend to be synchronized with cycles of light and dark, other factors—such as ambient temperature, meal times, stress and exercise—can influence the timing as well. *—K.W.*



SOURCE: The Body Clock Guide to Better Health, *by Michael Smolensky and Lynne Lamberg, Henry Holt and Company, 2000*

TERESE WINSLOW

human beings are among the least seasonally sensitive creatures around. SAD is nothing compared to the annual cycles other animals go through: hibernation, migration, molting and especially mating, the master metronome to which all other seasonal cycles keep time. It is possible that these seasonal cycles may also be regulated by the circadian clock, which is equipped to keep track of the length of days and nights. Darkness, as detected by the SCN and the pineal gland, prolongs melatonin signals in the long nights of winter and reduces them in the summer. "Hamsters can tell the difference between a 12-hour day, when their gonads don't grow, and a 12-hour-15-minute day, when their gonads do grow," Menaker says [*see box below*].

If seasonal rhythms are so robust in other animals, and if humans have the equipment to express them, then how did we ever lose them? "What makes you think we ever had them?" Menaker asks. "We evolved in the tropics." Menaker's point is that many tropical animals don't exhibit dramatic patterns of annual behavior. They don't need them, because the seasons themselves vary so little. Most tropical animals mate without regard to seasons because there is no "best time" to give birth. People, too, are always in heat. As our ancestors gained greater control of their environment over the millennia, seasons probably became an even less significant evolutionary force.

But one aspect of human fertility is cyclical: women and other female primates produce eggs just once a month. The clock that regulates ovulation and menstruation is a well-documented chemical feedback loop that can be manipulated by hormone treatments, exercise and even the presence of other menstruating women. But the reason for the specific duration of the menstrual cycle is unknown. The fact that it is the same length as the lunar cycle is a coincidence few scientists have bothered to investigate, let alone explain. No convincing link has yet been found between the moon's radiant or gravitational energy and a woman's reproductive hormones. In that regard, the monthly menstrual clock remains a mystery—outdone perhaps only by the ultimate conundrum, mortality.

SEASONAL CLOCKS

Turn, Turn

Most animals experience dramatic seasonal cycles: they migrate, hibernate, mate and molt at specific times of the year (*top four photographs*). The testicles of hamsters, for example, quadruple in size as mating season approaches. These cycles are hardwired: captive ground squirrels continue to hibernate seasonally even when kept in constant temperatures with unvarying periods of light and dark. Likewise, birds in stable laboratory conditions get restless at migration time and keep molting and fattening in yearly cycles.

The only vestige of seasonality in humans may be seasonal affective disorder, commonly referred to as SAD, a yearly bout of depression that strikes some individuals in winter and can be remedied with light therapy (*bottom photograph*)—or merely by sleeping until the sun comes up.

—K.W.

Time the Avenger

PEOPLE TEND TO EQUATE aging with 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 developed countries have a life expectancy of more than 70 years. The life expectancy of your average mayfly, in contrast, is a day. Biologists are just beginning to explore why different species have different life expectancies. If your days are numbered, what's doing the counting?

At a 2002 meeting hosted by the National Institute on Aging, participants challenged many common assumptions about the factors that determine natural life span. The answer cannot lie solely with a species' genetics: worker honeybees, for example, last a few months, whereas queen bees live for years. But genetics are important: a single-gene mutation in mice can produce a strain that lives up to 50 percent 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 do not necessarily outlast the small ones. The life expectancy of a parrot is about the same as a human's. Among dog species, small breeds typically live longer than large ones.

Scientists in search of the limits to human life span have traditionally approached the subject from the cellular

TOM DRAPER DESIGN; FRANS LANTING *Minden Pictures* (*swans and butterflies*); GEORGE McCARTHY *Corbis* (*mouse*); MARK JONES *Minden Pictures* (*penguin*); NAJLAH FEANNY SABA (*light therapy*)

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. The mitotic clock is like an hourglass in which each grain of sand represents one episode of cell division. Just as there is a finite number of grains in an hourglass, 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 call it quits. "All of a sudden they just stop growing," says John Sedivy of Brown University. "They respire, they metabolize, they move, but they will never divide again."

Cultured cells usually reach this state of senescence in a few months.

It is possible that seasonal cycles in animals may be regulated by the circadian clock.

Fortunately, most cells in the body divide much, much more slowly than cultured cells. But eventually—perhaps after 70 years or so—they, too, can get put out to pasture. "What the cells are counting is not chronological time," Sedivy says. "It's the number of cell divisions."

In the late 1990s Sedivy reported 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 end of chromosomes. Telomeres are made of the same stuff that genes are: DNA. They consist of thousands of repetitions of a six-base DNA sequence that does not 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 of the Rockefeller University has proposed a new 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. Other cells bred to ignore short telomeres have turned cancerous. The job of normal p21 and telomeres themselves may be to stop cells from dividing so much that they die or become malignant. Cellular senescence could actually be prolonging human life rather than spelling its doom. It might be cells' imperfect defense against malignant growth and certain death.

"Our hope is that we'll gain enough information from this reductionist approach to help us understand what's going on in the whole person," de Lange comments.

For now, the link between shortened telomeres and aging is tenuous at best. Most cells do not need to keep dividing to do their job—white blood cells that fight infection and sperm precursors being obvious exceptions. But many older people do die of simple infections that a younger body could withstand. "Senescence probably has nothing to do with the nervous system," Sedivy says, because most nerve cells do not divide. "On the other hand, it might very well have something to do with the aging of the immune system."

In any case, telomere loss is just one of the numerous insults cells sustain when they divide, says Judith Campisi of Lawrence Berkeley National Laboratory. DNA often gets 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. Genes related to aging in animals and people often code for proteins that prevent or repair those mistakes. And with each mitotic episode, the by-products of copying DNA build up in cell nuclei, complicating subsequent bouts of replication.

"Cell division is very risky business," Campisi observes. So perhaps it is not surprising that the body puts a cap on mitosis. And cheating cell senescence probably wouldn't grant immortality. Once the grains of sand have fallen through the mitotic hourglass, there's no point in turning it over again. SA

Karen Wright is a science writer based in New Hampshire. Her work is featured in The Best American Science and Nature Writing 2002 *(Mariner Books).*

MORE TO EXPLORE

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REMEMBERING WHEN

Several brain structures contribute to "mind time," organizing our experiences into chronologies of remembered events

By Antonio R. Damasio

OVERVIEW

- Researchers understand how the body keeps time through circadian rhythms but not how the brain is able to place events in the proper chronological sequence.
- Recent studies suggest that various brain structures, including the hippocampus, basal forebrain and temporal lobe, have some part to play in keeping "mind time."

IRAIDA ICAZA

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We wake up to time, courtesy of an alarm clock, and go through a day run by time—the meeting, the visitors, the conference call, the luncheon are all set to begin at a particular hour. We can coordinate our own activities with those of others because we all implicitly agree to follow a single system for measuring time, one based on the inexorable rise and fall of daylight. In the course of evolution, humans have developed a biological clock set to this alternating rhythm of light and dark. This clock, located in the brain's hypothalamus, governs what I call body time [see "Times of Our Lives," by Karen Wright, on page 26].

But there is another kind of time altogether. "Mind time" has to do with how we experience the passage of time and how we organize chronology. Despite the steady tick of the clock, duration 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, whether that of a lifetime or of a few seconds.

> Amnesics lose the ability to estimate the passage of time accurately at the scale of hours, months, years and decades.

How mind time relates to the biological clock of body time is unknown. It is 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 information processing. If the latter alternative proves to be 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 and Memory

I WAS FIRST DRAWN to the problems of time processing through my 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 epoch and sequence. Moreover, these amnesics 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 ability 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.

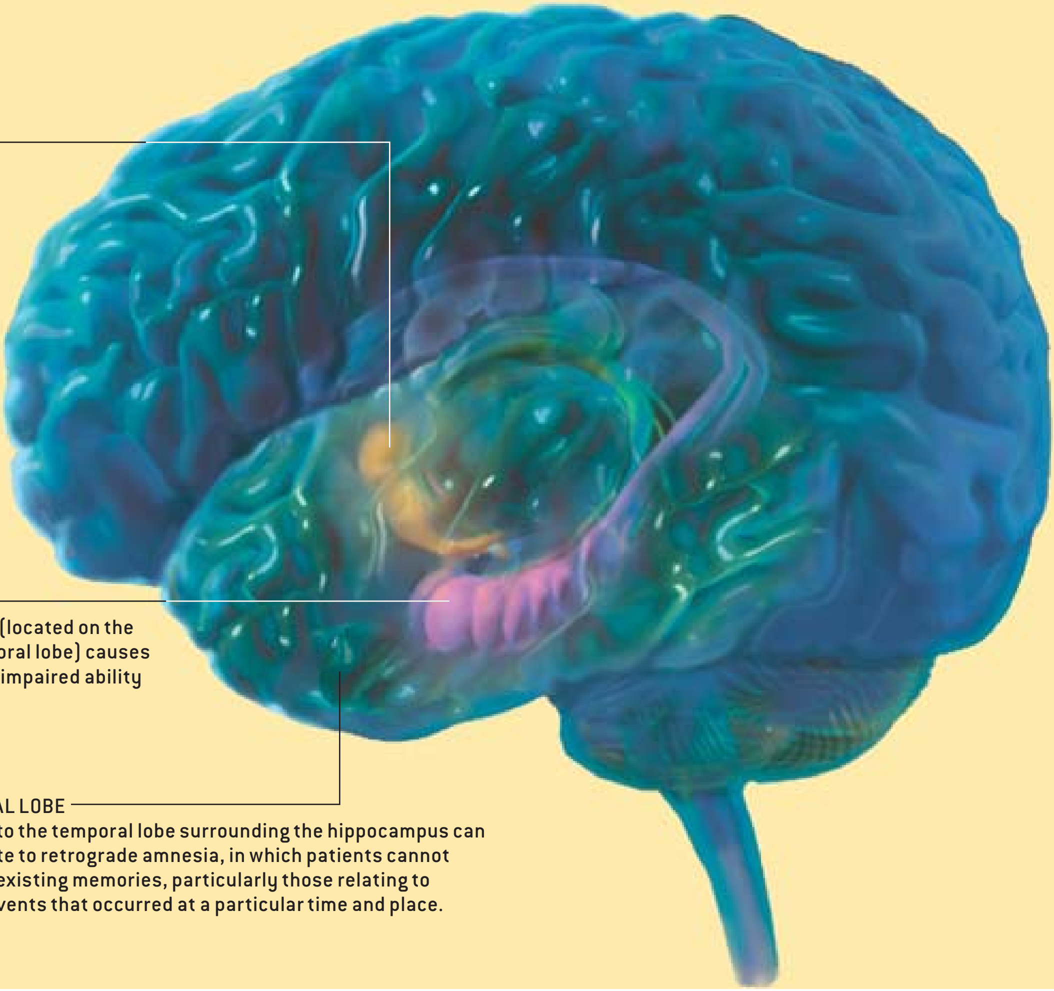
The association between amnesia and time can be seen most dramatically in cases of permanent brain damage to the hippocampus, a region of the brain important to memory, and to the nearby temporal lobe, the region through which the hippocampus holds a two-way communication with the rest of the cerebral cortex. Damage to the hippocampus prevents the creation of new memories. The ability to form memories is an indispensable part of the construction of a sense of our own chronology. We build our time line event by event, and we connect personal happenings to those that occur around us. When the hippocampus is impaired, patients become unable to hold factual memories for longer than about one minute. Patients so afflicted are said to have anterograde amnesia.

Intriguingly, the memories that the hippocampus helps to create are not stored in the hippocampus. They are distributed in neural networks located in parts of the cerebral cortex (including the temporal lobe) 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 are destroyed, patients cannot 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—say, that of the concept of

BRAIN BASICS

Finding Time

Studies of brain-damaged patients suggest that structures in the temporal lobe of the brain and in the basal forebrain play important roles in laying down and unearthing information about when events occurred and in what order. —*A.R.D.*



BASAL FOREBRAIN
Injury to this area spares the ability to remember some events but impairs recall of when they happened—indicating that the region plays a role in identifying the chronology of past occurrences.

HIPPOCAMPUS
Damage to this structure (located on the inner surface of the temporal lobe) causes anterograde amnesia: an impaired ability to form new memories.

TEMPORAL LOBE
Damage to the temporal lobe surrounding the hippocampus can contribute to retrograde amnesia, in which patients cannot retrieve existing memories, particularly those relating to unique events that occurred at a particular time and place.

CAROL DONNER

marriage—carries no such date with it. The temporal lobe that surrounds the hippocampus is critical in the making and recalling of 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.

For one such patient, whom my colleagues and I have studied for 25 years, the time gap goes almost all the way to the cradle. When my patient was 46, he sustained damage both to the hippocampus and to parts of the temporal lobe. Accordingly, he has both anterograde and retrograde amnesia: he cannot form new factual memories, and he cannot recall old ones. The patient inhabits a permanent present, unable to remember what happened a minute ago or 20 years ago.

Indeed, he has no sense of time at all. He cannot tell us the date, and when asked to guess, his responses are wild—as disparate as 1942 and 2013. He can guess time more accurately if he has access to a window and can approximate it based on light and shadows. But if he is deprived of a watch or a window, morning is no different from afternoon, and night is no different from day; the

THE AUTHOR

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How Hitchcock's Rope *Stretches Time*

The elasticity of time is perhaps best appreciated when we are the spectators of a performance, be it a film, a play, a concert or a lecture. The actual duration of the performance and its mental duration are different things. To illustrate the factors that contribute to this varied experience of time, I cannot think of a better example than Alfred Hitchcock's 1948 film *Rope,* a technically remarkable work that was shot in continuous, unedited 10-minute takes; few features have been produced in their entirety using this approach. Orson Welles in *Touch of Evil,* Robert Altman in *The Player* and Martin Scorsese in *GoodFellas* employed long continuous shots, but not as consistently as in *Rope*. (In spite of the many plaudits the innovation earned the director, filming proved a nightmare for all concerned, and Hitchcock used the method again only in part of his next film, *Under Capricorn*.)

Hitchcock invented this technique for a sensible and specific reason. He was attempting to depict a story that had been told in a play occurring in continuous time. But he was limited to the amount of film that could be loaded into the camera, roughly enough for 10 minutes of action.

Now let us consider how *Rope*'s real time plays in our minds. In an interview with François Truffaut in 1966, Hitchcock stated that the story begins at 7:30 P.M. and terminates at 9:15, 105 minutes later. Yet the film consists of eight reels of 10 minutes each: a total of 81 minutes, when the credits at the beginning and end are added in. Where did the missing 25 minutes go? Do we experience the film as shorter than 105 minutes? Not at all. The film never seems shorter than it should, and a viewer has no sense of haste or clipping. On the contrary, for many the film seems longer than its projection time.

I suspect that several aspects account for this alteration of perceived time. First, most of the action takes place in the living room of a penthouse in summer, and the skyline of New York is visible through a panoramic window. At the beginning of the film the light suggests late afternoon; by the end, night has set in. Our daily experience of fading daylight makes us perceive the real-time action as taking long enough to cover the several hours of the coming of night when in fact those changes in light are artificially accelerated by Hitchcock.

In the same way, the nature and context of the depicted actions elicit other automatic judgments about time. After the proverbial Hitchcock murder, which occurs at the beginning of the film's first reel, the story focuses on an elegant dinner party hosted by the two unsavory murderers and attended by the relatives and friends of the victim. The actual time during which food is served is about two reels. Yet viewers attribute more time to that sequence because we know that neither the hosts nor the guests, who look cool, polite and unhurried, would swallow dinner at such breakneck speed. When the action later splits—some guests converse in the living room in front of the camera, while others repair to the dining room to look at rare books—we sensibly attribute a longer duration to this offscreen episode than the few minutes it takes up in the actual film.

Another factor may also contribute to the deceleration of time. There are no jump cuts within each 10-minute reel; the camera glides slowly toward and clock of body time is of no help. This patient cannot state his age, either. He can guess, but the guess tends to be wrong.

Two of the few specific things he knows for certain are that he was married and that he is the father of two children. But when did he get married? He cannot say. When were the children born? He does not know. He cannot place himself in the time line of his family life. He was indeed married, but his wife divorced him more than two decades ago. His children have long been married and have children of their own.

Time Stamps

HOW THE BRAIN ASSIGNS an event to a specific time and then puts that event in a chronological sequence—or in the case of my patient, fails to do so—is still a mystery. We know only that both the memory of facts and the memory of spatial and temporal relationships between those facts are involved. Accordingly, when I was at the University of Iowa, my colleagues Daniel Tranel and Robert Jones and I decided to investigate how an autobiographical time line is established. By looking at people with different kinds of memory impairment, we hoped to identify what region or regions of the brain are required to place memories in the correct epoch.

We selected four groups of participants, 20 people in total. The first group consisted of 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, made up the second set. The third group was composed of patients without amnesia who had damage in places other than the temporal lobe or basal forebrain. We chose as control subjects individuals without neurological disease, who had normal memories and who 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. We asked them about parents, siblings and various relatives, schools, friendships and professional activities, and then we verified the an-

EVERETT COLLECTION

ROPE'S SKYLINE LIGHT fades more quickly than in real life, but viewers attribute real time to the coming of night. They therefore experience time as passing more slowly than it does in the film.

away from each character. Yet to join each segment to the next, Hitchcock finished most takes with a close-up on an object. In most instances, the camera moves to the back of an actor wearing a dark suit and the screen goes black for a few seconds; the next take begins as the camera pulls away from the actor's back. Although the interruption is brief and is not meant to signal a time break, it may nonetheless contribute to the elongation of time because we are used to interpreting breaks in the continuity of visual perception as a lapse in the continuity of time. Film-editing devices such as the dissolve and the fade often cause spectators to infer that time has passed between the preceding shot and the following one. In *Rope* each of the seven breaks delays real time by a fraction of a second. But cumulatively for some viewers, the breaks may suggest that more time has passed.

The emotional content of the material may also extend time. When we are uncomfortable or worried, we often experience time more slowly because we focus on negative images associated with our anxiety. Studies in my laboratory show that the brain generates images at faster rates when we are experiencing positive emotions (perhaps this is why time flies when we're having fun) and reduces the rate of image making during negative emotions. On a recent flight with heavy turbulence, for instance, I experienced the passage of time as achingly slow because my attention was directed to the discomfort of the experience. Perhaps the unpleasantness of the situation in *Rope* similarly conspires to stretch time.

Rope provides a noticeable discrepancy between real time and the audience's perception of time. In so doing, it illustrates how the experience of duration is a construct. It is based on factors as various as the content of the events being perceived, the emotional reactions those events provoke and the way in which images are presented to us, as well as the conscious and unconscious inferences that accompany them. *—A.R.D.*

IRAIDA ICAZA

swers with relatives and records. We also established what the participants remembered of key public events, such as the election of officials, wars and natural disasters, and prominent cultural developments. We then 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. For the participants, the situation was an experience similar to playing the board game Life. For the investigators, the setup permitted a measurement of the accuracy of time placement.

A lag exists between the beginning of neural events leading to consciousness and the moment one experiences the consequences of those events.

Predictably, the amnesic patients differed from the controls. Normal individuals were relatively accurate in their time placements: on average they were wrong by 1.9 years. Amnesic patients made far more errors, especially those with basal forebrain damage. Although they recalled the event exactly, they were off the mark by an average of 5.2 years. But their recall of events was superior to that of temporal lobe patients, who 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 epoch. This notion is in keeping with the clinical observation of basal forebrain patients. Unlike certain of their counterparts with temporal lobe damage, these patients do learn new facts. But they often recall the facts they have just learned in the incorrect order, reconstructing sequences of events in a fictional narrative that can change from occasion to occasion.

Being Late for Consciousness

MOST OF US do not have to grapple with the large gaps of memory or the chronological confusion that many of my patients do. Yet we all share a strange mental time lag, a phenomenon first brought to light in the 1970s by neurophysiologist Benjamin Libet of the University of California, San Francisco. In one experiment, Libet documented a gap between the time an individual was conscious of the decision to flex his finger (and recorded the exact moment of that consciousness) 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. In another experiment, Libet tested whether a stimulus applied directly to the brain caused any sensation in some of his surgery patients, who were awake, as most patients are in such operations. He found that a mild electrical charge to the cortex produced a tingling in the patient's hand—a full half a second after the stimulus was applied.

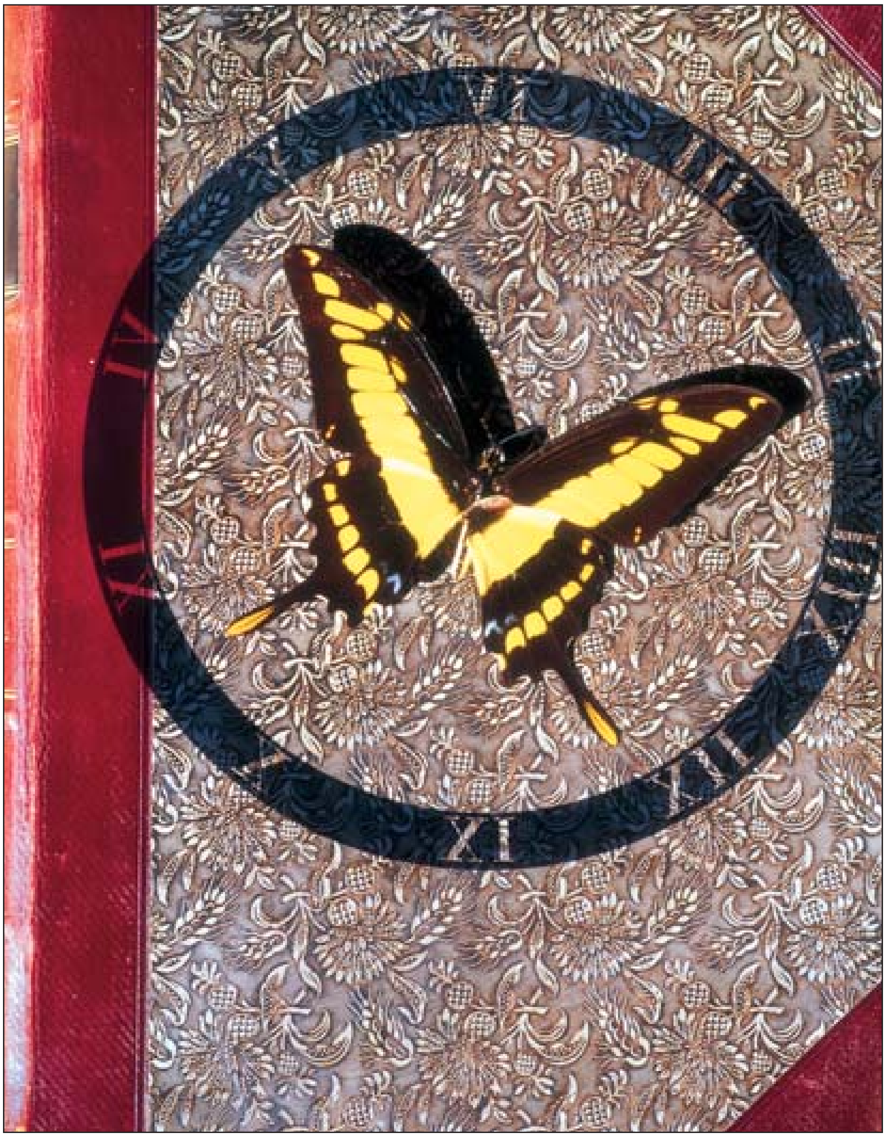
Although the interpretation of those experiments, and others in the field of consciousness studies, is entangled in controversy, one general fact emerged from Libet's work. It is apparent that a lag exists between the beginning of the neural events leading to consciousness and the moment one actually experiences the consequence of those events.

This finding may be shocking at first glance, and yet the reasons for the delay are fairly obvious. It takes time for the physical changes that constitute an event to impinge on the body and 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 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—the last and critical step without which the event will never become conscious.

We are describing nothing more than mere milliseconds, but there is a delay nonetheless. This situation is so strange that the reader may well wonder why we are not aware of this delay. One attractive explanation is that because we have similar brains and they work similarly, we are all hopelessly late for consciousness and no one notices it. But perhaps other reasons apply. The brain can institute its own connections on the central processing of events such that, at the microtemporal level, it 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 that attends the eye movement nor the time it takes to get the eyes from one place to the other. Patrick Haggard of University College London and John C. Rothwell of the Institute of Cognitive Neuroscience in London suggest that the brain predates the perception of the target by as much as 120 milliseconds, thereby giving us all the perception of seamless viewing.

The brain's ability to edit our 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 are gradually coming to know more about why we experience time so variably and about what the brain needs to create a time line. SA



IRAIDA ICAZA

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CLOCK TOWERS—from left, in Malaysia, New York City, Saudi Arabia and Hong Kong—are popular places to rendezvous, but failure to appear on time has vastly different repercussions depending on your meeting place. Show up half an hour late under the tower in New York, and the clock may toll the end of a beautiful friendship.

CLOCKING

CULTURES

What is time? The answer varies from society to society

By Carol Ezzell

Show up an hour late in Brazil, and no one bats an eyelash. But keep someone in Switzerland waiting for five or 10 minutes, and you have some explaining to do.

Time is elastic in many cultures but snaps taut in others. Indeed, the way members of a culture perceive and use time reflects their society's priorities and even their own worldview.

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 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. Interestingly, however, some views of time—such as the idea that it is acceptable for a more powerful person to keep someone of lower status waiting—cut across cultural differences and seem to be found universally.

OVERVIEW

- The way the world's cultures keep time reflects their priorities and even the way they view the world. Despite the near universal use of clocks and calendars, different societies march to different beats.
- In perceiving time, cultures emphasize the past, present and future differently. For example, the followers of Wahhabism—the strict form of Islam that prevails in Saudi Arabia—are intent on replicating a romanticized vision of the past.

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 "they exist in the air.... They 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. "An ambassador who has been kept waiting for more than half an hour by a foreign visitor needs to understand that if his visitor 'just mutters an apology' this is not necessarily an insult," Hall wrote. "The time system in the foreign country may be composed of different basic units, so that the visitor is not as late as he may appear to us. You must know the time system of the country to know at what point apologies are really due.... Different cultures simply place different values on the time units."

Most cultures around the world now have watches 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. "One of the beauties of studying time is that it's a wonderful window on culture," says Robert V. Levine, a social psychologist at California State University, Fresno. "You get answers on what cultures value and believe in. You get a really good idea of what's important to people."

Levine and his colleagues have conducted so-called pace-of-life studies in 31 countries. In *A Geography of Time*, published in 1997, Levine describes how he ranked the countries by using three measures: walking speed on urban sidewalks, how quickly postal clerks could fulfill a request for a common stamp, and the accuracy of public clocks. Based on these variables, he concluded that the five fastest-paced countries are Switzerland, Ireland, Germany, Japan and Italy; the five slowest are Syria, El Salvador, Brazil, Indonesia and Mexico. The U.S., at 16th, ranks near the middle.

Kevin K. Birth, an anthropologist at Queens College, 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. For them,

PRECEDING PAGES, LEFT TO RIGHT: PIXTAL/AGE FOTOSTOCK; BARTOMEU AMENGUAL *age fotostock*; JON HICKS *Corbis*; DIOMEDIA RF/AGE FOTOSTOCK

“RUSH HOUR” literally describes the pace of commuters in New York City’s subway system. In contrast, on the sunny streets of Manzanares, Spain, no one seems eager to get anywhere.

MARK PETERSON *Corbis* (*top*); OWEN FRANKEN *Corbis* (*bottom*)

the saying goes, “time is time.” Birth adds that the tie between power and waiting time is true for many other cultures as well.

The nebulous nature of time can make it difficult for anthropologists and social psychologists to study. “You can’t simply go into a society, walk up to some poor soul and say, ‘Tell me about your notions of time,’ ” Birth says. “People don’t really have an answer to that. You have to come up with other ways to find out.”

Birth attempted to get at how Trinidadians value time by exploring how closely their society links time and money. He surveyed rural residents and found that farmers—whose days are dictated by natural events, such as sunrise—did not recognize the phrases “time is money,” “budget your time” or “time management,” even though they had satellite TV and were familiar with Western popular culture. But tailors in the same areas were aware of such notions. Birth concluded that wage work altered the tailors’ views of time. “The ideas of associating time with money are not found globally,” he says, “but are attached to your job and the people you work with.”

How people deal with time on a day-to-day basis often has nothing to do with how they conceive of time as an abstract entity. “There’s often a disjunction between how a culture views the mythology of time and how [people] think about time in their daily lives,” Birth asserts. “We don’t think of Stephen Hawking’s theories as we go about our daily lives.”

Some cultures do not draw neat distinctions between the past, present and future. Australian Aborigines, 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, which brought them into being. Even today, an entity does not exist unless an Aborigine “sings” it.

Ziauddin Sardar, a British Muslim author and critic, has written about time and Islamic cultures, particularly the fundamentalist sect Wahhabism. Muslims “always carry the past with them,” claims Sardar, who is editor of the journal *Futures* and visiting professor of postcolonial studies at City University, London. “In Islam, time is a tapestry incorporating the past, present and future. The past is ever present.” The followers of Wahhabism, which is practiced in Saudi Arabia and by Osama bin Laden, seek to re-create the idyllic days of the prophet Muhammad’s life. “The worldly future dimension has been suppressed” by them, Sardar says. “They have romanticized a particular vision of the past. All they are doing is trying to replicate that past.”

Sardar asserts that the West has “colonized” time by spreading the expectation that life should become better as time passes: “If you colonize time, you also colonize the future. If you think of time as an arrow, of course you think of the future as progress, going in one direction. But different people may desire different futures.” SA

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MORE TO EXPLORE

A Geography of Time: The Temporal Misadventures of a Social Psychologist. Robert V. Levine. Basic Books, 1998.

INSTRUMENTS OF TIME have become markedly more complex and accurate over the millennia, progressing, for example, from the hemispherical sundial of first- or second-century A.D. Rome (*left*) to the 18th-century American grandfather clock (*right*) and on to the atomic hydrogen maser clock, which was introduced in the early 1960s (*bottom left*).

A CHRONICLE OF TIMEKEEPING

Our conception of time depends on the way we measure it

By William J. H. Andrewes

Humankind's efforts to tell time have helped drive the evolution of our technology and science throughout history. The need to gauge the divisions of the day and night led the ancient Egyptians, Greeks and Romans to create sundials, water clocks and other early chronometric tools. Western Europeans adopted these technologies, but by the 13th century, demand for a dependable timekeeping instrument led medieval artisans to invent the mechanical clock. Although this new device satisfied the requirements of monastic and urban communities, it was too inaccurate and unreliable for scientific application until the pendulum was employed to govern its operation. The precision timekeepers that were subsequently developed resolved the critical problem of finding a ship's position at sea and went on to play key roles in the industrial revolution and the advance of Western civilization.

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. Moreover, not only do time signals beamed down from Global Positioning System satellites calibrate the functions of precision navigation equipment, they do so as well for cellular telephones, instant stock-trading systems and nationwide power-distribution grids. So integral have these time-based technologies become to our day-to-day lives that we recognize our dependency on them only when they fail to work.

Reckoning Dates

ACCORDING TO archaeological evidence, the Babylonians and Egyptians began to measure time at least 5,000 years ago, introducing calen-

NATIONAL TIME MUSEUM (*top*); COURTESY OF THE TIME MUSEUM, ROCKFORD, ILL., PHOTOGRAPH BY DIRK FLETCHER (*bottom*)

CORBIS

dars 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.

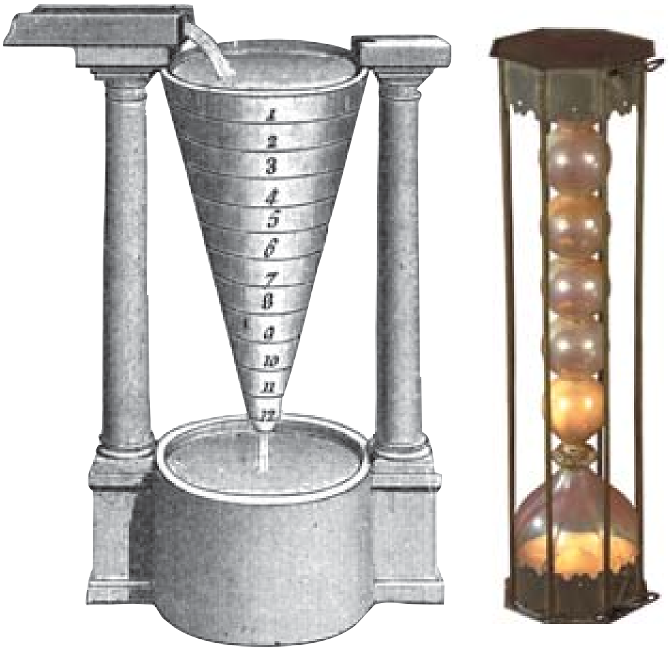
Before the invention of artificial light, the moon had greater social impact. And, for those living near the equator in particular, its waxing and waning was more conspicuous than the passing of the seasons. Hence, the calendars developed at the lower latitudes were influenced more by the lunar cycle 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 star groups (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. The cosmic significance the Egyptians placed 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, winter ones short; only at the spring and autumn equinoxes were the hours of daylight and darkness equal. Temporal hours, which were adopted by the Greeks and then the Romans (who spread them throughout Europe), remained in use for more than 2,500 years.

Inventors created sundials, which indicate time by the length or direction of the sun's shadow, to track temporal hours during the day. The sundial's nocturnal counterpart, the water clock, was designed to measure temporal hours at night. One of the first water clocks was a basin with a small hole near the bottom through which the water dripped out. The falling water level denoted the passing hour as it dipped below hour lines inscribed on the inner surface. Although these devices performed satisfactorily around the Mediterranean, they could not always be depended on in the cloudy and often freezing weather of northern Europe.

The Pulse of Time

THE EARLIEST RECORDED weight-driven mechanical clock was installed in 1283 at Dunstable Priory in Bedfordshire, England. That the Roman Catholic Church should have played a major role in the invention and development of clock



FLOWING MATERIALS have long been used to measure time. As water trickles out of an early water clock (*left*), the falling level in the basin marks off the passing hours. Sandglasses—such as this 18th-century French example (*right*), which divides the passage of an hour into 10-minute intervals—were used for gauging specific time periods.

technology is not surprising: the strict observance of prayer times by monastic orders occasioned the need for a more reliable instrument of time measurement. Further, the Church not only controlled education but also possessed the wherewithal to employ the most skillful craftsmen. Additionally, the growth of urban mercantile populations in Europe during the second half of the 13th century created demand for improved timekeeping devices. By 1300 artisans were building clocks for churches and cathedrals in France and Italy. Because the initial examples indicated the time by striking a bell (thereby alerting the surrounding community to its daily duties), the name for this new machine was adopted from the Latin word for "bell," *clocca*.

The revolutionary aspect of this new timekeeper was neither the descending weight that provided its motive force nor the gear wheels (which had been around for at least 1,300 years) that transferred the power; 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 [*for an explanation of early clockworks, see box on pages 50 and 51*]. The inventor of the clock escapement is unknown.

Uniform Hours

ALTHOUGH THE MECHANICAL CLOCK could be adjusted to maintain temporal hours, it was naturally suited to keeping equal ones. With uniform hours, however, arose the question of when to begin counting them, and so, in the early 14th century, a number of systems evolved. The schemes that divided the day into 24 equal parts varied according to the start of the count: Italian hours began at sunset, Babylonian hours at sunrise, astronomical hours 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, which split the day, as we currently do, into two 12-hour periods commencing at midnight.

During the 1580s clockmakers received commissions for timekeepers showing minutes and seconds, but their mechanisms were insufficiently accurate for these fractions to be included on dials until the 1660s, when the pendulum clock was developed. Minutes and seconds derive from the sexagesimal partitions of the degree introduced by Babylonian astronomers. The word "minute" has its origins in the Latin *prima minuta,* the first small division; "second" comes from *secunda minuta,* the second small division. The sectioning of the day into 24 hours and of hours and minutes into 60 parts became so well established in Western culture that all efforts to change this arrangement failed. The most notable attempt took place in revolutionary France in the 1790s, when the government adopted the decimal system. Although the French successfully introduced the meter, liter and other base-10 measures, the bid to break the day into 10 hours, each consisting of 100 minutes split into 100 seconds, lasted only 16 months.

Portable Clocks

FOR CENTURIES after the invention of the mechanical clock, the periodic tolling of the bell in the town church or clock tower was enough to demarcate the day for most people. But 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 accomplished portability by replacing the weight with a coiled spring. The tension of a spring, however, is greater after it is wound. The contrivance that overcame this problem, known as a fusee (from *fusus,* the Latin term for "spindle"), was invented by an unknown mechanical genius probably between 1400 and 1450 [*see illustration in box on page 50*]. 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 importance of the fusee should not be underestimated: it made possible 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.

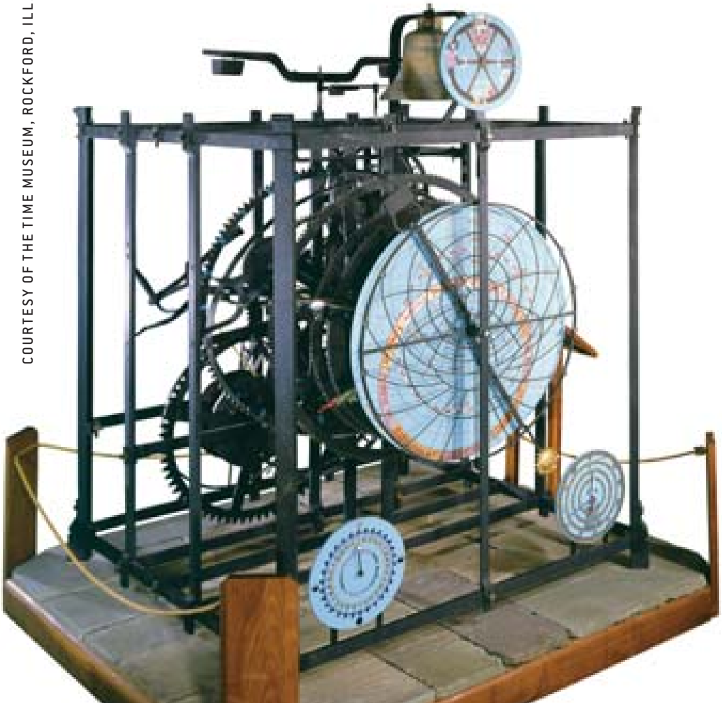
CORBIS (*left*); COURTESY OF THE TIME MUSEUM, ROCKFORD, ILL. (*right*)

Pendulums Get into the Swing

IN THE 16TH CENTURY Danish astronomer Tycho Brahe and his contemporaries tried to use clocks for scientific purposes, yet even the best ones were still too unreliable. Astronomers in particular needed a better tool for timing the transit of stars and thereby creating more accurate maps of the heavens. The pendulum proved to be the key to boosting the accuracy and dependability of timekeepers. Galileo Galilei, the Italian physicist and astronomer, and others before him experimented with pendulums, but a young Dutch astronomer and mathematician named Christiaan Huygens devised the first pendulum clock on Christmas Day in 1656. Huygens recognized the commercial as well as the scientific significance of his invention immediately, and within six months a local maker in the Hague had been granted a license to manufacture pendulum clocks.

Huygens saw that a pendulum traversing a circular arc completed small oscillations faster than large ones. Therefore, any variation in the extent of the pendulum's swing would cause the clock to gain or lose time. Realizing that maintaining a constant amplitude (amount of travel) from swing to swing was impossible, Huygens devised a pendulum suspension that caused the bob to move in a cycloid-shaped arc rather than a circular one. This enabled it to oscillate in the same time regardless of its amplitude [*see illustration in box on next page*]. 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. News of the invention spread rapidly, and by 1660 English and French artisans were developing their own versions of this new timekeeper.

SPRING-DRIVEN MECHANICAL CLOCK was constructed by Dutch clockmaker Salomon Coster in 1657. Coster collaborated with Christiaan Huygens, the Dutch scientist who first applied the pendulum to the mechanical clock.



RECONSTRUCTION is shown of the early mechanical clock designed about 1330 by Richard of Wallingford, English mathematician and abbot of St. Alban's Abbey, to simulate the motions of the heavens and provide astronomical information.

COURTESY OF THE TIME MUSEUM, ROCKFORD, ILL. (*top and bottom*)

The advent of the pendulum not only heightened demand for clocks but also resulted in their development as furniture. National styles soon began to emerge: English makers designed the case to fit around the clock movement; in contrast, the French placed greater emphasis on the shape and decoration of the case. Huygens, however, had little interest in these fashions, devoting much of his time to improving the device both for astronomical use and for solving the problem of finding longitude at sea.

Innovative Clockworks

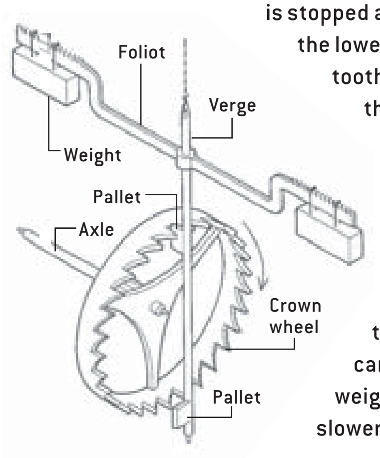
IN 1675 HUYGENS devised his next major improvement, the spiral balance spring. Just as gravity controls the swinging oscillation of a pendulum in clocks, this spring regulates the rotary oscillation of a balance wheel in portable timepieces.

THE AUTHOR

WILLIAM J. H. ANDREWES is a museum consultant and maker of precision sundials who has specialized in the history of time measurement for more than 30 years. He has worked at several scholarly institutions, including Harvard University. In addition to writing articles for popular and academic journals, Andrewes edited *The Quest for Longitude* and co-wrote *The Illustrated Longitude* with Dava Sobel. His past exhibitions include "The Art of the Timekeeper" at the Frick Collection in New York City.

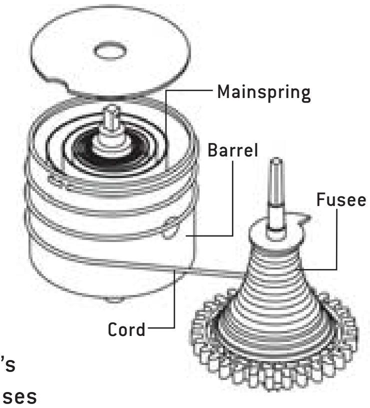
1 *Verge and Foliot Escapement*

The innovative component of the first mechanical clocks (circa 1300) was the escapement, a device that both controlled the crown wheel's rotation and transmitted the power needed to sustain the motion of the oscillator, which in turn regulated the speed at which the timekeeper operated. The sawtoothed crown, or escape, wheel is driven by a gear train powered by a weighted cord wound around the axle. The clockwise rotation of the crown wheel is obstructed by two pallets protruding from a vertical shaft, called a verge, which carries a bar known as a foliot. When the top pallet checks the crown wheel's rotation (causing a "tick"), the engaged wheel tooth gradually forces the pallet back until it is free to escape. The wheel's movement, however, is stopped almost immediately when the lower pallet arrests another tooth (causing a "tock") and then pushes the verge in the opposite direction. Driven by the crown wheel, the to-and-fro oscillation of the verge and foliot continues until the cord fully unwinds. The rate at which the mechanism operates can be adjusted by moving the weights on the foliot arms out (for slower) and in (for faster).



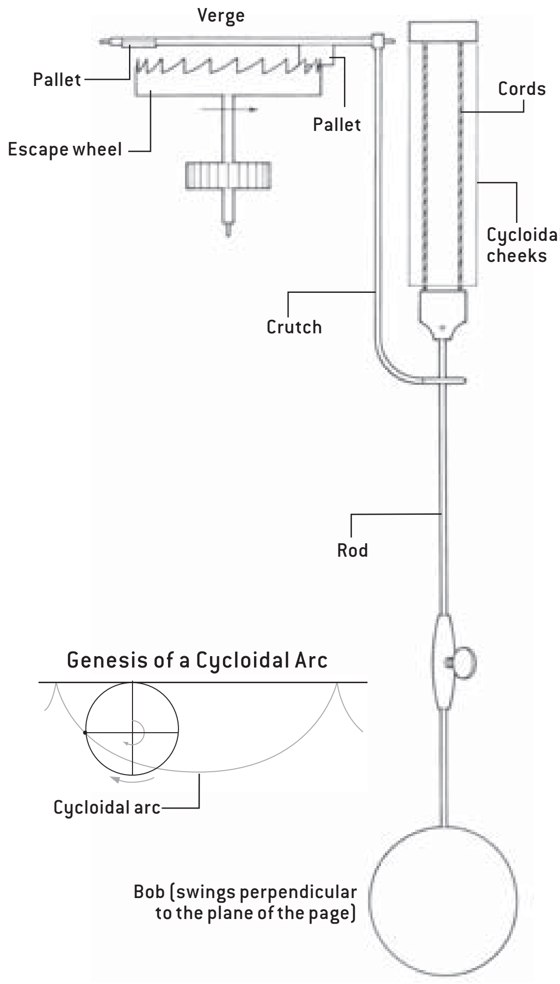
2 *Fusee*

The use of coiled springs as the motive force for timekeepers was made practical by the invention of the fusee in the early to mid-1400s. Although a spring is a compact power source, its force varies, increasing as it is wound more tightly. The fusee, a cone-shaped grooved pulley, was devised to compensate for the variable strength of a timekeeper's mainspring. The barrel, which houses the spring, is connected to the fusee by a cord or chain. When the mainspring is fully wound, the cord pulls on the narrow end of the fusee, where a short torque arm produces relatively little leverage. As the clock runs, the cord is gradually drawn back onto the barrel. To compensate for the mainspring's diminishing strength, the cord's spiral track on the fusee increases in diameter. Thus, the force delivered to the gear wheels of the timekeeper remains constant despite the changing tension of its mainspring.



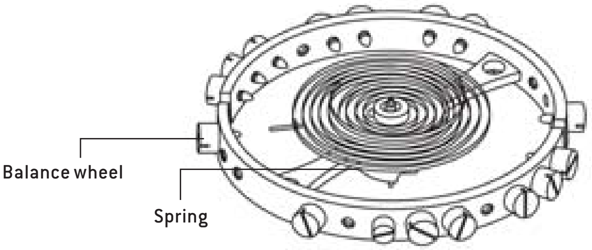
3 *Pendulum Clock*

Although Galileo Galilei and other 16th-century scientists knew about the potential of the pendulum as a timing instrument, Christiaan Huygens was the first to devise a pendulum clock. Huygens soon realized that a pendulum swinging in a small arc would perform its oscillations faster than one moving in a large arc. He overcame this problem by installing two curved "cycloidal cheeks" (*shown in side view*) at the pendulum's suspension point. Acting on the suspension cords, these curved stops reduced the effective length of the pendulum as its arc increased so that it maintained a cycloidal rather than a circular path (*below*). Thus, in theory the pendulum completed every swing in the same time period, regardless of amplitude (swing distance). In Huygens's clock, the gravity-influenced motion of the pendulum replaced the purely mechanically driven oscillation of the horizontal foliot. Now it was the pendulum's beat that regulated the action of the verge escapement and the rotation of the wheels, which in turn delivered this far more reliable and accurate time measurement to the hands of the clock dial.



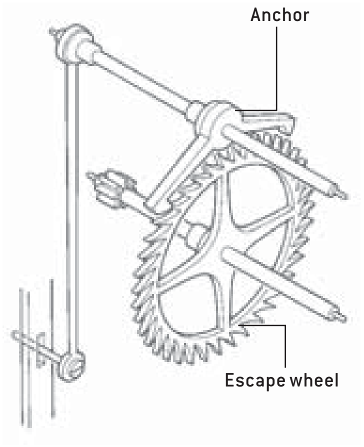
4 *Spiral Balance Spring*

In 1675 Huygens invented the spiral balance spring. Just as gravity controls the swinging oscillation of a pendulum in a clock, this spring regulates the rotary oscillation of a balance wheel in portable timepieces. A balance wheel is a rotor that spins one way and then the other, repeating the cycle over and over. Depicted here is a modern version, finely balanced with adjustable timing screws.



5 *Anchor Escapement*

Developed around 1670 in England, the anchor escapement is a lever-based device shaped like a ship's anchor. The motion of a pendulum rocks the anchor so that it catches and then releases each tooth of the escape wheel, in turn allowing the wheel to turn a precise amount in a ratchetlike movement. Unlike the verge escapement used in early pendulum clocks, the anchor escapement permitted the pendulum to travel in such a small arc that maintaining a cycloidal swing path became unnecessary. Moreover, this invention made practical the use of a long, seconds-beating pendulum and thus led to the development of a new, floor-standing case design, which became known as the longcase, or grandfather, clock.



A balance wheel is a finely balanced disk that rotates fully one way and then the other, repeating the cycle over and over [*see illustration in box at left*]. 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 rise in the market for watches, which were now no longer typically worn on a chain around the neck but were carried in a pocket, a wholly new fashion in clothing.

At about the same time, Huygens heard of an important English invention. The anchor escapement, unlike the verge escapement he had been using in his pendulum clocks, allowed the pendulum to swing in such a small arc that maintaining a cycloidal pathway became unnecessary. Moreover, this escapement made practical the use of a long, seconds-beating pendulum and thus led to the development of a new case design. The longcase clock, commonly known since 1876 as the grandfather clock (after a song by American Henry Clay Work), began to emerge as one of the most popular English styles. 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 widespread type used in precision timekeeping for the next 150 years.

ROYAL OBSERVATORY AT GREENWICH, England, installed clocks equipped with anchor escapements in 1675 to time the movements of stars more exactly than had previously been possible. Improved astronomical maps were of fundamental importance for reliable navigation at sea.

DAVID PENNEY (*drawings*); NATIONAL MARITIME MUSEUM, LONDON (*photograph*)

JOHN HARRISON'S H1 sea clock gained its place in history in 1736, when it proved its value in finding longitude on its trial voyage. This replica of the English carpenter's invention was built in 1984.

Solving the Longitude Problem

WHEN THE ROYAL OBSERVATORY at Greenwich, England, was founded in 1675, part of its charter was to find "the so-much-desired longitude of places." The first Astronomer Royal, John Flamsteed, used clocks fitted with anchor escapements to time the exact moments that stars crossed the celestial meridian, an imaginary line that connects the poles of the celestial sphere and defines the due-south point in the night sky. This allowed him to gather more accurate information on star positions than had hitherto been possible by making angular measurements with sextants or quadrants alone.

Although navigators could find their latitude (their position north or south of the equator) at sea by gauging the altitude of the sun or the polestar, the heavens did not 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 only 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 Scilly Isles. 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 (which is equivalent to about $12 million today), 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. Two approaches, however, had long been known to be theoretically sound. The first, called the lunar-distance method, involved precise observations of the moon's position in relation to the stars to determine the time at a reference point from which longitude could be measured; the other required a very accurate clock to make the same determination. Because the earth rotates every 24 hours, or 15 degrees in an hour, a two-hour time difference represents a 30-degree difference in longitude. The seemingly overwhelming obstacles to keeping accurate time at sea—among them the often violent motions of ships, extreme changes in temperature, and variations in gravity at different latitudes—led English physicist Isaac Newton and his followers to believe that the lunar-distance method, though problematic, was the only viable solution.

Newton was wrong, however. In 1737 the board finally met for the first time to discuss the work of a most unlikely candidate, a Yorkshire carpenter named John Harrison. Harrison's bulky longitude timekeeper had been used on a voyage to Lisbon and on the return trip had proved its worth by cor-

SHELF CLOCK with its revolutionary wooden movement was developed by Eli Terry, a Connecticut clockmaker working in the 19th century. Terry's ingenious mass-production techniques made possible the manufacture of affordable clocks.

COURTESY OF THE TIME MUSEUM, ROCKFORD, ILL. (*top* and *bottom*), PHOTOGRAPH BY DIRK FLETCHER (*top*)

recting the navigator's dead reckoning of the ship's longitude by 68 miles. Its maker, however, was dissatisfied. 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, laboring on it for 19 years. But 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.

Mass-Produced Timepieces

AT THE TURN of the 19th century, clocks and watches were relatively accurate, but they remained expensive. Recognizing the potential market for a low-cost timekeeper, two investors in Waterbury, Conn., 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 made it possible for 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. Unlike the longcase design, which required the buyer to purchase a case separately, Terry's shelf clock was completely self-contained. The customer needed only to place it on a level shelf and wind it up. For the relatively modest sum of $15, many average people could now afford a clock. This achievement led to the establishment of what was to become the renowned Connecticut clockmaking industry.

Before the expansion of railroads in the 19th century, towns in the U.S. and Europe used the sun to determine local time. For example, because noon occurs in Boston about three minutes before it does in Worcester, Mass., Boston's clocks were set about three minutes ahead of those in Worcester. The expanding railroad network, however, needed a uniform time standard for all the stations along the line. Astronomical observatories began to distribute the precise time 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, Mass. The Royal Observatory introduced its time service the next year, creating a single standard time for Great Britain.

The U.S. 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, D.C., the globe was divided into 24 time zones. Signatories 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.

PRECISION TIMEKEEPING started to come of age in 1889, when Siegmund Riefler of Germany designed a clock that operated in a partial vacuum to minimize the effects of barometric pressure. Riefler's regulator also featured a pendulum (*not visible*) that was largely unaffected by ambient temperature changes. Thus, the device featured an accuracy of a tenth of a second a day.

COURTESY OF THE TIME MUSEUM, ROCKFORD, ILL.

Watches for the Masses

MANY CLOCKMAKERS of this era realized that the market for watches would far exceed that for clocks if production costs could be reduced. The problem of mass-fabricating interchangeable parts for watches, however, was considerably more complicated because the precision demanded in making the necessary miniaturized components was so much greater. Although improvements in quantity manufacture had been instituted in Europe since the late 18th century, European watchmakers' fears of saturating the market and threatening their workers' jobs by abandoning traditional practices stifled most thoughts of introducing machinery for the production of interchangeable watch parts.

Disturbed that American watchmakers seemed unable to compete with their counterparts in Europe, which controlled the market in the late 1840s, a watchmaker in Maine named Aaron L. Dennison met with Edward Howard, the operator of a clock factory in Roxbury, Mass., to discuss mass-production methods for watches. Howard and his partner gave Dennison space to experiment and develop machinery for the project. By the fall of 1852, 20 watches had been completed under Dennison's supervision. His workmen finished 100 watches by the following spring, and 1,000 more were produced a year later. By that time the manufacturing facilities in Roxbury were proving too small, so the newly named Boston Watch Company moved to Waltham, Mass., where by the end of 1854 it was assembling 36 watches a week.

The American Waltham Watch Company, as it eventually became known, 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 cut prices. Meanwhile other U.S. companies formed in the hope of capturing part of the burgeoning trade. The Swiss, who had previously dominated the industry, grew concerned when their exports plummeted in the 1870s. The investigator they sent to Massachusetts discovered that not only was productivity higher at the Waltham factory but production costs were less. Even some of the lower-grade American watches could be expected to keep reasonably good time. The watch was at last a commodity accessible to the masses.

Because women had worn bracelet watches in the 19th century, wristwatches were long considered feminine accoutrements. During World War I, however, the pocket watch was modified so that it could be strapped to the wrist, where it could be viewed more readily on the battlefield. With the help of a substantial marketing campaign, the masculine fashion for wristwatches caught on after the war. Self-winding mechanical wristwatches made their appearance during the 1920s.

High-Precision Clocks

AT THE END of the 19th century, Siegmund Riefler of Munich developed a radical new design of regulator—a highly accurate timekeeper that served as a standard for controlling others. Housed in a partial vacuum to minimize the effects of barometric pressure and equipped with a pendulum largely unaffected by temperature variations, Riefler's regulators attained an accuracy of a tenth of a second a day and were thus adopted by nearly every astronomical observatory.

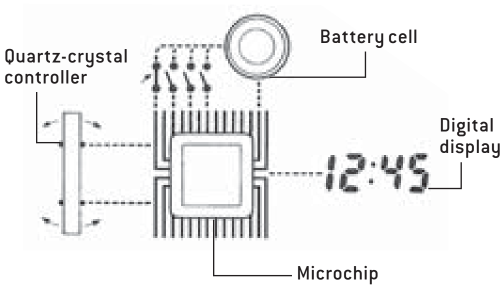
Further progress came several decades later, when English railroad engineer William H. Shortt designed a so-called free pendulum clock that reputedly kept time to within about a second a year. Shortt's system incorporated two pendulum clocks, one a "master" (housed in an evacuated tank) and the other a "slave" (which contained the time dials). Every 30 seconds the slave clock gave an electromagnetic impulse to, and was in turn regulated by, the master clock pendulum, which was thus nearly free from mechanical disturbances.

Although Shortt clocks began to displace Rieflers as ob-

TWO MODERN PRECISION TIMEKEEPERS

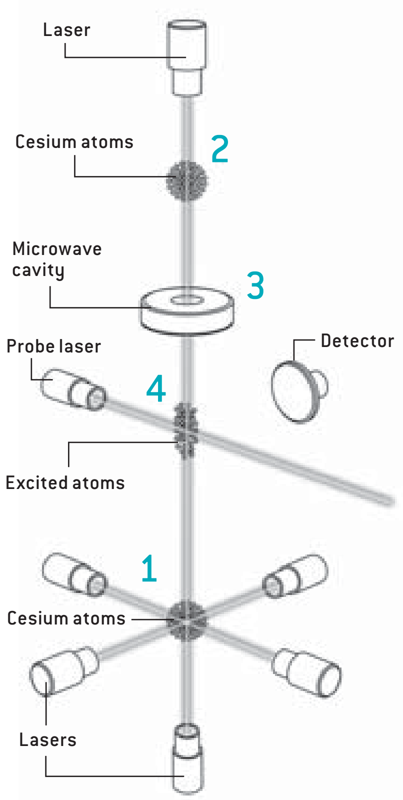
1 *Quartz Movement*

By the end of the 1960s watchmakers had taken a step away from the traditional oscillating balance wheel with the development of an electronic transistor-based oscillator comprising a tiny tuning fork whose vibrations were converted into the movement of the hands. With the simultaneous rise of cheap, low-power integrated circuits and light-emitting diodes (LEDs), the search for a more accurate timing element was on. Watchmakers soon adopted the quartz-crystal resonator from radio transmitters. Quartz crystals are piezoelectric; they vibrate when subjected to a changing electric voltage, and vice versa. When driven by a voltage at its harmonic frequency, the crystal oscillates resonantly, ringing like a bell. The output of the oscillator is then converted to pulses suitable for the watch's digital circuits, which operate an LED display or electrically actuated hands.



2 *Cesium Fountain (Atomic) Clock*

Cesium fountain clocks derive their timing reference from the frequency of an electron spin-flip transition that occurs in a cesium 133 atom when probed by tuned microwaves. In a vacuum chamber, six lasers slow the movements of gaseous cesium atoms, forming a small cloud (*1*). A change in the operating frequency of the upper and lower lasers launches the atomic cloud, fountainlike (*2*), up through a magnetically shielded microwave cavity (*3*). As gravity pulls the cloud back down through the cavity, the electrons in the atoms interact with the microwaves for a second time. The microwaves flip the spins of the electrons, changing their quantum-mechanical energy states. After the cloud falls farther, a laser probe causes the cesium to fluoresce, revealing whether its electrons have flipped their spins, a reaction that is monitored by a detector (*4*). The detector's output signal is then used to make the slight correction needed to tune the microwave emitter to a precise resonant frequency that can serve as the time beat for a clock.



DAVID PENNEY (*left*); ALAN DANIELS (*right*)

FREE PENDULUM CLOCKS were developed by William H. Shortt, an English railroad engineer, in the early 1920s. Shortt's timekeeping systems, which incorporated two pendulum clocks—a "master" (*right*) and a "slave" (*left*)—were reportedly able to keep time to within about a second a year.

COURTESY OF THE TIME MUSEUM, ROCKFORD, ILL. (*left*); NATIONAL TIME MUSEUM (*right*)

servatory regulators during the 1920s, their superiority was short-lived. In 1928 Warren A. Marrison, an engineer at Bell Laboratories in New York, discovered an extremely uniform and reliable frequency source that was as revolutionary for timekeeping as the pendulum had been 272 years earlier. Developed originally for use in radio broadcasting, the quartz crystal vibrates at a highly regular rate when excited by an electric current [*see illustration in box on opposite page*]. 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 did not remain the premier frequency standard for long either, however. By 1948 Harold Lyons and his associates at the National Bureau of Standards in Washington, D.C., 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 [*see illustration in box on opposite page*]. Subsequent experiments in both the U.S. 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.

Up to the mid-20th century, the sidereal day, the period of the earth's rotation on its axis in relation to the stars, was used to determine standard time. This practice had been retained even though it had been suspected since the late 18th century that our planet's axial rotation was not entirely constant. The rise of cesium clocks capable of measuring discrepancies in the earth's spin, however, meant that a change was necessary. A new definition of the second, based on the resonant frequency of the cesium atom, was adopted as the new standard unit of time in 1967.

The precise measurement of time is of such fundamental importance to science that the search for even greater accuracy continues. Current and coming generations of atomic clocks, such as the hydrogen maser (a frequency oscillator), the cesium fountain and, in particular, the optical clock (both frequency discriminators), are expected to deliver an accuracy (more precisely, a stability) of 100 femtoseconds (100 quadrillionths of a second) over a day [see "Ultimate Clocks," by W. Wayt Gibbs, on page 56].

Although our ability to measure time will surely improve in the future, nothing will change the fact that it is the one thing of which we will never have enough. SA

MORE TO EXPLORE

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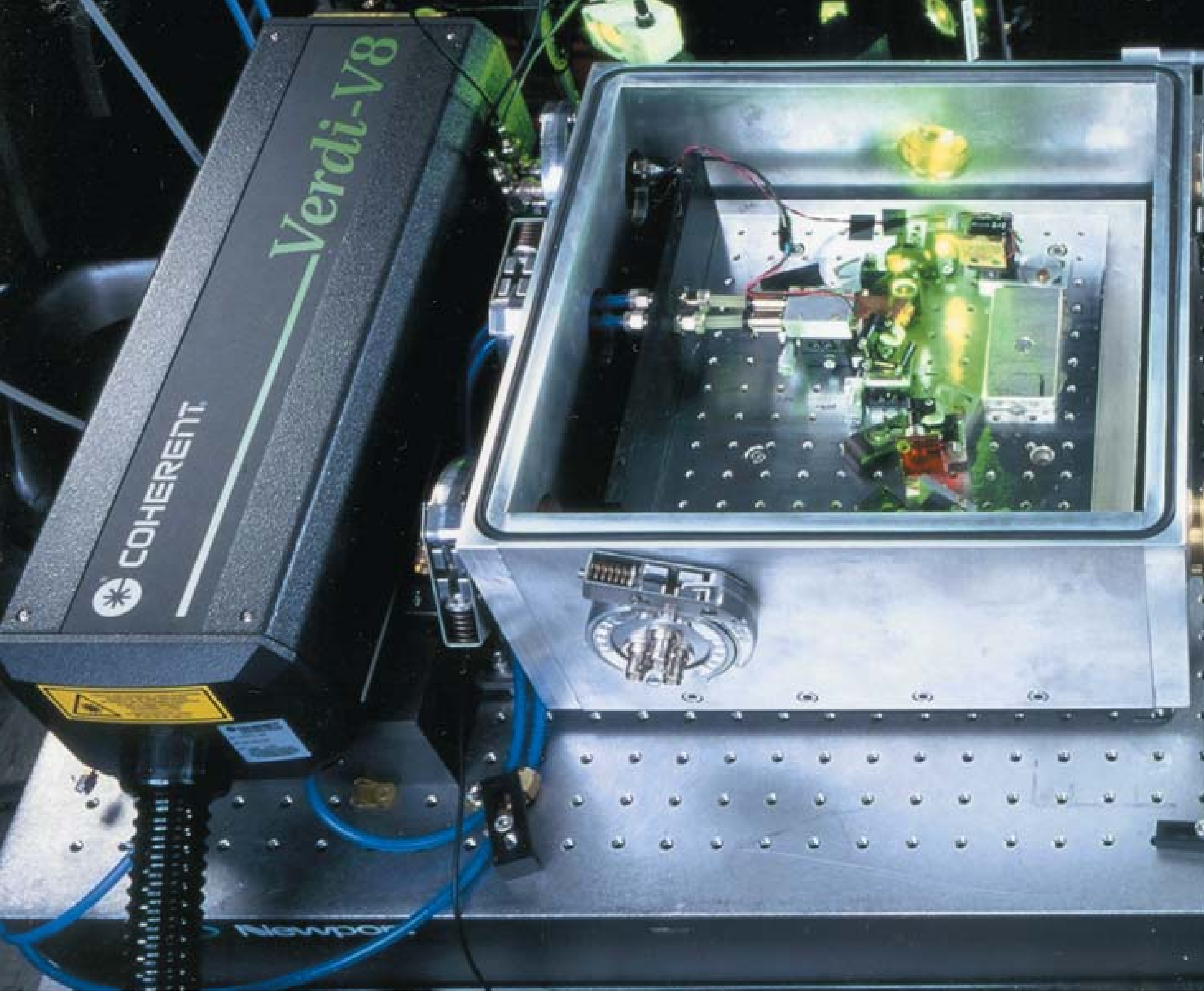


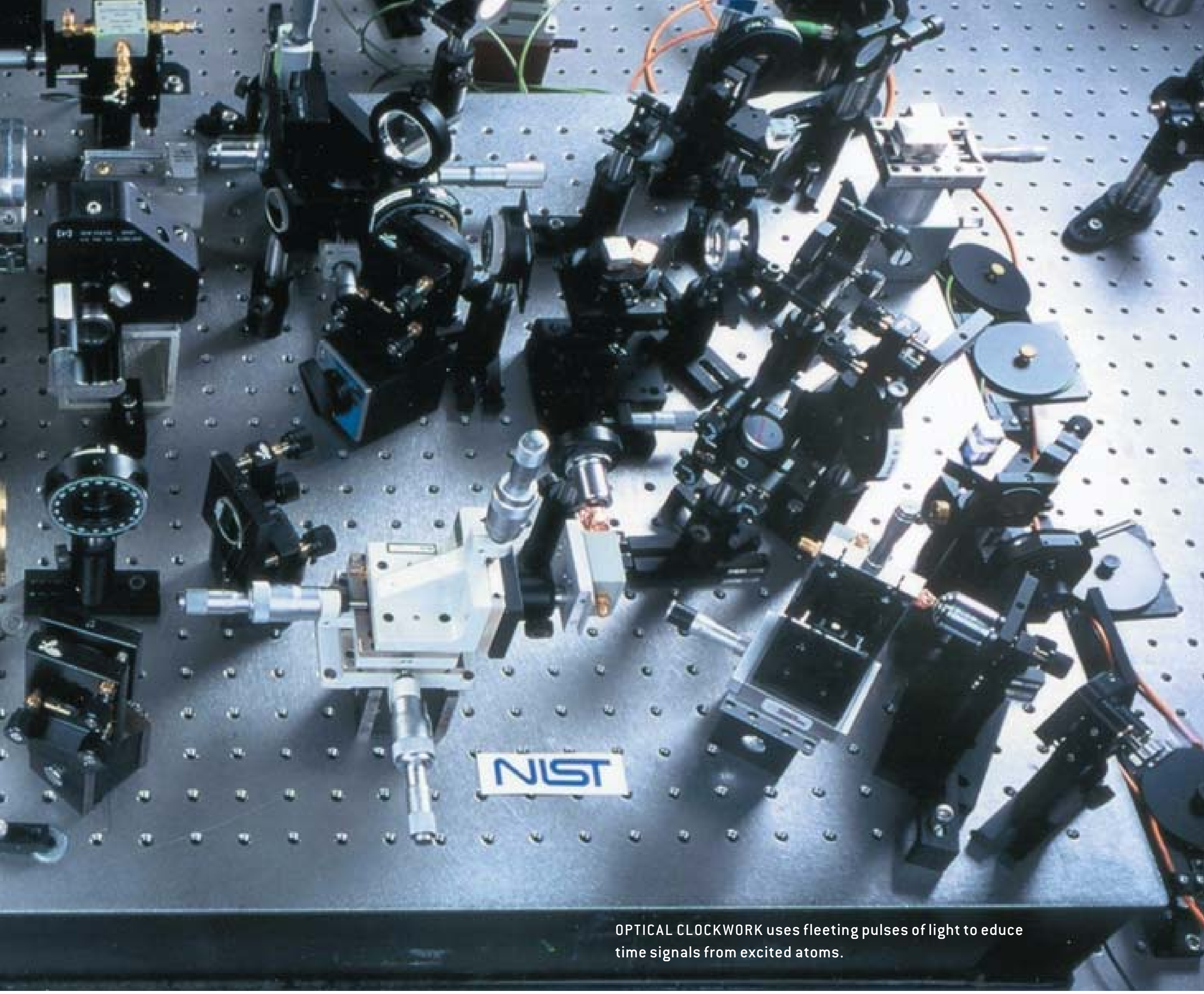
OVERVIEW

- A renaissance under way in atomic clock building is expected to improve the precision of timekeeping by 1,000-fold.
- In theory, one can measure time with infinite accuracy. But gravity and motion distort time, imposing a practical limit to clocks' precision.
- Atomic clocks are short-lived. Engineers are also designing a mechanical clock that could operate through the year 12000.

ULTIMATE CLOCKS

Atomic clocks are shrinking to microchip size, heading for space—and approaching the limits of useful precision

By W. Wayt Gibbs



OPTICAL CLOCKWORK uses fleeting pulses of light to educe time signals from excited atoms.

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

Dozens of the top clockmakers in the world convened in New Orleans one muggy week in May 2002 to present their latest inventions. There was not a mechanic among them; these were scientists, and their conversations buzzed with talk of spectrums and quantum levels, not gears and escapements. Today those who would build a more accurate clock must advance into the frontiers of physics and engineering in several directions at once. They are cobbling lasers that spit out pulses a quadrillionth of a second long together with chambers that chill atoms to a few millionths of a degree above absolute zero. They are snaring individual ions in tar pits of light and magnetism and manipulating the spin of electrons in their orbits.

And thanks to major technical advances, the art of ultraprecise timekeeping is progressing with a speed not seen for 30 years or more. These days a good cesium beam clock, of the kind Symmetricon sells for $49,000, 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 U.S., a cesium fountain clock installed in 1999 by the National Institute of Standards and Technology (NIST) at its Boulder, Colo., laboratory, is good to five parts in 10^{16} (usually written simply as 10^{-16}). That is 1,000 times the accuracy of NIST's best clock in 1975. But space-based clocks set to fly on the International Space Station by 2008 are expected to tick with uncertainties on the order of 10^{-17}. And successful prototypes of new clock designs—devices that extract time from calcium atoms or mercury ions instead of cesium—lead physicists to expect that accuracy will soon reach the 10^{-18} range, a 1,000-fold improvement in less than a decade.

Accuracy may not be quite the right word. 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." Leave aside for the moment what that means: the point is that to measure a second, you have to look at cesium. Very soon now the best clocks won't—so, strictly speaking, they won't be measuring seconds. That is one predicament the clockmakers face.

Further down the road lies a more fundamental limitation: as Albert Einstein theorized and experiment has confirmed, time is not absolute. The rate of any clock slows down when gravity gets stronger or when the clock moves quickly relative to its observer—even a single photon emitted as an electron reorients its magnetic poles or jumps from one orbit to another. By putting ultraprecise clocks on the space station, scientists hope to put relativity theory through its toughest tests yet. But once clocks reach a precision of 10^{-18}—proportions that correspond to a deviation of less than half a second over the age of the universe—the effects of relativity will test the scientists. No technology exists that can synchronize clocks around the world with such exactness.

Inventing Accuracy

SO WHY BOTHER to improve atomic clocks? The duration of the second can already be measured to 14 decimal places, a precision 1,000 times that of any other fundamental unit. One reason to do better is that the second is increasingly *the* fundamental unit. Three of the six other basic units—the meter, lumen and ampere—are now defined in terms of the second. The kilogram and the mole may be next. "It is just a matter of time before [the kilogram] is redefined," says Richard L. Steiner of NIST. Using the famous $E = mc^2$ equation, scientists could set the unit of mass to an equivalent amount of energy, such as a collection of photons whose frequencies sum to a certain number. By improving clocks, scientists can improve measurements of much more than time.

PORTABLE PRECISION

Atomic Micro Clocks

"FOR LESS THAN $100, I could build a 10-watt jammer, drop it in New York, and block all GPS signals in the city," says Donald Sullivan of NIST. Navigation of all kinds depends on the Global Positioning System; smaller atomic clocks could make it more reliable. Shrunk to microchip size, they could be put into GPS receivers. The extra precision would allow the system to work on a much smaller frequency range, frustrating would-be jammers.

"DARPA [the Defense Advanced Research Projects Agency] has a $20-million program to develop an atomic clock on a chip for encrypted communications and GPS receivers," Sullivan reports. NIST scientists built a prototype in 2005 that is the size of a grain of rice and accurate to five parts in 10^{11} (*below*). If atomic wristwatches ever arrive, they won't be for telling time to the nearest nanosecond—but they might help keep our wristphone conversations private. *—W.W.G.*

NIST

More stable and portable clock designs could also be a big boon to navigation, enhancing the accuracy and reliability of the Global Positioning System and of Galileo, a competing system under development in Europe. Better clocks would help NASA track its satellites, enable utilities and communications firms to trace faults in their networks, and enhance geologists' ability to pinpoint earthquakes and nuclear bomb tests. Astronomers could use them to connect telescopes in ways that dramatically sharpen their images. And inexpensive, microchip-size atomic clocks [*see box below*] are likely to have myriad uses not yet imagined.

To understand why timekeeping has suddenly lurched into high gear, it helps to know a little about how atomic clocks work. In principle, an atomic clock is just like any other timepiece, with an oscillator that "ticks" in a regular way and a counter that converts the ticks to seconds. The ticker in a cesium clock is not mechanical (like a pendulum) or electromechanical (like a quartz crystal). It is quantum-mechanical: a photon of light is absorbed by the cesium atom's outermost electron, causing the electron to flip its magnetic field (and its associated spin) upside down.

Unlike pendulums and crystals, all cesium atoms are identical. And every one will flip its spin 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 sweet spot in the spectrum where the most cesium atoms react. Then it starts counting cycles.

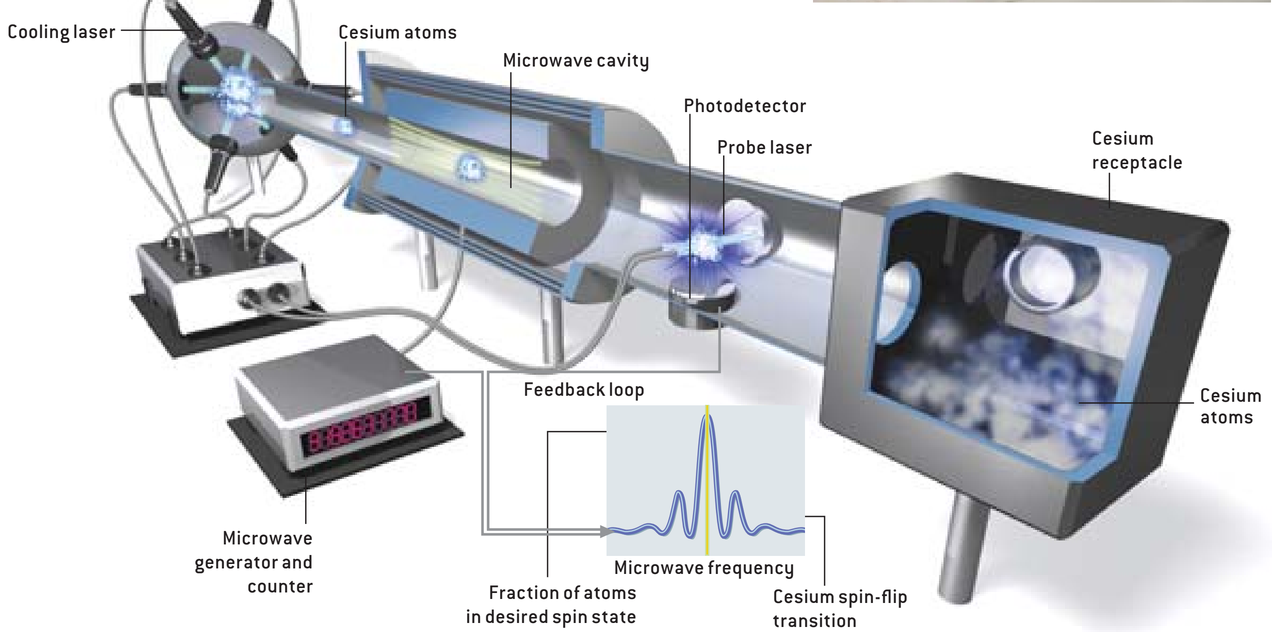
Of course, nothing in quantum physics is really that simple. Complicating things, as usual, is the Heisenberg indeterminacy principle, which puts strict limits on how precisely one can measure the frequency of a single photon. The best clocks now scan a one-hertz-wide sweet spot to find its exact center, 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," Kurt Gibble, a physicist at Pennsylvania State University, explained in New Orleans. "Because it isn't really just one measurement, it doesn't violate the laws of quantum mechanics."

But that solution creates other problems. At room temperature, cesium is a soft, silvery metal. It would melt in your palm to a golden puddle—although you wouldn't want to touch it, because 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. To other atoms, the microwaves appear (because of Doppler shifting) to be higher or lower in frequency than they are.

HOW TIME WILL FLY

The Final Frontier?

PHARAO ATOMIC CLOCK, built by the French National Space Studies Center and other laboratories as part of a mission called ACES, has been tested on zero-gravity airplane flights (*right*). It is scheduled to fly on the International Space Station in 2009. Like PARCS, a similar instrument under development in American laboratories, Pharao aims to keep time more accurately than any clock on earth. Cesium atoms, supercooled into gaseous balls by lasers, are launched through a microwave cavity, which alters the spin of their electrons. A probe laser zaps the atoms again to reveal how many were put into the desired state. A feedback loop adjusts the microwave frequency until it locks on to the natural resonance of the cesium atom "spin-flip" transition, which steadies the clock's "ticker." Electronics can then count 9,192,631,770 microwave cycles—exactly one second, by international consensus. —*W.W.G.*



BRYAN CHRISTIE DESIGN; JEAN-LUC AURIOL *CNES* (*photograph*)

The atoms no longer behave identically, so the ticks grow less distinct.

Herr Doktor Heisenberg would probably have suggested slowing the atoms down, and that's what clockmakers have done. The four or five best clocks in the world—at NIST, the U.S. Naval Observatory in Washington, D.C., and the standards institutes in Paris and in Braunschweig, Germany—all toss supercooled balls of cesium atoms in a fountainlike arc through a microwave chamber [*see illustration in "A Chronicle of Timekeeping," on page 46*]. To condense the hot cesium gas into a ball, six intersecting laser beams decelerate the atoms to less than two microkelvins—almost a complete 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. Fountain clocks, introduced in 1996, rapidly knocked 90 percent off the uncertainty of international atomic time.

Time in Space

IT TAKES TIME to make a good second, and the fountain clocks still rush the job. "We would have to quadruple the height of the tower to double the observation time," says Donald Sullivan, chief of the time and frequency division at NIST. Instead of punching a hole through the ceiling of his lab, Sullivan is leading one of three projects to put fountainlike clocks on the International Space Station. "In space, we can launch a ball of atoms at 15 centimeters per second through a 74-centimeter cavity. So we have five to 10 seconds to observe them," he explains. The $25-million Primary Atomic Reference Clock in Space (PARCS) project on which he works should turn out seconds good to five parts in 10^{17}.

If PARCS is launched by 2009 as expected, it may be joined on the space station by a device from the European Space Agency called ACES (Atomic Clock Ensemble in Space). Both clocks aim to measure with 99.99997 percent

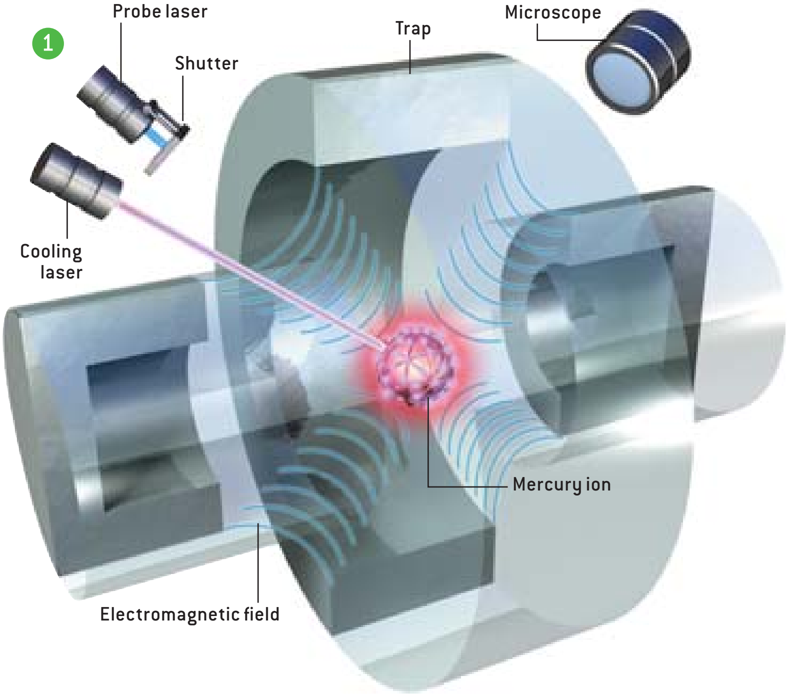
HOW AN ADVANCED ATOMIC CLOCK WORKS

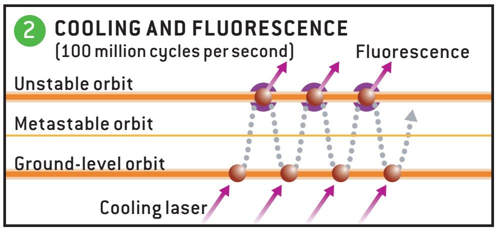
Extracting Time from an Atom

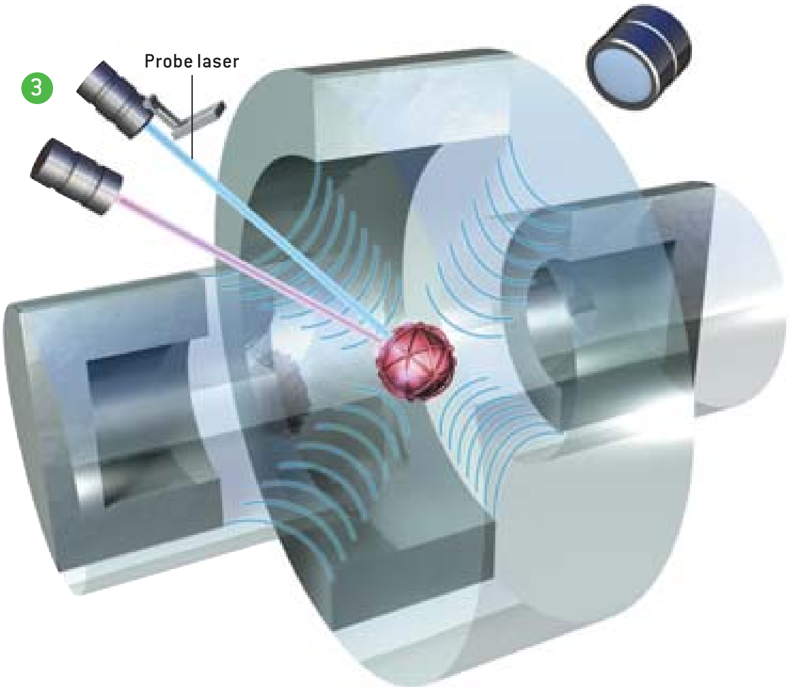
EVERY CLOCK has at least two basic components, an oscillator and a counter. An atomic clock is so accurate because it includes a third element: a feedback system that periodically checks an atomic reference to keep the oscillator ticking with nearly perfect regularity. In a state-of-the-art optical ion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

Trapped and Zapped

The atom, boiled off a piece of mercury in an oven, is ionized when a current strips away one of its electrons, leaving it with a positive charge. An electromagnetic field then confines the ion to the center of a ring-shaped trap (*1*). The beam of a so-called cooling laser (*purple*) causes the ion's outermost electron to jump millions of times a second to a higher, unstable orbit, fluorescing each time it falls back to the ground level (*2*). The fluorescence has two functions: it cools the atom to nearly absolute zero, and it allows scientists to verify (through a microscope) that the clock is still running. Once the atom is cool, stable and glowing, it is ready to serve as the clock's reference.

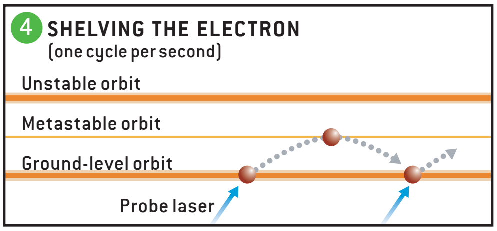



② COOLING AND FLUORESCENCE
(100 million cycles per second)



Probed and Shelved

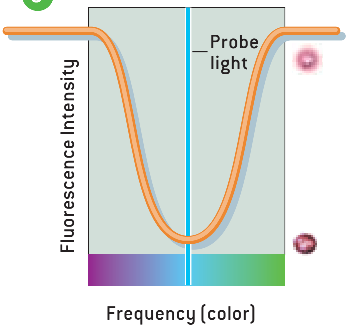
The closest thing to a "ticker" in an ion clock is the probe laser (*blue*). The color of the photons streaming from the laser reflects the frequency of their oscillation. To check that their frequency has not slowed or quickened, the laser periodically shines on the mercury atom (*3*). Scientists tune the color of the probe light to the precise frequency that knocks the ion's outer electron into a metastable orbit, thus "shelving" the electron for up to half a second (*4*). When the laser is tuned to this special frequency, the electron stops fluorescing, and the ion goes dark. If the laser oscillator drifts, the ion blinks back on.


④ SHELVING THE ELECTRON
(one cycle per second)

Matched and Metered

A feedback system adjusts the laser color until the fluorescence is at a minimum (5). The probe light, now rock steady, is next passed via optical fiber to a counter. The probe light oscillates about a quadrillion times a second, far too fast to count directly. A third laser acts like a reducing gear to translate the time signal from a quadrillion cycles a second to about a billion cycles a second. This third laser emits infrared pulses just a few femtoseconds long, with stretches of darkness between them (6).

5



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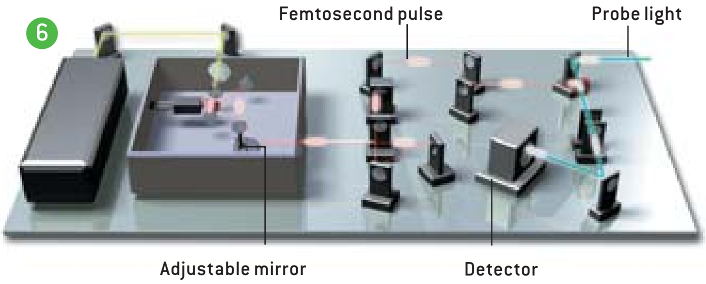
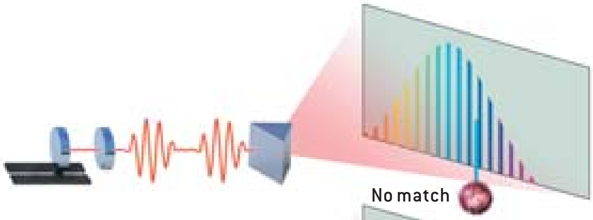


The trick is to lock its pulse rate in perfect synchronicity with the frequency of the probe light. To do this, the clockwork exploits a curious fact: when passed through a prism, each ultrashort pulse splits into a rainbow of colors spaced at regular frequency intervals, like the teeth on a gear (7 and 8). By moving an adjustable mirror, scientists alter the delay between pulses, thereby stretching or compressing the range of frequencies carried by each pulse. This allows them to position the "gear" so that one of its teeth matches the color (and thus the frequency) of the probe light—which means that it is also locked to the hardwired behavior of the mercury ion. An electronic detector then counts the synchronized pulses as they go by, a billion a second, ticking off the passage of time.

7



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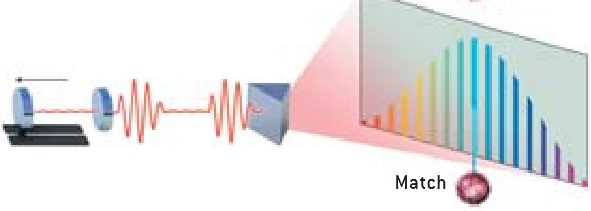


BRYAN CHRISTIE DESIGN

accuracy how much the microgravity of low earth orbit slows time compared with measurements made on the ground.

A third clock, called RACE (Rubidium Atomic Clock Experiment), is scheduled to follow. As its name suggests, RACE will replace the cesium so familiar to clockmakers with a different alkali element. "In the best cesium fountains the largest source of error are so-called cold collisions," explained Gibble, who directs 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, so they collide much more often. At a microkelvin, cesium has nearly the maximum possible cross section," he continued. "But the effective size for rubidium atoms is 50 times smaller." That should enable RACE to reach 10^{-17}, one fifth the uncertainty of PARCS and ACES.

Rubidium clocks offer another advantage: the opportunity to look for fluctuations in the fine-structure constant, alpha. Alpha determines the strength of electromagnetic interactions in atoms and molecules. It is very nearly $^1/_{137}$, a unitless number that falls out of the Standard Model of physics, with no apparent reason for the value it has. Yet it is an important number—change alpha very much, and the universe could not support life as we know it.

In the Standard Model, the fine-structure constant is immutable throughout eternity. But in some competing theories (such as certain string theories), alpha could waver slightly or grow as time goes by. In August 2001 a group of astronomers reported preliminary evidence that alpha may have increased by one part in 10,000 during the past six billion years. But the evidence is equivocal, and the question is a hard one to settle. By comparing rubidium clocks to those based on cesium and other elements, scientists may be able to lower the limit on possible alpha fluctuations by a factor of 20.

Lasers Rule

ASIDE FROM ITS REPLACEMENT of cesium with rubidium, RACE will be a fairly standard fountain clock, with lasers cooling the atoms but microwaves kicking the electrons around and ticking off the time. That is a proven and reliable design. But it will soon be obsolete.

In August 2001 Scott A. Diddams and his colleagues at NIST reported a short trial run of something many clock builders had thought they might never live to see: 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—no need to fuss with subtleties like spin. But although the ticker still works at terahertz frequencies, the counter breaks.

"Nobody knows how to count 10^{16} cycles per second," observes Eric A. Burt of the Jet Propulsion Laboratory in Pasadena, Calif. "We needed a bridge to the microwave regime, where we do have electronic counters."

Enter the optical ruler. In 1999 Thomas Udem, Theodor

COUNTING THE MILLENNIA

A Clock for All Time

SAN RAFAEL, CALIF.—A NASA Web site boasts that an atomic chronometer it has commissioned for the space station "will be the most accurate clock ever built, keeping time to within one second in 300 million years." Atomic horologists often speak as if their timepieces could run continuously for thousands of centuries. Balderdash—a typical cesium clock lasts no more than 20 years. A decent wristwatch runs longer.

But in a small machine shop here, just north of San Francisco, a small group of futurists and engineers is refining the design of a mechanical clock meant to tick through 1,000 decades. The Clock of the Long Now, as its chief designer, Danny Hillis, calls it, is as much a sociological experiment as a functional chronometer.

"A clock is a symbol of continuity; one that lasts a really long time might give people a sense of perspective, help them think about the year 3000 as more than just an abstraction," Hillis says. "Our record of civilization extends back roughly 10,000 years, so that struck me as a good interval to look forward."

Hillis may seem like an unlikely leader of a movement to reverse society's preoccupation with the fast and soon. In the 1980s he designed supercomputers; in the 1990s, theme park rides. Today he can spare an hour for an interview only if half of it is done on the trip to Silicon Valley for his next meeting.

Nevertheless, Hillis, with help from writer Stewart Brand, musician Brian Eno and others, is trying to craft an artifact that will not just endure but will also inspire. The clock will have to be wound once a year. "And when you first come up to it, it will only display what time it was when the last person was there," Hillis explains. "It will track the current time, but you will have to wind it—put some energy into it—to get it to advance to show what time it is now."

Brand and Hillis co-chair a foundation (longnow.org) that purchased a Nevada mountain peak, inside which they hope the final, monument-size clock will sit. Through a slit in the cavern ceiling, rays of the noon sun will focus onto a bimetallic strip, triggering a weight to resynchronize the clock in case its time has drifted.

Although this all may sound quite spiritual, "we don't want to create a religion," Brand avers as he stands next to a mock-up of the second prototype. This version is twice the size of the first, on exhibit at the Science Museum in London. In place of a circular dial, however, the clock is now crowned with a large orrery indicating planetary positions.

Below the "face" sits a stack of seven metal rings, each about 75 centimeters in diameter and fringed with levers. Vertical pins stuck into the rings engage the levers as the rings rotate, working as a mechanical binary computer to count the hours and compute the date. Because the clockwork is strictly mechanical and is open to inspection, "you can figure out how to restart it if it hasn't been on in 100-odd years," Hillis says. But whether his idea gathers enough currency to get a 10,000-year clock started in the first place, only time will tell. *—W.W.G.*

10,000-YEAR CLOCK under development by the Long Now Foundation will be strictly mechanical. Like the first prototype of the clock (*top*), the final, monument-size version will probably use a torsional pendulum to count minutes but will display only the current year, century and millennium (*bottom*).

JACOB APPELBAUM

PRIMARY CLOCK for the U.S. is the NIST-F1 cesium fountain in Boulder, Colo. It is one of 200-odd clocks whose times are averaged to produce Coordinated Universal Time (UTC).

NIST

W. Hänsch and others 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 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 pulse that laser and you get 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—like tick marks on a ruler. “That you could make a laser that pulses a billion times a second and whose constituent frequencies are all stable to one hertz is just short of unbelievable,” Gibble said, shaking his head.

Diddams’s group at NIST has built a rudimentary optical clockwork around mercury ions, which they immobilize in an electromagnetic trap [*see box on pages 60 and 61*]. Because each atom is missing an electron, the ions carry a positive charge. They repel one another, so collisions are no longer a problem. Though still too fragile to run constantly, the device is stable to better than six parts in 10^{16} over the course of a second. Over longer periods the uncertainty could approach 10^{-18}. “Mercury is not an ideal element to use,” Sullivan acknowledges. “The clock transition we use in it can shift with magnetic fields, which are hard to eliminate completely. But there is a transition in indium that looks attractive.”

Udem and Hänsch are one step ahead of him. They have been investigating the indium ion, and indeed it seems quite capable of carrying clocks down “into the eighteens,” as Gibble put it. Groups at the Federal Institute of Physics and Metrology in Braunschweig and elsewhere are experimenting with uncharged calcium atoms. Because neutral atoms can be crammed more densely into the trap than can ions, the signal soars higher over the noise. “It’s still an open question whether a clock with just 50 ions will do better than one with 100 million neutral atoms,” Gibble mused.

Inconstant Time

ONE WAY OR ANOTHER, however, “it seems clear that we will soon have clocks that go into the seventeens in accuracy,” Gibble said. But there’s that word again: accuracy. “Optical 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. Sullivan says the time committee of the International Bureau of Weights and Measures (BIPM), which decides such things, recently accepted his proposal to allow “secondary” definitions that state the equivalence of a cesium frequency to that of other atoms. If the full BIPM assembly approves the idea, the definition of the second will be broadened but also weakened.

Clock builders will not get around relativity so easily. Clocks accurate to one part in 10^{17}—a millisecond in three million years—will be easily thrown out of whack by two relativistic effects. First there is time dilation: moving clocks run slow. “A frequency shift of 10^{-17} corresponds to a time dilation due to walking speed,” Gibble said.

The other confounder is gravity. The stronger its pull, the slower time passes. Clocks at the top of Mount Everest pull ahead of those at sea level by about 30 microseconds a year. “We already have to correct for this effect when we compare clocks on different floors of our building,” Sullivan says. Raising a clock 10 centimeters will change its rate by one part in 10^{17}. And elevation is relatively easy to measure, compared with variations in gravity caused by local geology, the tides or even magma shifting miles underground.

Ultimately, Gibble said, “if you take our ability to split spectral lines with microwave clocks and extrapolate to optical rulers, that puts you at uncertainties of order 10^{-22}. I certainly would not claim that we are going to get there anytime soon, however.” And there is no particular rush: no one has the first idea how to transfer time that precisely between two clocks. And what good is a clock if you can’t move it and can’t check it against another?

W. Wayt Gibbs is senior writer at Scientific American.

MORE TO EXPLORE

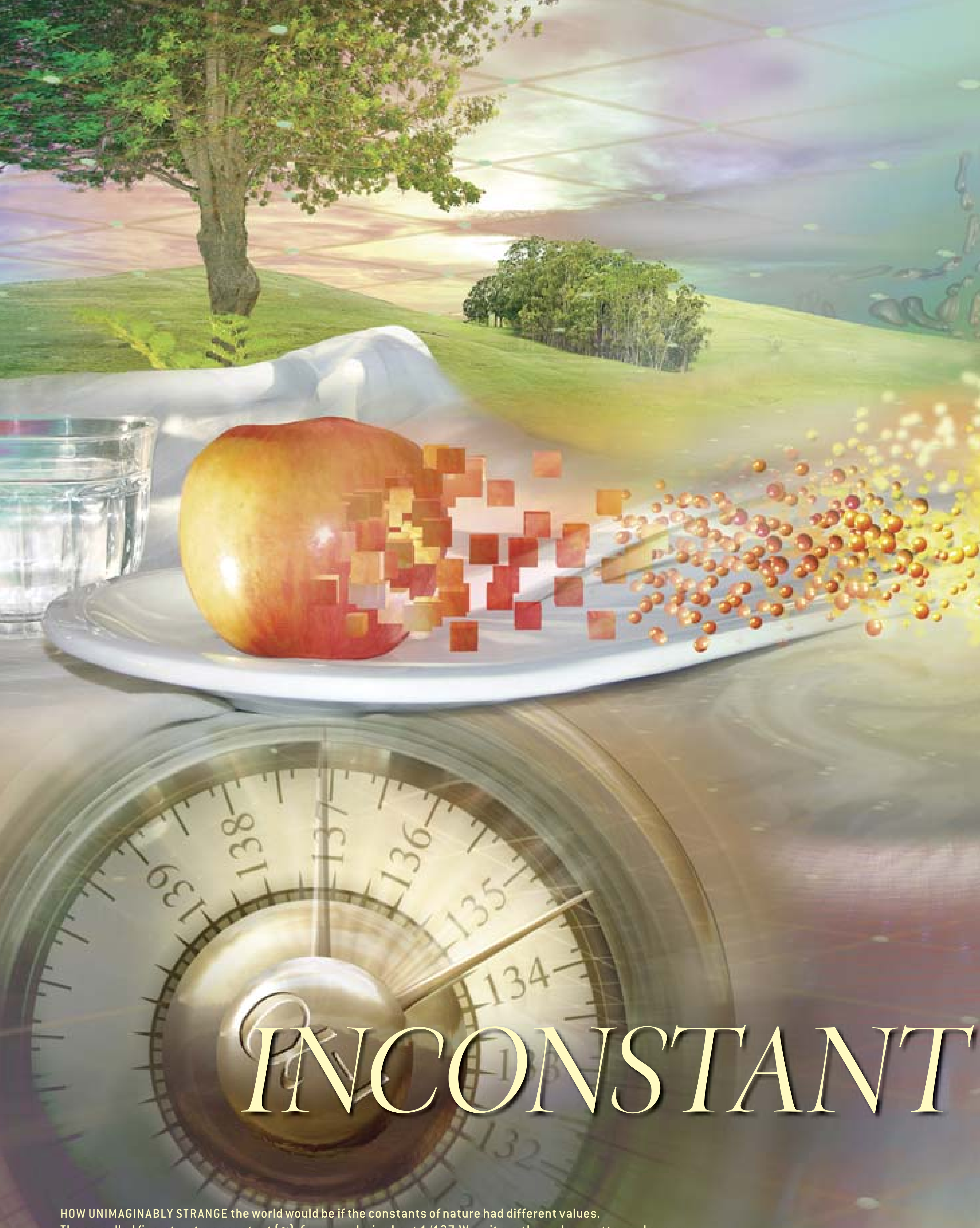
Ultrashort-Pulse Lasers. John-Mark Hopkins and Wilson Sibbett in *Scientific American,* Vol. 283, No. 3, pages 72–79; September 2000.

Splitting the Second: The Story of Atomic Time. Tony Jones. Institute of Physics Publishing, 2000.

An Optical Clock Based on a Single Trapped ^{199}Hg+ Ion. Scott A. Diddams et al. in *Science,* Vol. 293, pages 825–828; August 3, 2001.

NIST Time and Frequency Division: **tf.nist.gov**

The measurement of time: **www.npl.co.uk/npl/ctm/time_measure.html**



INCONSTANT

HOW UNIMAGINABLY STRANGE the world would be if the constants of nature had different values. The so-called fine-structure constant (α), for example, is about 1/137. Were it another value, matter and energy would interact in bizarre ways; indeed, the very distinction between matter and energy could melt away.

CONSTANTS

Do the inner workings of nature change with time?

By John D. Barrow and John K. Webb

Some things never change. Physicists call them the constants of nature. 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 scaffolding around which the theories of physics are erected, and they define the fabric of our universe. Physics has progressed by making ever more accurate measurements of their values.

And yet, remarkably, no one has ever successfully predicted or explained any of the constants. Physicists have no idea why constants take the special numerical values that they do (given the choice of units). In SI units, c is 299,792,458; G is 6.673×10^{-11}; and m_e is $9.10938188 \times 10^{-31}$—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 not be possible. 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 that such a theory would show that each of the constants of nature could have only one logically possible value. It would reveal an underlying order to the seeming arbitrariness of nature.

In recent years, however, the status of the constants has grown more muddled, 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 live 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 be the result of mere 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 [see "The String Theory Landscape," by Raphael Bousso and Joseph Polchinski; SCIENTIFIC AMERICAN, September 2004]. So far researchers have no idea why our combination was selected. Continued study may reduce the number of logically possible worlds to 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—and that different parts of the multiverse exhibit different solutions to the theory, our observed laws of nature being merely one edition of many systems of local bylaws [see "Parallel Universes," by Max Tegmark; SCIENTIFIC AMERICAN, May 2003].

No further explanation would then be possible for many of our numerical constants other than that they constitute a rare combination that permits consciousness to evolve. Our observable universe could be one of many isolated oases surrounded by an infinity of lifeless space—a surreal place where different forces of nature hold sway and particles such as electrons or structures such as carbon atoms and DNA molecules could be impossibilities. If you tried to venture into that outside world, you would cease to be.

OVERVIEW

- The equations of physics are filled with quantities such as the speed of light. Physicists routinely assume that these quantities are constant: they have the same values everywhere in space and time.
- Over the past seven years, the authors and their collaborators have called that assumption into question. By comparing quasar observations with laboratory reference measurements, they have argued that chemical elements in the distant past absorbed light differently than the same elements do today. The difference can be explained by a change in one of the constants, known as the fine-structure constant, of a few parts per million.
- Small though it might seem, this change, if confirmed, would be revolutionary. It would mean that the observed constants are not universal and could be a sign that space has extra dimensions.

Thus, string theory gives with the right hand and takes with the left. It was devised in part to explain the seemingly arbitrary values of the physical constants, and the basic equations of the theory contain few arbitrary parameters. Yet so far string theory offers no explanation for the observed values of the constants.

A Ruler You Can Trust

INDEED, THE WORD "constant" 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. And if we looked far enough out in space, we might begin to see regions where the "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 you are using to measure them is getting longer, too, you would never be able to tell. Experimenters routinely assume that their reference standards—rulers, masses, clocks—are fixed, but they cannot do so when testing the constants. They must focus on constants that have no units—they are pure numbers—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.

One ratio of particular interest combines the velocity of light, *c*, the electric charge on a single electron, *e*, Planck's constant, *h*, and the so-called vacuum permittivity, ε_0. This famous quantity, $\alpha = e^2/2\varepsilon_0 hc$, called the fine-structure constant, was first introduced in 1916 by Arnold Sommerfeld, a pioneer in applying the theory of quantum mechanics to electromagnetism. It quantifies the relativistic (*c*) and quantum (*h*) qualities of electromagnetic (*e*) interactions involving charged particles in empty space (ε_0). Measured to be equal to 1/137.03599976, or approximately 1/137, α has endowed the number 137 with a legendary status among physicists (it usually opens the combination locks on their briefcases).

If α had a different value, all sorts of vital features of the world around us would change. If the value were lower, the density of solid atomic matter would fall (in proportion to α^3), molecular bonds would break at lower temperatures (α^2), and the number of stable elements in the periodic table could increase ($1/\alpha$). If α were too big, small atomic nuclei could not exist, because the electrical repulsion of their protons would overwhelm the strong nuclear force binding them together. A value as big as 0.1 would blow apart carbon.

The nuclear reactions in stars are especially sensitive to α. For fusion to occur, a star's gravity must produce temperatures high enough to force nuclei together despite their tendency to repel one another. If α exceeded 0.1, fusion would be impossible (unless other parameters, such as the electron-to-proton mass ratio, were adjusted to compensate). A shift of just 4 percent in α would alter the energy levels in the nucleus of carbon to such an extent that the production of this element by stars would shut down.

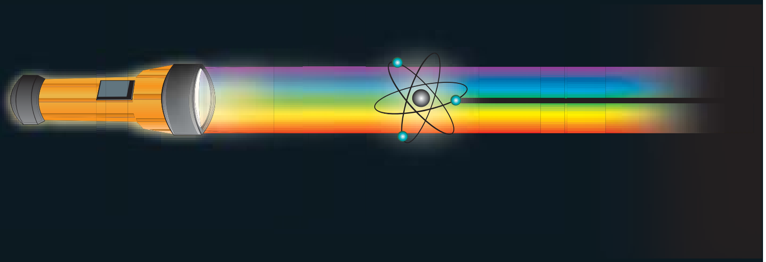
Nuclear Proliferation

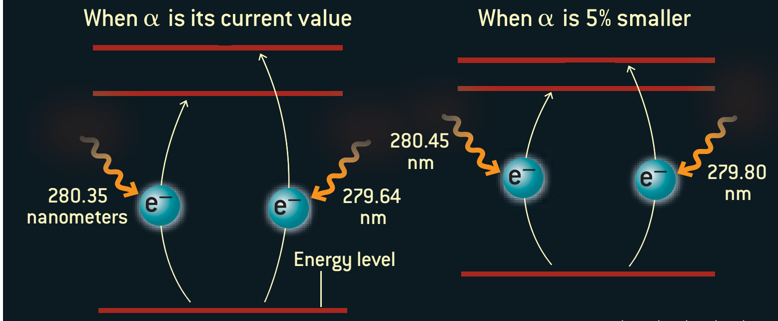
THE SECOND experimental problem, less easily solved, is that measuring changes in the constants requires high-precision equipment that remains stable long enough to register any changes. Even atomic clocks can detect drifts in the fine-structure constant only over days or, at most, years. If α changed by more than four parts in 10^{15} over a three-year period, the best clocks would

JEAN-FRANCOIS PODEVIN (*preceding pages*)

LIGHT AND THE FINE-STRUCTURE CONSTANT

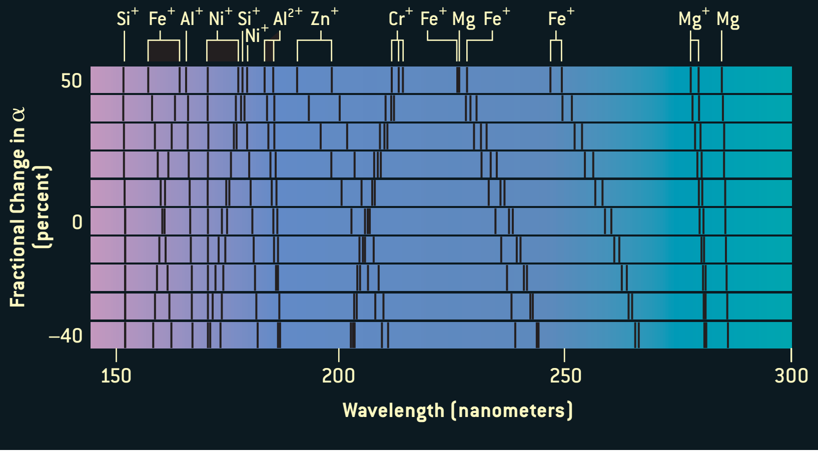
Several of the best-known constants of nature, including the speed of light, can be combined into the fine-structure constant (α)—a number that represents how strongly particles interact through electromagnetic forces. One such interaction is the absorption of photons by atoms. Illuminated by light, an atom absorbs specific colors, each corresponding to photons of a certain wavelength.





ENERGY LEVELS of electrons within the atom describe the absorption process. The energy of a photon is transferred to an electron, which jumps up the ladder of allowable levels. Each possible jump corresponds to a distinct wavelength. The spacing of levels depends on how strongly the electron is attracted to the atomic nucleus and therefore on α. In the case of magnesium ions (Mg^+), if α were smaller, the levels would be closer together. Photons would need less energy (meaning a longer wavelength) to kick electrons up the ladder.

SIMULATED SPECTRA show how changing α affects the absorption of near-ultraviolet light by various atomic species. The horizontal black lines represent absorbed wavelengths. Each type of atom or ion has a unique pattern of lines. Changes in the fine-structure constant affect magnesium (Mg), silicon (Si) and aluminum (Al) less than iron (Fe), zinc (Zn), chromium (Cr) and nickel (Ni).



ALISON KENDALL; SOURCE: JOHN K. WEBB

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 have gone unnoticed.

Fortunately, physicists have found other tests. During the 1970s, scientists from the French atomic energy commission noticed something peculiar about the isotopic composition of ore from a uranium mine at Oklo in Gabon, West Africa: it looked like the waste products of a nuclear reactor. About two billion years ago, Oklo must have been the site of a natural reactor [see "A Natural Fission Reactor," by George A. Cowan; Scientific American, July 1976].

In 1976 Alexander Shlyakhter of the Nuclear Physics Institute in St. Petersburg, 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. And that energy depends sensitively on the value of α. So if the fine-structure constant had been slightly different, no chain reaction could have occurred. But one did occur, which implies that the constant has not changed by more than one part in 10^8 over the past two billion years. (Physicists continue to debate the exact quantitative results because of the inevitable uncertainties about the conditions inside the natural reactor.)

In 1962 P. James E. 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. According to recent work by Keith Olive of the University of Minnesota, Maxim Pospelov of the University of Victoria in British Columbia and their colleagues, 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 the solar system 4.6 billion years ago.

To probe possible changes over even longer time spans, researchers must look to the heavens. Light takes billions of years to reach our telescopes from distant astronomical sources. It carries a snapshot of the laws and constants of physics

LOOKING FOR CHANGES IN QUASAR LIGHT

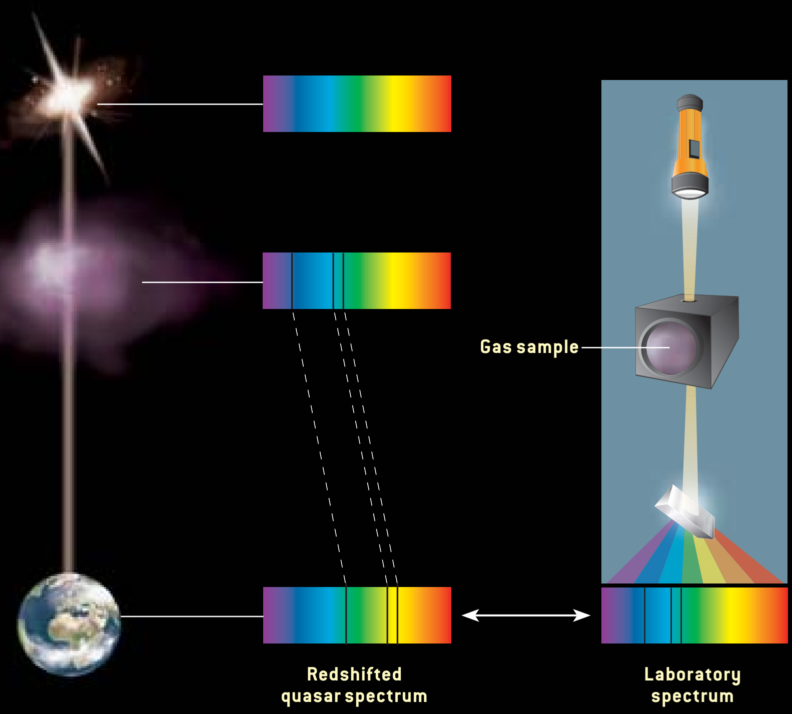
A distant gas cloud, backlit by a quasar, gives astronomers an opportunity to probe the process of light absorption—and therefore the value of the fine-structure constant—earlier in cosmic history.

1 Light from a quasar begins its journey to Earth billions of years ago with a smooth spectrum

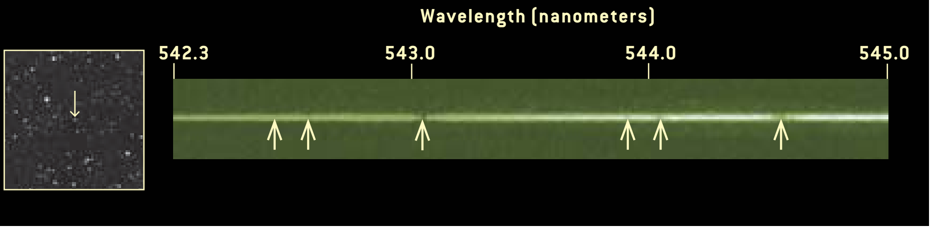
2 On its way, the light passes through one or more gas clouds. The gas blocks specific wavelengths, creating a series of black lines in the spectrum. For studies of the fine-structure constant, astronomers focus on absorption by metals

3 By the time the light arrives on Earth, the wavelengths of the lines have been shifted by cosmic expansion. The amount of shift indicates the distance of the cloud and, hence, its age

4 The spacing of the spectral lines can be compared with values measured in the laboratory. A discrepancy suggests that the fine-structure constant used to have a different value



QUASAR SPECTRUM, taken at the European Southern Observatory's Very Large Telescope, shows absorption lines produced by gas clouds between the quasar (*arrowed at right*) and us. The position of the lines (*arrowed at far right*) indicates that the light passed through the clouds about 7.5 billion years ago.



ALISON KENDALL

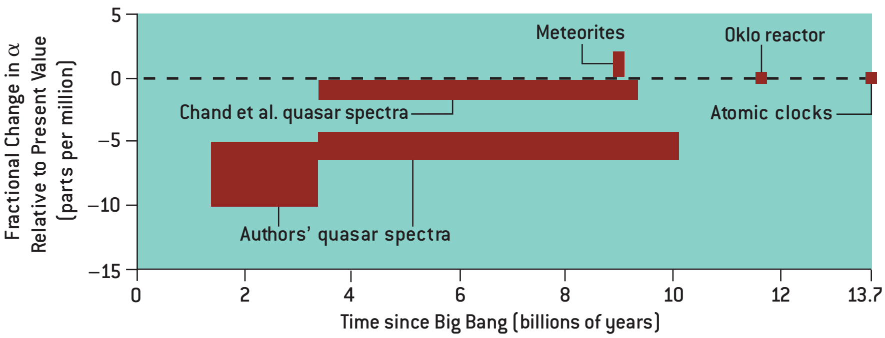
at the time when it started its journey or encountered material en route.

Line Editing

ASTRONOMY FIRST entered the constants story soon after the discovery of quasars in 1965. The idea was simple. Quasars had just been discovered and 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 [*see box above*].

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. 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 electron would differ from that required today in laboratory experiments, and the wavelengths of the transitions seen in the spectra would differ. The way in which 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.

Before we began our work seven years ago, attempts to perform the measurement had suffered from two limitations. First, laboratory researchers had not measured the wavelengths of many of the relevant spectral lines with sufficient precision. Ironically, scientists used to know more about the spectra of quasars billions of light-years away than about the spectra of samples here on Earth. We needed high-precision laboratory measurements against which to compare the quasar spectra, so we persuaded experimenters to undertake them. Initial measurements were done by Anne Thorne and Juliet Pickering of Imperial College London, followed by groups led by Sveneric Johansson of Lund Observatory in Sweden and Ulf Griesmann and Rainer Kling of the National Institute of Standards and Technology in Maryland.



MEASUREMENTS of the fine-structure constant are inconclusive. Some indicate that the constant used to be smaller, and some do not. Perhaps the constant varied earlier in cosmic history and no longer does so. (The boxes represent a range of data.)

ALISON KENDALL; SOURCE: JOHN K. WEBB

The second problem 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 laboratory measurements. This method, however, 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. In fact, this second effect is even stronger than the first. Consequently, the highest precision observers achieved was only about one part in 10^4.

In 1999 one of us (Webb) and Victor V. Flambaum of the University of New South Wales in Australia came up with a method to take both effects into account. The result was a breakthrough: it meant 10 times higher sensitivity. Moreover, the method allows different species (for instance, magnesium and iron) to be compared, which allows additional cross-checks. Putting this idea into practice took complicated numerical calculations to establish exactly how the observed wavelengths depend on α in all different atom types. Combined with modern telescopes and detectors, the new approach, known as the many-multiplet method, has enabled us to test the constancy of α with unprecedented precision.

Changing Minds

WHEN EMBARKING ON this project, we anticipated establishing that the value of the fine-structure constant long ago was the same as it is today; our contribution would simply be higher precision. To our surprise, the first results, in 1999, showed small but statistically significant differences. Further data confirmed this finding. Based on a total of 128 quasar absorption lines, we found an average increase in α of close to six parts in a million over the past six billion to 12 billion years.

Extraordinary claims require extraordinary evidence, so our immediate thoughts turned to potential problems with the data or the analysis methods. These uncertainties can be classified into two types: systematic and random. Random uncertainties are easier to understand; they are just that—random. They differ for each individual measurement but average out to be close to zero over a large sample. Systematic uncertainties, which do not average out, are harder to deal with. They are endemic in astronomy. Laboratory experimenters can alter their instrumental setup to minimize them, but astronomers cannot change the universe, and so they are forced to accept that all their methods of gathering data have an irremovable bias. For example, any survey of galaxies will tend to be overrepresented by bright galaxies because they are easier to see. Identifying and neutralizing these biases is a constant challenge.

The first one we looked for was a distortion of the wavelength scale against which the quasar spectral lines were measured. Such a distortion might conceivably be introduced, for example, during the processing of the quasar data from their raw form at the telescope into a calibrated spectrum. Although a simple linear stretching or compression of the wavelength scale could not precisely mimic a change in α, even an imprecise mimicry might be enough to explain our results. To test for problems of this kind, we substituted calibration data for the quasar data and analyzed them, pretending they were quasar data. This experiment ruled out simple distortion errors with high confidence.

For more than two years, we put up one potential bias after another, only to rule it out after detailed investigation as too small an effect. So far we have identified just one potentially serious source of bias. It concerns the absorption lines produced by the element magnesium. Each of the three stable isotopes of magnesium absorbs light of a different wavelength, but the three wavelengths are very close to one another, and quasar spectroscopy generally sees the three lines blended as one. Based on lab measurements of the relative abundances of the three isotopes, researchers infer the contribution of each. If these abundances in the young universe differed substantially—as might have happened if the stars that

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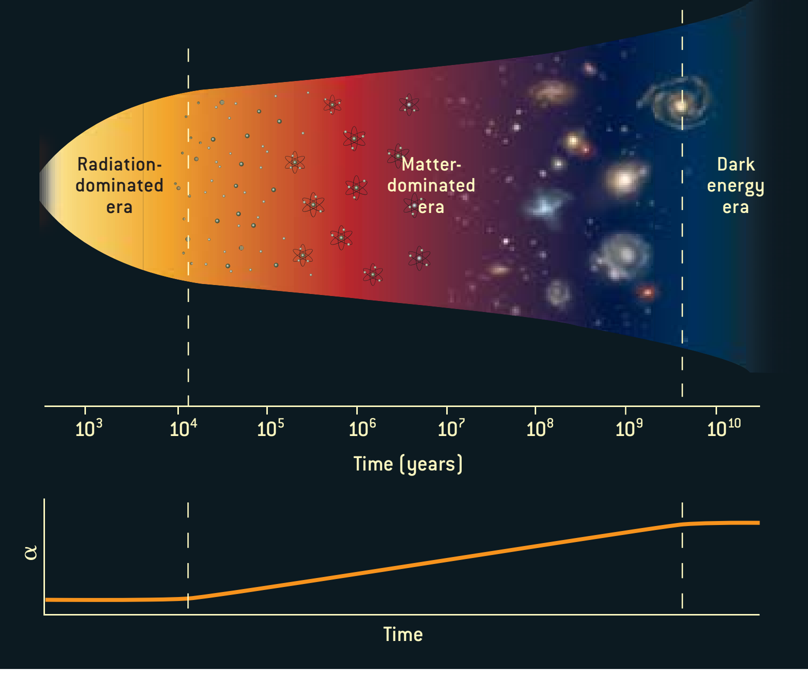
THE AUTHORS

JOHN D. BARROW and *JOHN K. WEBB* began to work together to probe the constants of nature in 1996, when Webb spent a sabbatical with Barrow at the University of Sussex in England. Barrow had been exploring new theoretical possibilities for varying constants, and Webb was immersed in quasar observations. Their project soon drew in other physicists and astronomers, notably Victor V. Flambaum of the University of New South Wales in Australia, Michael T. Murphy of the University of Cambridge and João Magueijo of Imperial College London. Barrow is now a professor at Cambridge and a Fellow of the Royal Society, and Webb is a professor at New South Wales. Both are known for their efforts to explain science to the public. Barrow has written 17 nontechnical books; his play, *Infinities,* has been staged in Italy; and he has spoken in venues as diverse as the Venice Film Festival, 10 Downing Street and the Vatican. Webb regularly lectures internationally and has worked on more than a dozen TV and radio programs.

SOMETIMES IT CHANGES, SOMETIMES NOT

According to the authors' theory, the fine-structure constant should have stayed constant during certain periods of cosmic history and increased during others. The data [*see box on preceding page*] are consistent with this prediction.



spilled magnesium into their galaxies were, on average, heavier than their counterparts today—those differences could simulate a change in α.

But a study published in 2005 indicates that the results cannot be so easily explained away. Yeshe Fenner and Brad K. Gibson of Swinburne University of Technology in Australia and Michael T. Murphy of the University of Cambridge found that matching the isotopic abundances to emulate a variation in α also results in the overproduction of nitrogen in the early universe—in direct conflict with observations. If so, we must confront the likelihood that α really has been changing.

The scientific community quickly realized the immense potential significance of our results. Quasar spectroscopists around the world were hot on the trail and rapidly produced their own measurements. In 2003 teams led by Sergei Levshakov of the Ioffe Physico-Technical Institute in St. Petersburg, Russia, and Ralf Quast of the University of Hamburg in Germany investigated three new quasar systems. In 2004 Hum Chand and Raghunathan Srianand of the Inter-University Center for Astronomy and Astrophysics in India, Patrick Petitjean of the Institute of Astrophysics in Paris and Bastien Aracil of LERMA in Paris analyzed 23 more. None of these groups saw a change in α. Chand argued that any change must be less than one part in 10^6 over the past six billion to 10 billion years.

How could a fairly similar analysis, just using different data, produce such a radical discrepancy? As yet the answer is unknown. The data from these groups are of excellent quality, but their samples are substantially smaller than ours and do not go as far back in time. The Chand analysis did not fully assess all the experimental and systematic errors—and, being based on a simplified version of the many-multiplet method, might have introduced new ones of its own.

One prominent astrophysicist, the late John Bahcall of Princeton, criticized the many-multiplet method itself, but the problems he identified fall into the category of random uncertainties, which should wash out in a large sample. He and his colleagues, as well as a team led by Jeffrey Newman of Lawrence Berkeley National Laboratory, looked at emission lines rather than absorption lines. So far this approach is much less precise, but in the future it may yield useful constraints.

Reforming the Laws

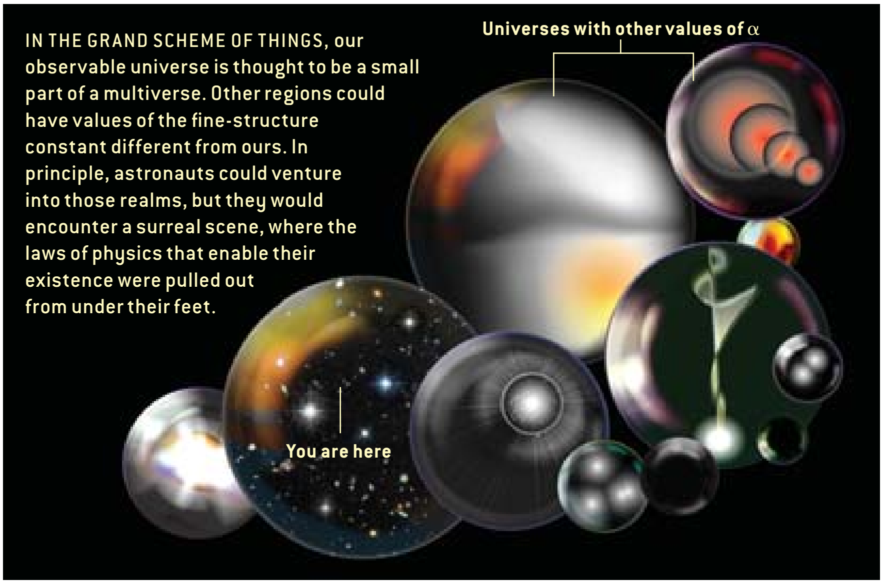
IF OUR FINDINGS prove to be right, the consequences are enormous, though only partially explored. Until quite recently, all attempts to evaluate what happens to the universe if the fine-structure constant changes were unsatisfactory. They amounted to nothing more than assuming that α became a variable in the same formulas that had been derived assuming it is a constant. This is a dubious practice. If α varies, then its effects must conserve energy and momentum, and they must influence the gravitational field in the universe. In 1982 Jacob D. Bekenstein of the Hebrew University of Jerusalem was the first to generalize the laws of electromagnetism to handle inconstant constants rigorously. The theory elevates α from a mere number to a so-called scalar field, a dynamic ingredient of nature. His theory did not include gravity, however. Four years ago one of us (Barrow), with Håvard Sandvik and João Magueijo of Imperial College London, extended it to do so.

This theory makes appealingly simple predictions. Variations in α of a few parts per million should have a completely negligible effect on the expansion of the universe. That is because electromagnetism is much weaker than gravity on cosmic scales. But although changes in the fine-structure constant do not affect the expansion of the universe significantly, the expansion affects α. Changes to α are driven by imbalances between the electric field energy and magnetic field energy. During the first tens of thousands of years of cosmic history, radiation dominated over charged particles and kept the electric and magnetic fields in balance. As the universe expanded, radiation thinned out, and matter became the dominant constituent of the cosmos. The electric and magnetic energies became unequal, and α started to increase very slowly, growing as the

ALISON KENDALL

logarithm of time. About six billion years ago dark energy took over and accelerated the expansion, making it difficult for all physical influences to propagate through space. So α became nearly constant again.

This predicted pattern is consistent with our observations. The quasar spectral lines represent the matter-dominated period of cosmic history, when α was increasing. The laboratory and Oklo results fall in the dark-energy-dominated period, during which α has been constant. The continued study of the effect of changing α on radioactive elements in meteorites is particularly interesting, because it probes the transition between these two periods.



IN THE GRAND SCHEME OF THINGS, our observable universe is thought to be a small part of a multiverse. Other regions could have values of the fine-structure constant different from ours. In principle, astronauts could venture into those realms, but they would encounter a surreal scene, where the laws of physics that enable their existence were pulled out from under their feet.

RICHARD SWORD

Alpha Is Just the Beginning

ANY THEORY worthy of consideration does not merely reproduce observations; it must make novel predictions. The above 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 are made of—an idea known as the weak equivalence principle, which was famously demonstrated when Apollo 15 astronaut David Scott dropped a feather and a hammer and saw them hit the lunar dirt at the same time. 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 will feel this force. If our quasar observations are correct, then the accelerations of different materials differ by about one part in 10^{14}—too small to see in the laboratory by a factor of about 100 but large enough to show up in planned missions such as STEP (*s*pace-based *t*est of the *e*quivalence *p*rinciple).

There is a last twist to the story. Previous studies of α neglected to include one vital consideration: the lumpiness of the universe. Like all galaxies, our Milky Way is about a million times denser than the cosmic average, so it is not expanding along with the universe. In 2003 Barrow and David F. Mota of Cambridge calculated that α may behave differently within the galaxy than inside emptier regions of space. Once a young galaxy condenses and relaxes into gravitational equilibrium, α nearly stops changing inside it but keeps on changing outside. Thus, the terrestrial experiments that probe the constancy of α suffer from a selection bias. We need to study this effect more to see how it would affect the tests of the weak equivalence principle. No spatial variations of α have yet been seen. Based on the uniformity of the cosmic microwave background radiation, Barrow recently showed that α does not vary by more than one part in 10^8 between regions separated by 10 degrees on the sky.

So where does this flurry of activity leave science as far as α is concerned? We await new data and new analyses to confirm or disprove that α varies at the level claimed. Researchers focus on α, over the other constants of nature, simply because its effects are more readily seen. If α is susceptible to change, however, other constants should vary as well, making the inner workings of nature more fickle than scientists ever suspected.

The constants are a tantalizing mystery. Every equation of physics is filled with them, and they seem so prosaic that people tend to forget how unaccountable their values are. Their origin is bound up with some of the grandest questions of modern science, from the unification of physics to the expansion of the universe. They may be the superficial shadow of a structure larger and more complex than the three-dimensional universe we witness around us. Determining whether constants are truly constant is only the first step on a path that leads to a deeper and wider appreciation of that ultimate vista. SA

MORE TO EXPLORE

Further Evidence for Cosmological Evolution of the Fine Structure Constant. J. K. Webb, M. T. Murphy, V. V. Flambaum, V. A. Dzuba, J. D. Barrow, C. W. Churchill, J. X. Prochaska and A. M. Wolfe in *Physical Review Letters,* Vol. 87, No. 9, Paper No. 091301; August 27, 2001. Preprint available online at **arxiv.org/abs/astro-ph/0012539**

A Simple Cosmology with a Varying Fine Structure Constant. H. B. Sandvik , J. D. Barrow and J. Magueijo in *Physical Review Letters,* Vol. 88, Paper No. 031302; January 2, 2002. **astro-ph/0107512**

The Constants of Nature: From Alpha to Omega. John D. Barrow. Jonathan Cape (London) and Pantheon (New York), 2002.

Are the Laws of Nature Changing with Time? J. Webb in *Physics World,* Vol. 16, Part 4, pages 33–38; April 2003.

Limits on the Time Variation of the Electromagnetic Fine-Structure Constant in the Low Energy Limit from Absorption Lines in the Spectra of Distant Quasars. R. Srianand, H. Chand, P. Petitjean and B. Aracil in *Physical Review Letters,* Vol. 92, Paper No. 121302; March 26, 2004. **astro-ph/0402177**

the myth of the beginning of TIME

By Gabriele Veneziano

String theory suggests that the BIG BANG was not the origin of the universe but simply the outcome of a preexisting state

Was the big bang really the beginning of time?

Or did the universe exist before then? Such a question seemed almost blasphemous only a decade ago. Most cosmologists insisted that it simply made no sense—that to contemplate a time before the big bang was like asking for directions to a place north of the North Pole. But developments in theoretical physics, especially the rise of string theory, have changed their perspective. The pre-bang universe has become the latest frontier of cosmology.

The new willingness to consider what might have happened before the bang is the latest swing of an intellectual pendulum that has rocked back and forth for millennia. In one form or another, the issue of the ultimate beginning has engaged philosophers and theologians in nearly every culture. It is entwined with a grand set of concerns, one famously encapsulated in an 1897 painting by Paul Gauguin: *D’ou venons-nous? Que sommes-nous? Ou allons-nous?* “Where do we come from? What are we? Where are we going?” The piece depicts the cycle of birth, life and death—origin, identity and destiny for each individual—and these personal concerns connect directly to cosmic ones. We can trace our lineage back through the generations, back through our animal ancestors, to early forms of life and protolife, to the elements synthesized in the primordial universe, to the amorphous energy deposited in space before that. Does our family tree extend forever backward? Or do its roots terminate? Is the cosmos as impermanent as we are?

The ancient Greeks debated the origin of time fiercely. Aristotle, taking the no-beginning side, invoked the principle that out of nothing, nothing comes. If the universe could never have gone from nothingness to somethingness, it must always have existed. For this and other reasons, time must stretch eternally into the past and future. Christian theologians tended to take the opposite point of view. Augustine contended that God exists outside of space and time, able to bring these constructs into existence as surely as he could forge other aspects of our world. When asked, “What was God doing *before* he created the world?” Augustine answered, “Time itself being part of God’s creation, there was simply no *before!*”

Albert Einstein's general theory of relativity led modern cosmologists to much the same conclusion. The theory holds that space and time are soft, malleable entities. On the largest scales, space is naturally dynamic, expanding or contracting over time, carrying matter like driftwood on the tide. Astronomers confirmed in the 1920s that our universe is currently expanding: distant galaxies move apart from one another. One consequence, as physicists Stephen W. Hawking and Roger Penrose proved in the 1960s, is that time cannot extend back indefinitely. As you play cosmic history backward in time, the galaxies all come together to a single infinitesimal point, known as a singularity—almost as if they were descending into a black hole. 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.

OVERVIEW

- Philosophers, theologians and scientists have long debated whether time is eternal or finite—that is, whether the universe has always existed or whether it had a definite genesis. Einstein's general theory of relativity implies finiteness. An expanding universe must have begun at the big bang.
- Yet general relativity ceases to be valid in the vicinity of the bang because quantum mechanics comes into play. Today's leading candidate for a full quantum theory of gravity—string theory—introduces a minimal quantum of length as a new fundamental constant of nature, making the very concept of a bangian genesis untenable.
- The bang still took place, but it did not involve a moment of infinite density, and the universe may have predated it. The symmetries of string theory suggest that time did not have a beginning and will not have an end. The universe could have begun almost empty and built up to the bang, or it might even have gone through a cycle of death and rebirth. In either case, the pre-bang epoch would have shaped the present-day cosmos.

The unavoidable singularity poses serious problems for cosmologists. In particular, it sits uneasily with the high degree of homogeneity and isotropy that the universe exhibits on large scales. For the cosmos to look broadly the same everywhere, some kind of communication had to pass among distant regions of space, coordinating their properties. But the idea of such communication contradicts the old cosmological paradigm.

To be specific, consider what has happened over the 13.7 billion years since the release of the cosmic microwave background radiation. The distance between galaxies has grown by a factor of about 1,000 (because of the expansion), while the radius of the observable universe has grown by the much larger factor of about 100,000 (because light outpaces the expansion). We see parts of the universe today that we could not have seen 13.7 billion years ago. Indeed, this is the first time in cosmic history that light from the most distant galaxies has reached the Milky Way.

Strange Coincidence

NEVERTHELESS, the properties of the Milky Way are basically the same as those of distant galaxies. It is as though you showed up at a party only to find you were wearing exactly the same clothes as a dozen of your closest friends. If just two of you were dressed the same, it might be explained away as coincidence, but a dozen suggests that the partygoers had coordinated their attire in advance. In cosmology, the number is not a dozen but tens of thousands—the number of independent yet statistically identical patches of sky in the microwave background.

One possibility is that all those regions of space were endowed at birth with identical properties—in other words, that the homogeneity is mere coincidence. Physicists, however, have thought about two more natural ways out of the impasse: the early universe was much smaller or much older than in standard cosmology. Either (or both, acting together) would have made intercommunication possible.

The most popular choice 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 closely packed that they could easily coordinate their properties. During inflation, they fell out of contact because light was unable to keep pace with the frenetic expansion. After inflation ended, the expansion began to decelerate, so galaxies gradually came back into one another's view.

Physicists ascribe the inflationary spurt to the potential energy stored in a new quantum field, the inflaton, about 10^{-35} second after the big bang. Potential energy, as opposed to rest mass or kinetic energy, leads to gravitational repulsion. Rather than slowing down the expansion, as the gravitation of ordinary matter would, the inflaton accelerated it. Proposed in 1981, inflation has explained a wide variety of observations with precision [see "The Inflationary Universe," by Alan H. Guth and Paul J. Steinhardt; SCIENTIFIC AMERICAN, May 1984; and "Four Keys to Cosmology," Special report; SCIENTIFIC AMERICAN, February 2004]. A number of possible theoretical problems remain, though, beginning with the questions of what exactly the inflaton was and what gave it such a huge initial potential energy.

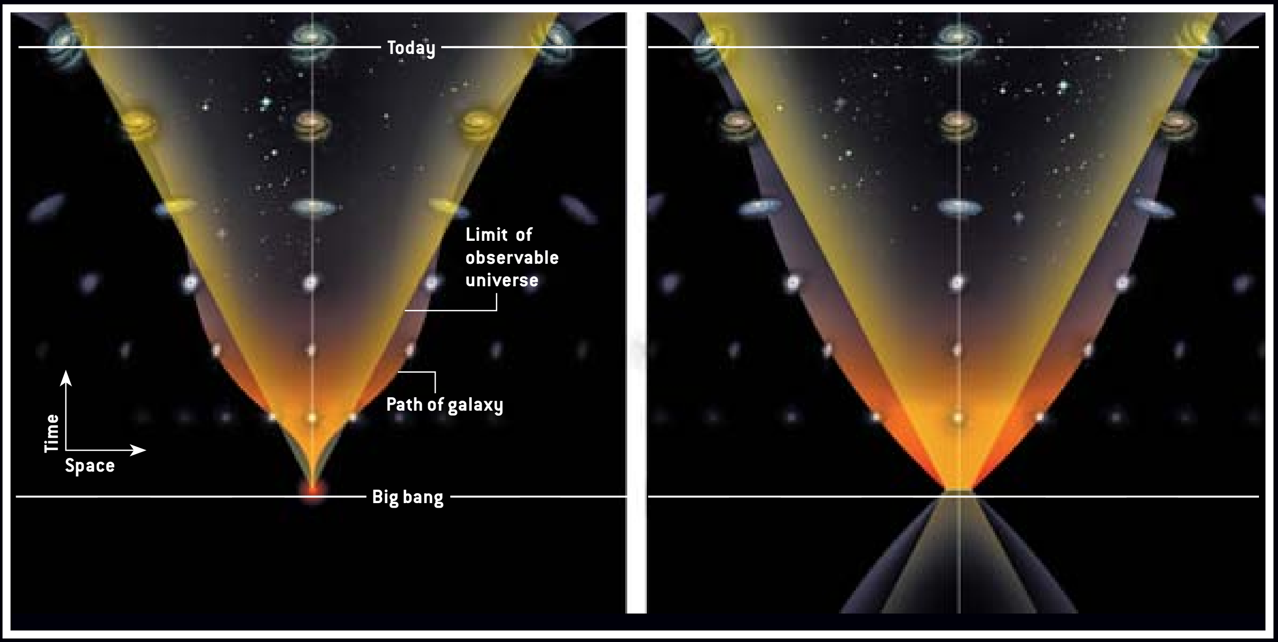
A less widely known way to solve the puzzle follows the second alternative by getting rid of the singularity. If time did not begin at the bang, if a long era preceded the onset of the present cosmic expansion, matter could have had plenty of time to arrange itself smoothly. Therefore, researchers have reexamined 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, even dominant. Standard relativity takes no account of such effects, so accepting the inevitability of the singularity amounts to trusting the theory beyond reason. To know what really happened, physicists need to sub-

ALFRED T. KAMAJIAN (*preceding pages*)

Two Views of the Beginning

In our expanding universe, galaxies rush away from one another like a dispersing mob. Any two galaxies recede at a speed proportional to the distance between them: a pair 500 million light-years apart separates twice as fast as one 250 million light-years apart. Therefore, all the galaxies we see must have started from the same place at the same time—the big bang. The conclusion holds even though cosmic expansion has gone through periods of acceleration and deceleration; in spacetime diagrams (*below*), galaxies follow sinuous paths that take them in and out of the observable region of space (*yellow wedge*). The situation became uncertain, however, at the precise moment when the galaxies (or their ancestors) began their outward motion.



In standard big bang cosmology, which is based on Albert Einstein's general theory of relativity, the distance between any two galaxies was zero a finite time ago. Before that moment, time loses meaning.

In more sophisticated models, which include quantum effects, any pair of galaxies must have started off a certain minimum distance apart. These models open up the possibility of a pre-bang universe.

sume relativity in a quantum theory of gravity. The task has occupied theorists from Einstein onward, but progress was almost zero until the mid-1980s.

Evolution of a Revolution

TODAY TWO APPROACHES stand out. One, going by the name of loop quantum gravity, retains Einstein's theory essentially intact but changes the procedure for implementing it in quantum mechanics [see "Atoms of Space and Time," by Lee Smolin, on page 82]. Practitioners of loop quantum gravity have taken great strides and achieved deep insights over the past several years. Still, their approach may not be revolutionary enough to resolve the fundamental problems of quantizing gravity. A similar problem faced particle theorists after Enrico Fermi introduced his effective theory of the weak nuclear force in 1934. All efforts to construct a quantum version of Fermi's theory failed miserably. What was needed was not a new technique but the deep modifications brought by the electroweak theory of Sheldon L. Glashow, Steven Weinberg and Abdus Salam in the late 1960s.

The second approach, which I consider more promising, is string theory—a truly revolutionary modification of Einstein's theory. This article will focus on it, although proponents of loop quantum gravity claim to reach many of the same conclusions.

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

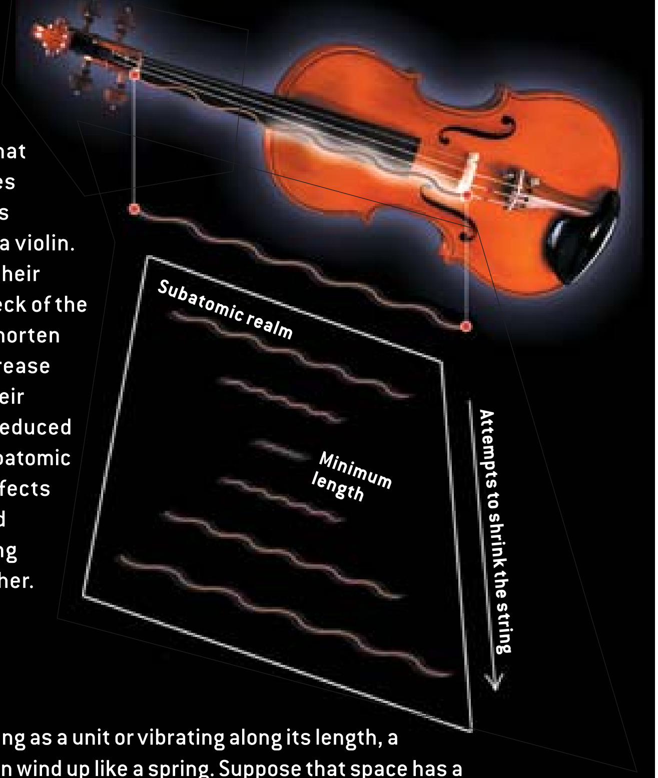
THE AUTHOR

GABRIELE VENEZIANO, a theoretical physicist at CERN, was the father of string theory in the late 1960s—an accomplishment for which he received the 2004 Heineman Prize of the American Physical Society and the American Institute of Physics. At the time, the theory was regarded as a failure; it did not achieve its goal of explaining the atomic nucleus, and Veneziano soon shifted his attention to quantum chromodynamics, to which he made major contributions. After string theory made its comeback as a theory of gravity in the 1980s, Veneziano became one of the first physicists to apply it to black holes and cosmology.

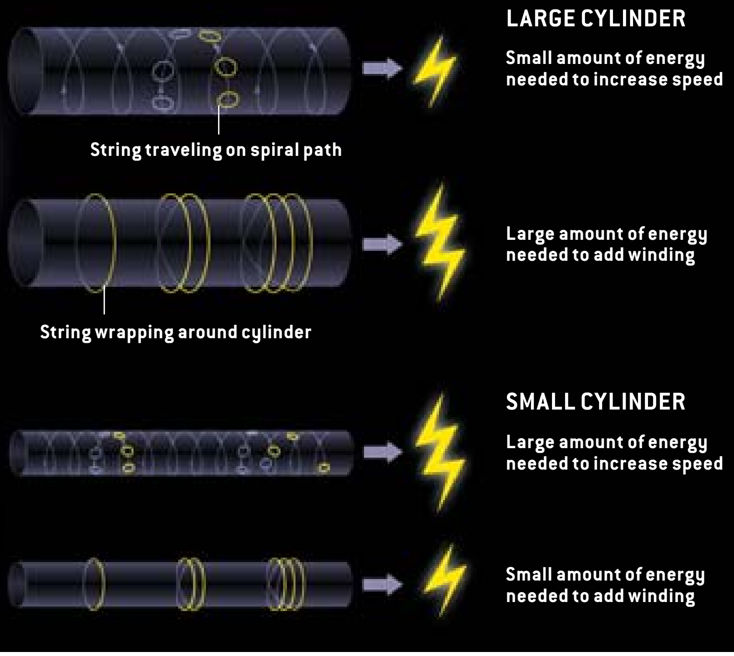
SAMUEL VELASCO

STRING THEORY 101

String theory is the leading (though not only) theory that tries to describe what happened at the moment of the big bang. The strings that the theory describes are material objects much like those on a violin. As violinists move their fingers down the neck of the instrument, they shorten the strings and increase the frequency of their vibrations. If they reduced a string to a sub-subatomic length, quantum effects would take over and prevent it from being shortened any further.



In addition to traveling as a unit or vibrating along its length, a subatomic string can wind up like a spring. Suppose that space has a cylindrical shape. If the circumference is larger than the minimum allowed string length, each increase in the travel speed requires a small increment of energy, whereas each extra winding requires a large one. But if the circumference is smaller than the minimum length, an extra winding is less costly than an extra bit of velocity. Thus, from a physical point of view, the minimal size of the circumference is not zero but the irreducible quantum of length, symbolized by l_s.



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 pointlike 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. How can such a simple-minded theory describe the complicated world of particles and their interactions? The answer can be found in what we may call 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. Were it not for quantum effects, a violin string could be cut in half, cut in half again and so on all the way down, finally becoming a massless pointlike particle. But the Heisenberg uncertainty principle eventually intrudes and prevents the lightest strings from being sliced smaller than about 10^{-34} meter. This irreducible quantum of length, denoted l_s, is a new constant of nature introduced by string theory side by side with the speed of light, c, and Planck's constant, h. It plays a crucial role in almost every aspect of 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, angular momentum is a property of an object that rotates with respect to an axis. The formula for angular momentum multiplies together velocity, mass and distance from the axis; hence, a massless object can have no angular momentum. But quantum fluctuations change the situation. A tiny string can acquire up to two units of h of angular momentum without gaining any mass. This feature is very welcome because it precisely matches the properties of the carriers of all known fundamental forces, such as the photon (for electromagnetism) and

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the graviton (for gravity). Historically, angular momentum is what clued in physicists to the quantum-gravitational implications of string theory.

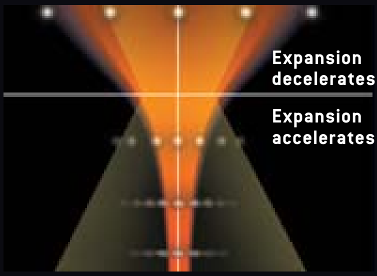
Third, quantum strings demand the existence of extra dimensions of space, in addition to the usual three. Whereas a classical violin string will vibrate no matter what the properties of space and time are, a quantum string is more finicky. The equations describing the vibration become inconsistent unless spacetime either is highly curved (in contradiction with observations) or contains six extra spatial dimensions.

Fourth, physical constants—such as Newton's and Coulomb's constants, which appear in the equations of physics and determine the properties of nature—no longer have arbitrary, fixed values. They occur in string theory as fields, rather like the electromagnetic field, 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.

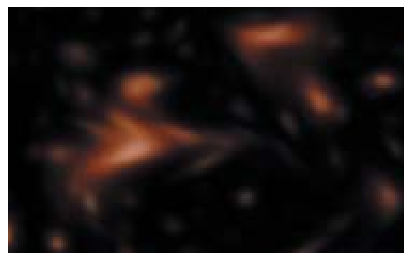
One such field, called the dilaton, is the master key to string theory; it determines the overall strength of all interactions. The dilaton fascinates string theorists because its value can be reinterpreted as the size of an extra dimension of space, giving a grand total of 11 spacetime dimensions.

PRE–BIG BANG SCENARIO

A pioneering effort to apply string theory to cosmology was the so-called pre–big bang scenario, according to which the bang is not the ultimate origin of the universe but a transition. Beforehand, expansion accelerated; afterward, it decelerated (at least initially). The path of a galaxy through spacetime (*right*) is shaped like a wineglass.



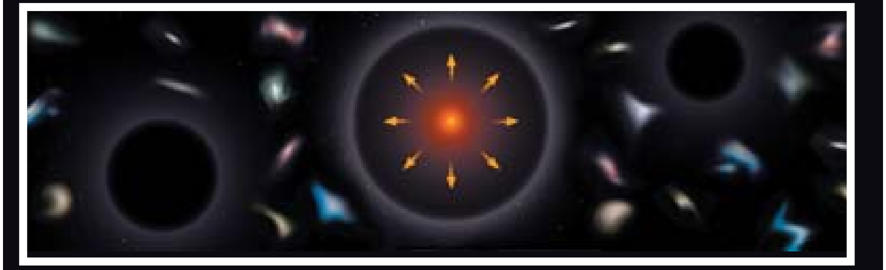
The universe has existed forever. In the distant past, it was nearly empty. Forces such as gravitation were inherently weak.



The forces gradually strengthened, so matter began to clump. In some regions, it grew so dense that a black hole formed.

Space inside the hole expanded at an accelerating rate. Matter inside was cut off from matter outside.

Inside the hole, matter fell toward the middle and increased in density until reaching the limit imposed by string theory.



When matter reached the maximum allowed density, quantum effects caused it to rebound in a big bang. Outside, other holes began to form—each, in effect, a distinct universe.

SAMUEL VELASCO

Tying Down the Loose Ends

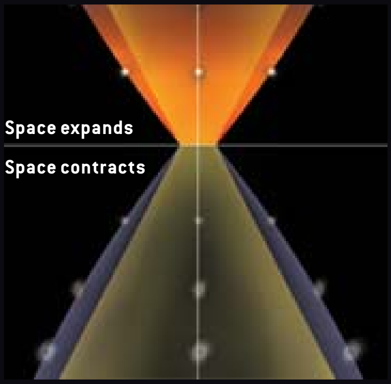
FINALLY, QUANTUM strings have introduced physicists to some striking new symmetries of nature known as dualities, which alter our intuition for what happens when objects get extremely small. I have already alluded to a form of duality: normally, a short string is lighter than a long one, but if we attempt to squeeze down its size below the fundamental length l_s, the string gets heavier again.

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 pointlike 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, one or several times, like a rubber band wrapped around a rolled-up poster [*see box on opposite page*].

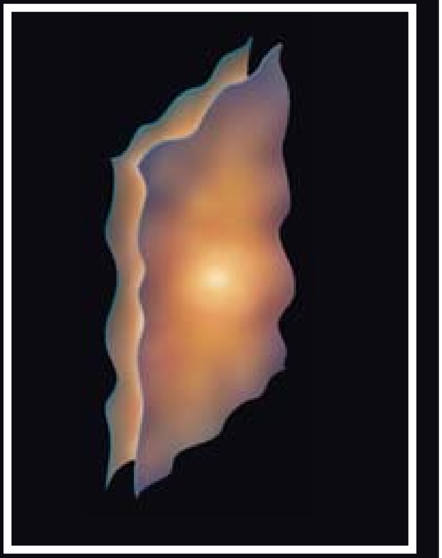
The energetic cost of these two states of the string depends on the size of the cylinder. The energy of winding is directly proportional to the cylinder radius: larger cylinders require the string to stretch more as it wraps around, so the

EKPYROTIC SCENARIO

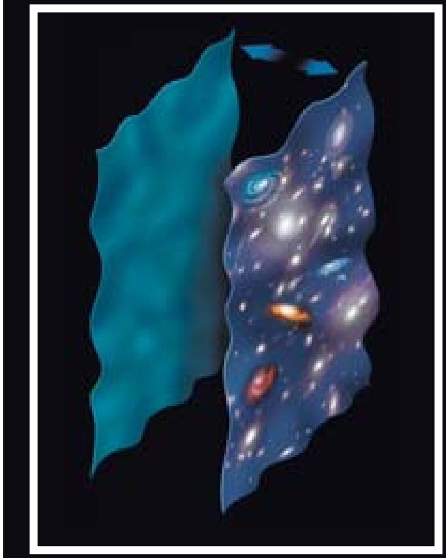
If our universe is a multidimensional membrane, or simply a "brane," cruising through a higher-dimensional space, the big bang may have been the collision of our brane with a parallel one. The collisions might recur cyclically. Each galaxy follows an hourglass-shaped path through spacetime (*below*).



Two nearly empty branes pull each other together. Each is contracting in a direction perpendicular to its motion.

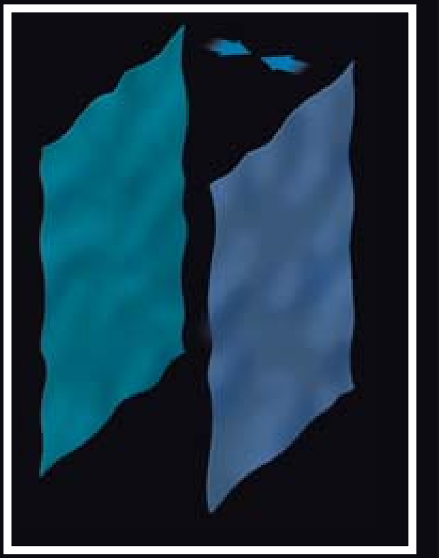


The branes collide, converting their kinetic energy into matter and radiation. This collision is the big bang.



The branes rebound. They start expanding at a decelerating rate. Matter clumps into structures such as galaxy clusters.

In the cyclic model, as the branes move apart, the attractive force between them slows them down. Matter thins out.



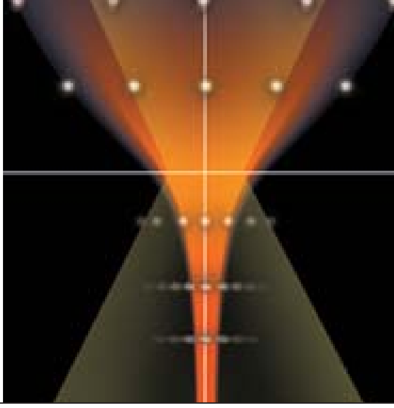
The branes stop moving apart and start approaching each other. During the reversal, each brane expands at an accelerated rate.

windings contain more energy than they would on a smaller cylinder. The energy associated with moving around the circle, on the other hand, is inversely proportional to the radius: larger cylinders allow for longer wavelengths (smaller frequencies), which represent less energy than shorter wavelengths do. 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, in which one dimension (the circumference) is finite, a variant of it applies to our ordinary three dimensions, which appear to stretch on indefinitely. One must be careful when talking about the expansion of an infinite space. Its overall size cannot 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—the factor by which the distance between galaxies changes, manifesting

SAMUEL VELASCO

Strings abhor infinity. They cannot collapse to an infinitesimal point, so they avoid the paradoxes that collapse would entail.



itself as the galactic redshift that astronomers observe. 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 cannot wind. In 1995 Joseph Polchinski of the University of California, Santa Barbara, realized that T-duality did apply to open strings, provided that the switch between large and small radii was accompanied by a change in the conditions at the end points of the string. Until then, physicists had postulated boundary conditions in which no force acted on the ends of the strings, leaving them free to flap around. Under T-duality, these conditions become so-called Dirichlet boundary conditions, whereby the ends stay put.

Any given string can mix both types of boundary conditions. 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 Horava of the University of California, Berkeley, and Edward Witten of the Institute for Advanced Study in Princeton, N.J., proposed that our universe resides on such a brane. The partial mobility of electrons and other particles explains why we are unable to perceive the full 10-dimensional glory of space.

All the magic properties of quantum strings point in one direction: strings abhor infinity. They cannot collapse to an infinitesimal point, so they avoid the paradoxes that collapse entails. Their nonzero size and novel symmetries 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 one plays 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 once more. Before string theory, physicists were hard-pressed to imagine any mechanism that could so cleanly eliminate the singularity.

Taming the Infinite

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, known as the pre–big bang scenario, which my colleagues and I began to develop in 1991, 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, say, five seconds before the big bang expanded at the same pace as it did five seconds after the bang. But the rate of change of the expansion was opposite at the two instants: if it was decelerating after the bang, it was accelerating before. In short, the big bang may not have been the origin of the universe but simply a violent transition from acceleration to deceleration.

The beauty of this picture is that it automatically incorporates the great insight of standard inflationary theory—namely, that the universe had to undergo a period of acceleration to become so homogeneous and isotropic. In the standard theory, acceleration occurs after the big bang because of an ad hoc inflaton field. In the pre–big bang scenario, it occurs before the bang as a natural outcome of the novel symmetries of string theory.

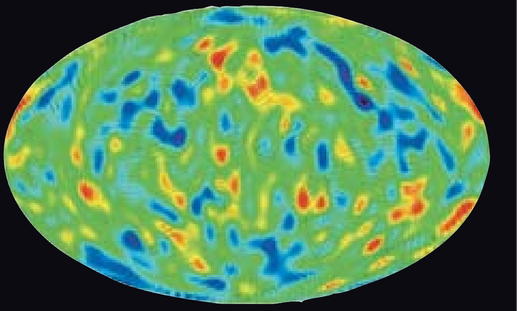
According to the scenario, the pre-bang universe was almost a perfect mirror image of the post-bang one [*see box on page 77*]. If the universe is eternal into the future, its contents thinning to a meager gruel, it is also eternal into the past. Infinitely long ago it was nearly empty, filled only with a tenuous, widely dispersed, chaotic gas of radiation and matter. The forces of nature, controlled by the dilaton field, were so feeble that particles in this gas barely interacted.

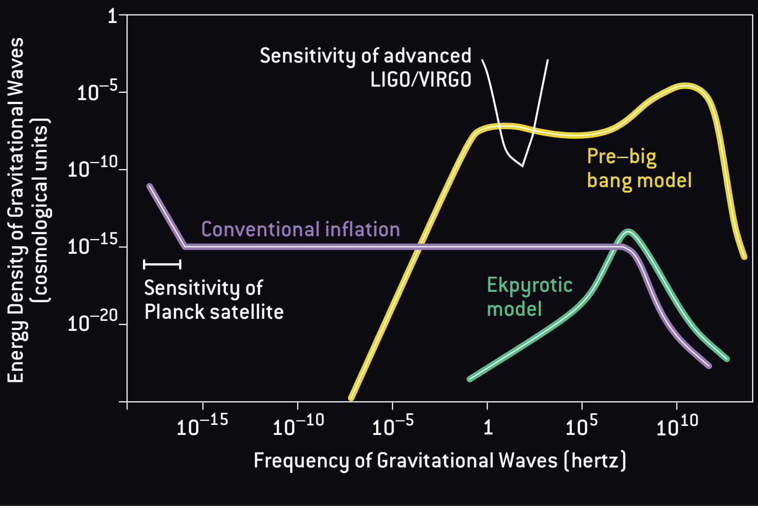
As time went on, the forces gained in strength and pulled matter together. Randomly, some regions accumulated matter at the expense of their surroundings. Eventually the density in these regions became so high that black holes started to form. Matter inside those regions was then cut off from the outside, breaking up the universe into disconnected pieces.

Inside a black hole, space and time swap roles. The center of the black hole is not a point in space but an instant in time. As the infalling matter approached the center, it reached higher and higher densities. But when the density, temperature and curvature reached the maximum values allowed by string theory, these quantities bounced and started decreasing. The moment of that reversal is what we call a big bang. The interior of one of those black holes became our universe.

OBSERVATIONS

Observing the pre-bang universe may sound like a hopeless task, but one form of radiation could survive from that epoch: gravitational radiation. These periodic variations in the gravitational field might be detected indirectly, by their effect on the polarization of the cosmic microwave background (*simulated view, below*), or directly, at ground-based observatories. The pre–big bang and ekpyrotic scenarios predict more high-frequency gravitational waves and fewer low-frequency ones than do conventional models of inflation (*bottom*). Existing measurements of various astronomical phenomena cannot distinguish among these models, but upcoming observations by the Planck satellite as well as the LIGO and VIRGO observatories should be able to.





Not surprisingly, such an unconventional scenario has provoked controversy. Andrei Linde of Stanford University has argued that for this scenario to match observations, the black hole that gave rise to our universe would have to have formed with an unusually large size—much larger than the length scale of string theory. An answer to this objection is that the equations predict black holes of all possible sizes. Our universe just happened to form inside a sufficiently large one.

A more serious objection, raised by Thibault Damour of the Institut des Hautes Études Scientifiques in Bures-sur-Yvette, France, and Marc Henneaux of the Free University of Brussels, is that matter and spacetime would have behaved chaotically near the moment of the bang, in possible contradiction with the observed regularity of the early universe. I have recently proposed that a chaotic state would produce a dense gas of miniature "string holes"—strings that were so small and massive that they were on the verge of becoming black holes. The behavior of these holes could solve the problem identified by Damour and Henneaux. A similar proposal has been put forward by Thomas Banks of Rutgers University and Willy Fischler of the University of Texas at Austin. Other critiques also exist, and whether they have uncovered a fatal flaw in the scenario remains to be determined.

The other leading model for the universe before the bang is the ekpyrotic ("conflagration") scenario. Developed five years ago by a team of cosmologists and string theorists—Justin Khoury of Columbia University, Paul J. Steinhardt of Princeton University, Burt A. Ovrut of the University of Pennsylvania, Nathan Seiberg of the Institute for Advanced Study and Neil Turok of the University of Cambridge—the ekpyrotic scenario relies on the previously mentioned Horava-Witten 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 [*see box on page 78*].

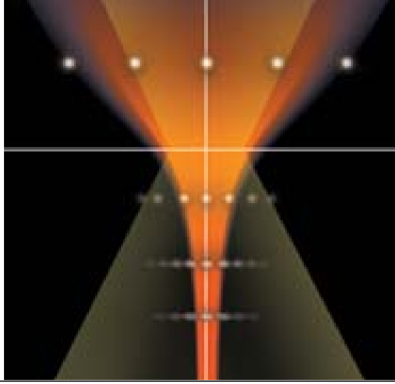
In a variant of this scenario, the collisions occur cyclically. Two branes might hit, bounce off each other, move apart, pull each other together, hit again, and so on. In between collisions, the branes behave like Silly Putty, expanding as they recede and contracting somewhat as they come back together. During the turnaround, the expansion rate accelerates; indeed, the present accelerating expansion of the universe may augur another collision.

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. Mathematically, the main difference between the scenarios is the behavior of the dilaton field. In the pre–big bang, the dilaton begins with a low value—so that the forces of nature are weak—and steadily gains strength. The opposite is true for the ekpyrotic scenario, in which the collision occurs when forces are at their weakest.

The developers of the ekpyrotic theory initially hoped that the weakness of the forces would allow the bounce to be analyzed more easily, but they were still confronted with a difficult high-curvature situation, so the jury is out on whether the scenario truly avoids a singularity. Also, the ekpyrotic scenario must entail very special conditions to solve the usual cosmological puzzles.

NASA (*top*); GABRIELE VENEZIANO (*bottom*)

Vestiges of the pre-bangian epoch might show up in galactic and intergalactic magnetic fields.



For instance, the about-to-collide branes must have been almost exactly parallel to one another, or else the collision could not have given rise to a sufficiently homogeneous bang. The cyclic version may be able to take care of this problem, because successive collisions would allow the branes to straighten themselves.

Leaving aside the difficult task of fully justifying these two scenarios mathematically, physicists must ask whether they have any observable physical consequences. At first sight, both scenarios might seem like an exercise not in physics but in metaphysics—interesting ideas that observers could never prove right or wrong. That attitude is too pessimistic. Like the details of the inflationary phase, those of a possible pre-bangian epoch could have observable consequences, especially for the small variations observed in the cosmic microwave background temperature.

First, observations show that the temperature fluctuations were shaped by acoustic waves for several hundred thousand years. The regularity of the fluctuations indicates that the waves were synchronized. Cosmologists have discarded many cosmological models over the years because they failed to account for this synchrony. The inflationary, pre–big bang and ekpyrotic scenarios all pass this first test. In these three models, the waves were triggered by quantum processes amplified during the period of accelerating cosmic expansion. The phases of the waves were aligned.

Second, each model predicts a different distribution of the temperature fluctuations with respect to angular size. Observers have found that fluctuations of all sizes have approximately the same amplitude. (Discernible deviations occur only on very small scales, for which the primordial fluctuations have been altered by subsequent processes.) Inflationary models neatly reproduce this distribution. During inflation, the curvature of space changed relatively slowly, so fluctuations of different sizes were generated under much the same conditions. In both the stringy models, the curvature evolved quickly, increasing the amplitude of small-scale fluctuations, but other processes boosted the large-scale ones, leaving all fluctuations with the same strength. For the ekpyrotic scenario, those other processes involved the extra dimension of space, the one that separated the colliding branes. For the pre–big bang scenario, they involved a quantum field, the axion, related to the dilaton. In short, all three models match the data.

Third, temperature variations can arise from two distinct processes in the early universe: fluctuations in the density of matter and rippling caused by gravitational waves. Inflation involves both processes, whereas the pre–big bang and ekpyrotic scenarios mostly involve density variations. Gravitational waves of certain sizes would leave a distinctive signature in the polarization of the microwave background [see "Echoes from the Big Bang," by Robert R. Caldwell and Marc Kamionkowski; Scientific American, January 2001]. Future observatories, such as the European Space Agency's Planck satellite, should be able to see that signature, if it exists—providing a nearly definitive test.

A fourth test pertains to the statistics of the fluctuations. In inflation the fluctuations follow a bell-shaped curve, which is known to physicists as a Gaussian. The same may be true in the ekpyrotic case, whereas the pre–big bang scenario allows for sizable deviation from Gaussianity.

Analysis of the microwave background is not the only way to verify these theories. The pre–big bang scenario should also produce a random background of gravitational waves in a range of frequencies that, though irrelevant for the microwave background, should be detectable by future gravitational-wave observatories. Moreover, because the pre–big bang and ekpyrotic scenarios involve changes in the dilaton field, which is coupled to the electromagnetic field, they would both lead to large-scale magnetic field fluctuations. Vestiges of these fluctuations might show up in galactic and intergalactic magnetic fields.

So, when did time begin? Science does not have a conclusive answer yet, but at least two potentially testable theories plausibly hold that the universe—and therefore time—existed well before the big bang. If either scenario is right, the cosmos has always been in existence and, even if it recollapses one day, will never end.

MORE TO EXPLORE

The Elegant Universe. Brian Greene. W. W. Norton, 1999.

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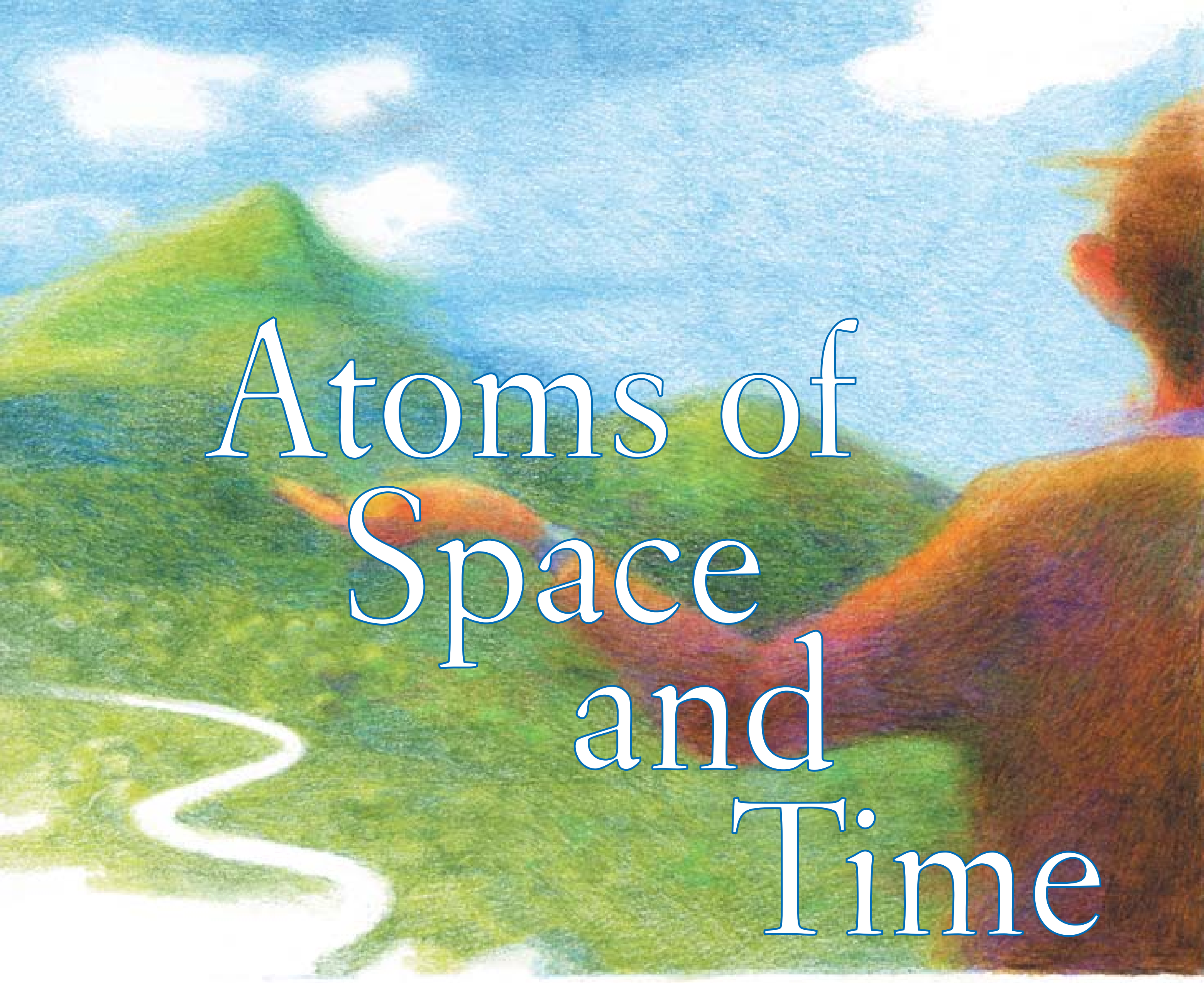
A Cyclic Model of the Universe. Paul J. Steinhardt and Neil Turok in *Science,* Vol. 296, No. 5572, pages 1436–1439; May 24, 2002. **hep-th/0111030**

The Pre–Big Bang Scenario in String Cosmology. Maurizio Gasperini and Gabriele Veneziano in *Physics Reports,* Vol. 373, Nos. 1–2, pages 1–212; January 2003. **hep-th/0207130**

Atoms of Space and Time



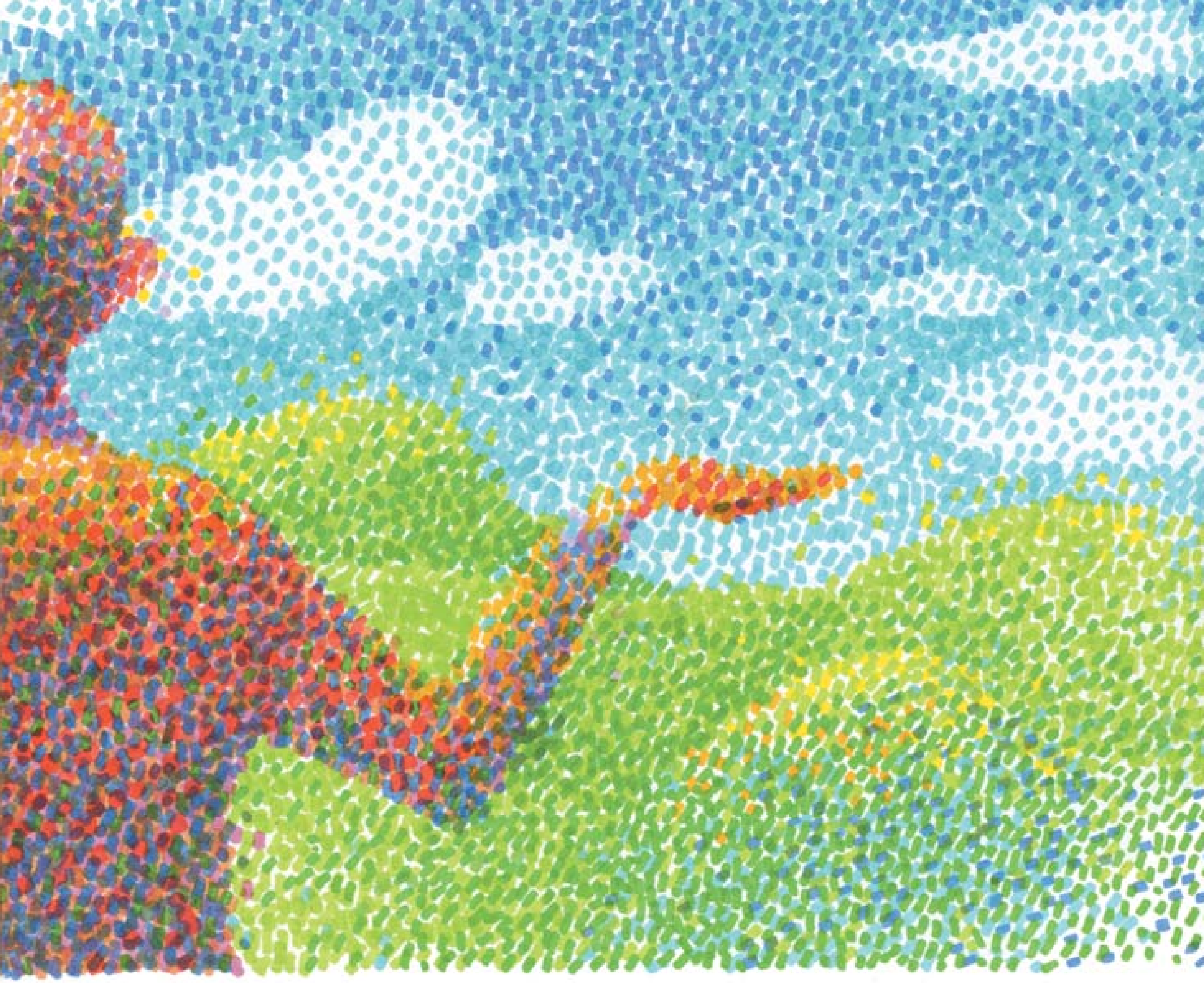
We perceive space and time to be continuous, but if the amazing theory of loop quantum gravity is correct, they actually come in discrete pieces

By Lee Smolin

A little more than 100 years ago most people—and most scientists—thought of matter as continuous. Although since ancient times some philosophers and scientists had speculated that if matter were broken up into small enough bits, it might turn out to be made up of very tiny atoms, few thought the existence of atoms could ever be proved. Today we have imaged individual atoms and have studied the particles that compose them. The granularity of matter is old news.

In recent decades, physicists and mathematicians have asked if space is also made of discrete pieces. Is it continuous, as we learn in school, or is it more like a piece of cloth, woven out of individual fibers? If we could probe to size scales that were small enough, would we see "atoms" of space, irreducible pieces of volume that cannot be broken into anything smaller? And what about time: Does nature change continuously, or does the world evolve in

DUSAN PETRICIC



series of very tiny steps, acting more like a digital computer?

The past two decades have seen great progress on these questions. A theory with the strange name of "loop quantum gravity" predicts that space and time are indeed made of discrete pieces. The picture revealed by calculations carried out within the framework of this theory is both simple and beautiful. The theory has deepened our understanding of puzzling phenomena having to do with black holes and the big bang. Best of all, it is testable; it makes predictions for experiments that can be done in the near future that will enable us to detect the atoms of space, if they are really there.

Quanta

MY COLLEAGUES AND I 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? To explain why this is an important question—and what it has to do with the granularity of space and time—I must first say a bit about quantum theory and the theory of gravity.

The theory of quantum mechanics was formulated in the first quarter of the 20th century, a development that was closely connected with the confirmation that matter is made of atoms. The equations of quantum mechanics require that certain quantities, such as the energy of an atom, can come only in specific, discrete units. Quantum theory successfully predicts the properties and behavior of atoms and the elementary particles and forces that compose them. No theory in the history of science has been more successful than quantum theory. It underlies our understanding of chemistry, atomic and subatomic physics, electronics and even biology.

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. A loose analogy is that of a bowling ball placed on a rubber sheet along with a marble that is rolling around nearby. The balls could represent the sun and the earth, and the sheet is space. The bowling ball creates a deep indentation in the rubber sheet, and the slope of this indentation causes the marble to be deflected toward the larger ball, as if some force—gravity—were pulling it in that direction. Similarly, any piece of matter or concentration of energy distorts the geometry of spacetime, causing other particles and light rays to be deflected toward it, a phenomenon we call gravity.

Quantum theory and Einstein's theory of general relativity separately have each been fantastically well confirmed by experiment—but no experiment has explored the regime where both theories predict significant effects. The problem is that quantum effects are most prominent at small size scales, whereas general relativistic effects require large masses, so it takes extraordinary circumstances to combine both conditions.

OVERVIEW

- To understand the structure of space on the very smallest size scale, we must turn to a quantum theory of gravity. Gravity is involved because Einstein's general theory of relativity reveals that gravity is caused by the warping of space and time.
- By carefully combining the fundamental principles of quantum mechanics and general relativity, physicists are led to the theory of "loop quantum gravity."
  In this theory, the allowed quantum states of space turn out to be related to diagrams of lines and nodes called spin networks. Quantum spacetime corresponds to similar diagrams called spin foams.
- Loop quantum gravity predicts that space comes in discrete lumps, the smallest of which is about a cubic Planck length, or 10^{-99} cubic centimeter. Time proceeds in discrete ticks of about a Planck time, or 10^{-43} second. The effects of this discrete structure might be seen in experiments in the near future.

SPACE IS WOVEN out of distinct threads.

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Allied with this hole in the experimental data is a huge conceptual problem: Einstein's theory of general 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. Because general relativity deals in the geometry of spacetime, a quantum theory of gravity will in addition be a quantum theory of spacetime.

Physicists have developed a considerable collection of 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 could not be successfully combined. Consequently, something fundamentally new seemed to be required, such as additional postulates or principles not included in quantum theory and general relativity, or new particles or fields, or new entities of some kind. Perhaps with the right additions or a new mathematical structure, a quantumlike theory could be developed that would successfully approximate general relativity in the nonquantum regime. To avoid spoiling the successful predictions of quantum theory and general relativity, the exotica contained in the full theory would remain hidden from experiment except in the extraordinary circumstances where both quantum theory and general relativity are expected to have large effects. Many different approaches along these lines have been tried, with names such as twistor theory, noncommutative geometry and supergravity.

An approach that is very popular with physicists is string theory, which postulates that space has six or seven dimensions—all so far completely unobserved—in addition to the three that we are familiar with. String theory also predicts the existence of a great many new elementary particles and forces, for which there is so far no observable evidence. Some researchers believe that string theory is subsumed in a theory called M-theory [see "The Theory Formerly Known as Strings," by Michael J. Duff; SCIENTIFIC AMERICAN, February 1998], but unfortunately no precise definition of this conjectured theory has ever been given. Thus, many physicists and mathematicians are convinced that alternatives must be studied. Our loop quantum gravity theory is the best-developed alternative.

A Big Loophole

IN THE MID-1980S a few of us—including Abhay Ashtekar, now at Pennsylvania State University, Ted Jacobson of the University of Maryland and Carlo Rovelli, now at the University of the Mediterranean in Marseille—decided to reexamine the question of whether quantum mechanics could be combined consistently with general relativity using the standard techniques. We knew that the negative results from the 1970s had an important loophole. Those calculations assumed that the geometry of space is continuous and smooth, no matter how minutely we examine it, just as people had expected matter to be before the discovery of atoms. Some of our teachers and mentors had pointed out that if this assumption was wrong, the old calculations would not be reliable.

So we began searching for a way to do calculations without assuming that space is smooth and continuous. We insisted on not making any assumptions beyond the experimentally well tested principles of general relativity and quantum theory. In particular, we kept two key principles of general relativity at the heart of our 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, dynamical quantity. To find the geometry, one has to solve certain equations that include all the effects of matter and energy. Incidentally, string theory, as currently formulated, is not background independent; the equations describing the strings are set up in a predetermined classical (that is, nonquantum) spacetime.

The second principle, known by the imposing name 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 (no coordinates are special). Diffeomorphism invariance is very powerful and is of fundamental importance in general relativity.

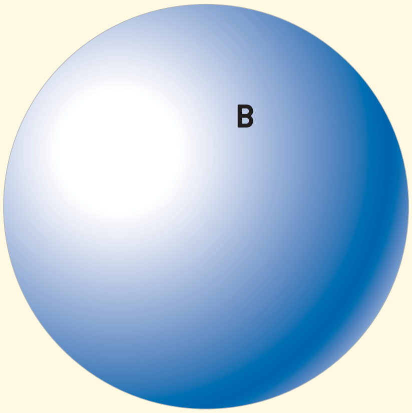
By carefully combining these two principles with the standard techniques of quantum mechanics, we developed a mathematical language that allowed us to do a computation to determine whether space is continuous or discrete. That calculation revealed, to our delight, that space is quantized. We had laid the foundations of our theory of loop quantum gravity. The term "loop," by the way, arises from how some computations in the theory involve small loops marked out in spacetime.

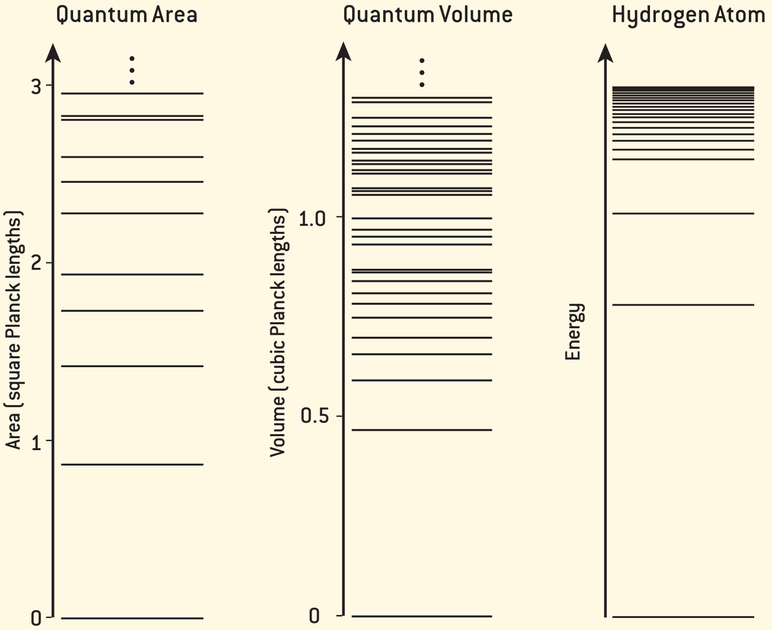
The calculations have been redone by a number of physicists and mathematicians using a range of methods. Over the years since, the study of loop quantum gravity has grown into a healthy field of research, with many contributors around the world; our combined efforts give us confidence in the picture of spacetime I will describe.

Ours is a quantum theory of the structure of spacetime at the smallest size scales, so to explain how the theory works we need to consider what it predicts for a small region or volume. In dealing with quantum physics, it is essential to specify precisely what physical quantities are to be measured. To do so, we consider a region somewhere that is marked out by a boundary, B [*see box below*]. 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 (a surface from within which even light cannot escape the black hole's gravitational clutches).

What happens if we measure the vol-

QUANTUM STATES OF VOLUME AND AREA





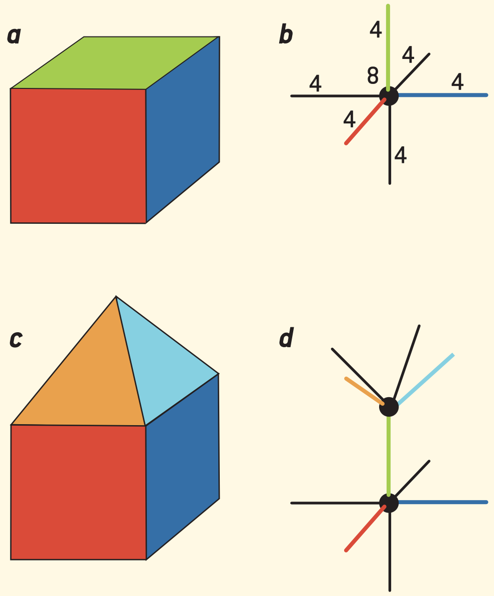
A central prediction of the loop quantum gravity theory relates to volumes and areas. Consider a spherical shell that defines the boundary, B, of a region of space having some volume (*above*). According to classical (nonquantum) physics, the volume could be any positive real number. The loop quantum gravity theory says, however, that there is a nonzero absolute minimum volume (about one cubic Planck length, or 10^{-99} cubic centimeter), and it restricts the set of larger volumes to a discrete series of numbers. Similarly, there is a nonzero minimum area (about one square Planck length, or 10^{-66} square centimeter) and a discrete series of larger allowed areas. The discrete spectrum of allowed quantum areas (*left*) and volumes (*center*) is broadly similar to the discrete quantum energy levels of a hydrogen atom (*right*).

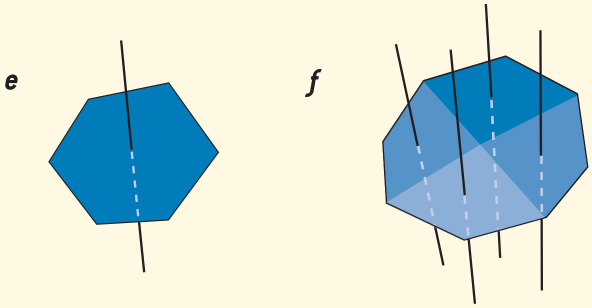
NADIA STRASSER; SOURCE: AREA AND VOLUME DATA FROM ROBERTO DE PIETRI AND CARLO ROVELLI (http://arxiv.org/abs/gr-qc/9602023)

VISUALIZING QUANTUM STATES OF VOLUME

Diagrams called spin networks are used by physicists who study loop quantum gravity to represent quantum states of space at a minuscule scale. Some such diagrams correspond to polyhedra-shaped volumes. For example, a cube (*a*) consists of a volume enclosed within six square faces. The corresponding spin network (*b*) has a dot, or node, representing the volume and six lines that represent the six faces. The complete spin network has a number at the node to indicate the cube's volume and a number on each line to indicate the area of the corresponding face. Here the volume is eight cubic Planck lengths, and the faces are each four square Planck lengths. (The rules of loop quantum gravity restrict the allowed volumes and areas to specific quantities: only certain combinations of numbers are allowed on the lines and nodes.)

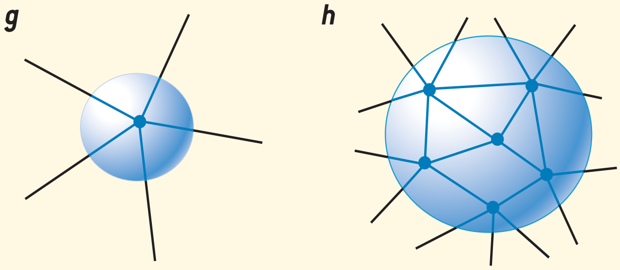
If a pyramid sat on the cube's top face (*c*), the line representing that face in the spin network would connect the cube's node to the pyramid's node (*d*). The lines corresponding to the four exposed faces of the pyramid and the five exposed faces of the cube would stick out from their respective nodes. (The numbers have been omitted for simplicity.)





One quantum of area

Larger area



One quantum of volume

Larger volume

In general, in a spin network, one quantum of area is represented by a single line (*e*), whereas an area composed of many quanta is represented by many lines (*f*). Similarly, a quantum of volume is represented by one node (*g*), whereas a larger volume takes many nodes (*h*). If we have a region of space defined by a spherical shell, the volume inside the shell is given by the sum of all the enclosed nodes and its surface area is given by the sum of all the lines that pierce it.

The spin networks are more fundamental than the polyhedra: any arrangement of polyhedra can be represented by a spin network in this fashion, but some valid spin networks represent combinations of volumes and areas that cannot be drawn as polyhedra. Such spin networks would occur when space is curved by a strong gravitational field or in the course of quantum fluctuations of the geometry of space at the Planck scale.

ume 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 cannot be smaller than a certain minimum possible volume. The question is similar to 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 (amounts in between those values do not occur). The difference is like 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. Volume comes in distinct pieces. Another quantity we can measure is the area of the boundary B. Again, calculations using the theory return an unambiguous

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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.

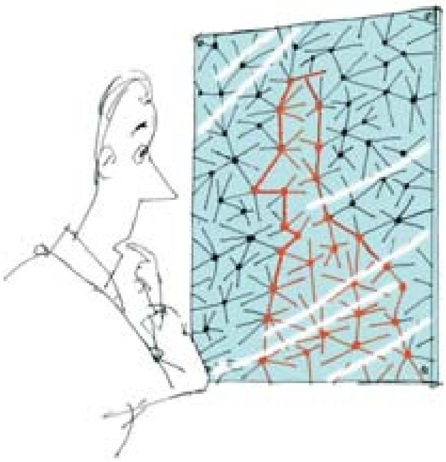
The possible values of volume and area are measured in units of a quantity called the Planck length. This length is related to the strength of gravity, the size of quanta and the speed of light. It measures the scale at which the geometry of space is no longer continuous. The Planck length is very small: 10^{-33} centimeter. The smallest possible nonzero area is about a square Planck length, or 10^{-66} cm^2. The smallest nonzero volume is approximately a cubic Planck length, 10^{-99} cm^3. Thus, 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 (10^{85}).

Spin Networks

WHAT ELSE DOES our theory tell us about spacetime? To start with, what do these quantum states of volume and area look like? Is space made up of a lot of little cubes or spheres? The answer is no—it's not that simple. Nevertheless, we can draw diagrams that represent the quantum states of volume and area. To those of us 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 that we have a lump of space shaped like a cube, as shown in the box on the opposite page. In our diagrams, we would depict this cube as a dot, which represents the volume, with six lines sticking out, each of which represents one of the cube's faces. We have to write a number next to the dot to specify the quantity of volume, and on each line we write a number to specify the area of the face that the line represents.

Next, suppose we put a pyramid on top of the cube. These two polyhedra, 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). It is clear how more complicated arrangements involving polyhedra other than cubes and pyramids could 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, and the lines join the nodes in the way that the faces join the polyhedra together. Mathematicians call these line diagrams graphs.



MATTER EXISTS at the nodes of the spin network.

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Now in our theory, 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 mathematics and other details of the quantum states are too complicated to discuss here; the best we can do is show some of the related diagrams.)

The graphs are a better representation of the quantum states than the polyhedra are. In particular, some graphs connect in strange ways that cannot 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, we often draw the graphs in two dimensions, but it is better to imagine them filling three-dimensional space, because that is what they represent. Yet there is a conceptual trap here: the lines and nodes of a graph do not live at specific locations in space. Each graph is defined only by the way its pieces connect together and how they relate to well-defined boundaries such as boundary B. The continuous, three-dimensional space that you are imagining the graphs occupy *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.

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. We were very pleased when we found, in 1994, that precise calculations confirmed his intuition. Readers familiar with Feynman diagrams should note that our spin networks are not Feynman diagrams, despite the superficial resemblance. Feynman diagrams represent quantum interactions between particles, which proceed from one quantum state to another. Our diagrams represent fixed quantum states of spatial volumes and areas.

The individual nodes and edges of the diagrams represent extremely small regions of space: a node is typically a

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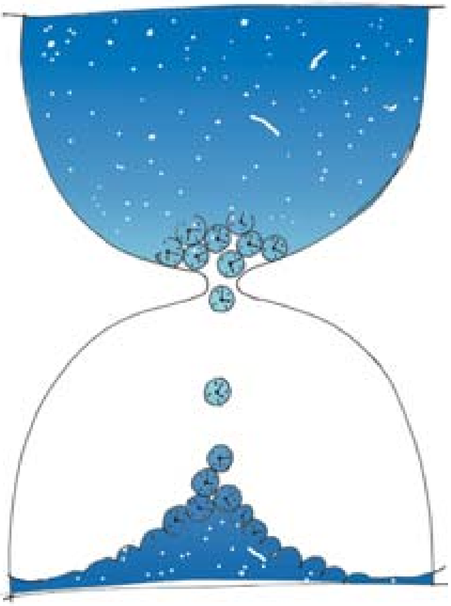
volume of about one cubic Planck length, and a line is typically an area of about one square Planck length. But in principle, nothing limits how big and complicated a spin network can be. If we could draw a detailed picture of the quantum state of our universe—the geometry of its space, as curved and 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 what about all the matter and energy contained in that space? 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.

Moves and Foams

PARTICLES AND FIELDS are not the only things that move around. 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 [see "Ripples in Space and Time," by W. Wayt Gibbs; SCIENTIFIC AMERICAN, April 2002]. 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 [*see box on opposite page*].

When physicists describe phenomena quantum-mechanically, they compute probabilities for different processes. We do the same when we apply loop quantum gravity theory to describe phenomena, whether it be particles and fields moving on the spin networks or the geometry of space itself evolving in time. In particular, Thomas Thiemann of the Perimeter Institute for Theoretical Physics in Waterloo, Ontario, has derived precise quantum probabilities for the spin network moves. With these the theory is completely specified: 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. It remains only to do the computations and work out predictions for what could be observed in experiments of one kind or another.



TIME ADVANCES by the discrete ticks of innumerable clocks.

Einstein's theories of special and general relativity join space and time together into the single, merged entity known as 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 (the moves discussed earlier) are now represented by nodes where the lines meet in the foam. The spin foam picture of spacetime was proposed by several people, including Carlo Rovelli, Mike Reisenberger (now at the University of Montevideo), John Barrett of the University of Nottingham, Louis Crane of Kansas State University, John Baez of the University of California, Riverside, and Fotini Markopoulou of the Perimeter Institute for Theoretical Physics.

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, as shown in the box on the opposite page. 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. Or, 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.

Predictions and Tests

I HAVE OUTLINED what loop quantum gravity has to say about space and time at the Planck scale, but we cannot verify the theory directly by examining spacetime on that scale. It is too small. So how can we test the theory? An important test is whether one can derive classical general relativity as an approximation to loop quantum gravity. In other words, if the spin networks are like the threads woven into a piece of cloth, this is analogous to asking whether we can compute the right elastic properties for a sheet of the material by averaging over thousands of threads. Similarly, when averaged over many Planck lengths, do spin networks describe the geometry of space and its evolution in a way that agrees roughly with the "smooth cloth" of Einstein's classical theory? This is a difficult problem, but recently researchers have made progress for some cases—for certain configurations of the material, so to speak. For example, long-wavelength gravitational waves propagating on otherwise flat (uncurved) space can be described as excitations of specific quantum states described by the loop quantum gravity theory.

Another fruitful test is to see what

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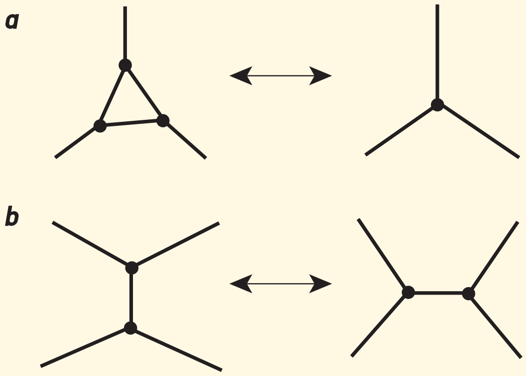
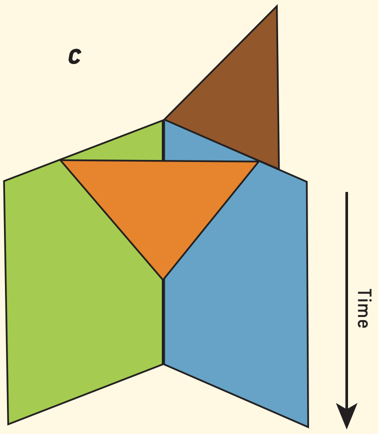
loop quantum gravity has to say about one of the long-standing mysteries of gravitational physics and quantum theory: the thermodynamics of black holes, in particular their entropy, which is related to disorder. Physicists have computed predictions regarding black hole thermodynamics using a hybrid, approximate theory in which matter is treated quantum-mechanically but spacetime is not. A full quantum theory of gravity, such as loop quantum gravity, should be able to reproduce these predictions. Specifically, in the 1970s Jacob D. Bekenstein, now at the Hebrew University of Jerusalem, inferred that black holes must be ascribed an entropy proportional to their surface area [see "Information in the Holographic Universe," by Jacob D. Bekenstein; Scientific American, August 2003]. Shortly after, Stephen W. Hawking of the University of Cambridge deduced that black holes, particularly small ones, must emit radiation. These predictions are among the greatest results of theoretical physics in the past 30 years.

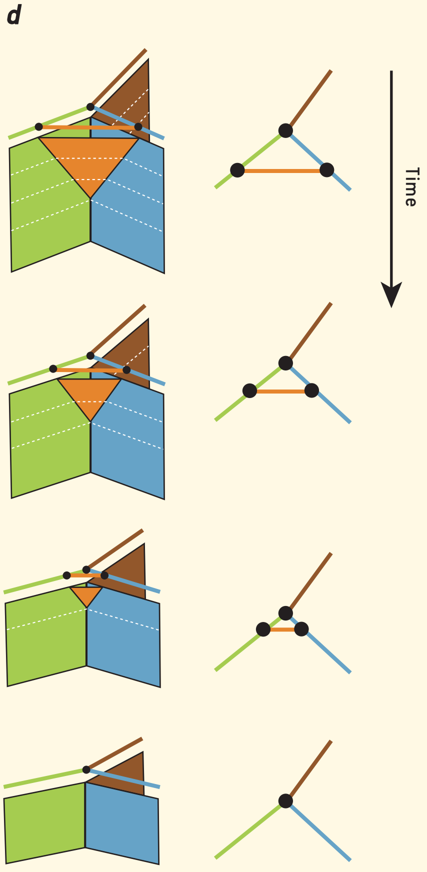
EVOLUTION OF GEOMETRY IN TIME

Changes in the shape of space—such as those occurring when matter and energy move around within it and when gravitational waves flow by—are represented by discrete rearrangements, or moves, of the spin network. In *a,* a connected group of three volume quanta merge to become a single volume quantum; the reverse process can also occur. In *b,* two volumes divide up space and connect to adjoining volumes in a different way. Represented as polyhedra, the two polyhedra would merge on their common face and then split like a crystal cleaving on a different plane. These spin-network moves take place not only when large-scale changes in the geometry of space occur but also incessantly as quantum fluctuations at the Planck scale.



Another way to represent moves is to add the time dimension to a spin network—the result is called a spin foam (*c*). The lines of the spin network become planes, and the nodes become lines. Taking a slice through a spin foam at a particular time yields a spin network; taking a series of slices at different times produces frames of a movie showing the spin network evolving in time (*d*). But notice that the evolution, which at first glance appears to be smooth and continuous, is in fact discontinuous. All the spin networks that include the orange line (*first three frames shown*) represent exactly the same geometry of space. The length of the orange line doesn't matter—all that matters for the geometry is how the lines are connected and what number labels each line. Those are what define how the quanta of volume and area are arranged and how big they are. Thus, in *d,* the geometry remains constant during the first three frames, with 3 quanta of volume and 6 quanta of surface area. Then the geometry changes discontinuously, becoming a single quantum of volume and 3 quanta of surface area, as shown in the last frame. In this way, time as defined by a spin foam evolves by a series of abrupt, discrete moves, not by a continuous flow.



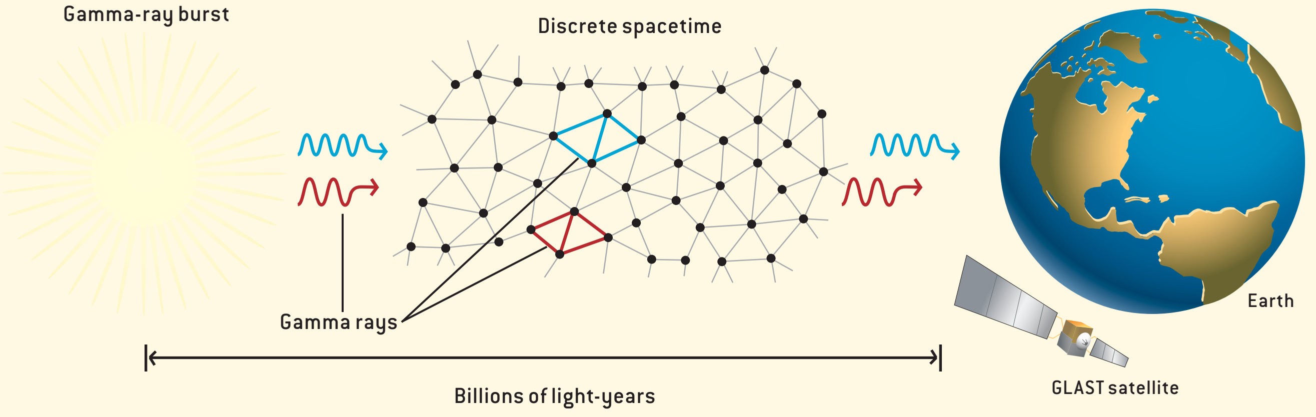


Although speaking of such sequences as frames of a movie is helpful for visualization, the more correct way to understand the evolution of the geometry is as discrete ticks of a clock. At one tick the orange quantum of area is present; at the next tick it is gone—in fact, the disappearance of the orange quantum of area *defines* the tick. The difference in time from one tick to the next is approximately the Planck time, 10^{-43} second. But time *does not exist* in between the ticks; there is no "in between," in the same way that there is no water in between two adjacent molecules of water.

NADIA STRASSER; SOURCE: *A* AND *B* ADAPTED FROM FOTINI MARKOPOULOU (http://arxiv.org/abs/gr-qc/9704013/); *C* ADAPTED FROM CARLO ROVELLI (http://arxiv.org/abs/gr-qc/9806121/)

AN EXPERIMENTAL TEST

Radiation from distant cosmic explosions called gamma-ray bursts might provide a way to test whether the theory of loop quantum gravity is correct. Gamma-ray bursts occur billions of light-years away and emit a huge amount of gamma rays within a short span. According to loop quantum gravity, each photon occupies a region of lines at each instant as it moves through the spin network that is space (in reality a very large number of lines, not just the five depicted here). The discrete nature of space causes higher-energy gamma rays to travel slightly faster than lower-energy ones. The difference is tiny, but its effect steadily accumulates during the rays' billion-year voyage. If a burst's gamma rays arrive at Earth at slightly different times according to their energy, that would be evidence for loop quantum gravity. The GLAST satellite, which is scheduled to be launched in 2007, will have the required sensitivity for this experiment.



To do the calculation in loop quantum gravity, we pick the boundary B to be the event horizon of a black hole. When we analyze the entropy of the relevant quantum states, we get *precisely* the prediction of Bekenstein. Similarly, the theory reproduces Hawking's prediction of black hole radiation. In fact, it makes further predictions for the fine structure of Hawking radiation. If a microscopic black hole were ever observed, this prediction could be tested by studying the spectrum of radiation it emits. That may be far off in time, however, because we have no technology to make black holes, small or otherwise.

Indeed, any experimental test of loop quantum gravity would appear at first to be an immense technological challenge. The problem is that the characteristic effects described by the theory become significant only at the Planck scale, the very tiny size of the quanta of area and volume. The Planck scale is 16 orders of magnitude below the scale probed in the highest-energy particle accelerators currently planned (higher energy is needed to probe shorter-distance scales). Because we cannot reach the Planck scale with an accelerator, many people have held out little hope for the confirmation of quantum gravity theories.

In the past several years, however, a few imaginative young researchers have thought up new ways to test the predictions of loop quantum gravity that can be done now. These methods depend on the propagation of light across the universe. When light moves through a medium, its wavelength suffers some distortions, leading to effects such as bending in water and the separation of different wavelengths, or colors. These effects also occur for light and particles moving through the discrete space described by a spin network.

Unfortunately, the magnitude of the effects is proportional to the ratio of the Planck length to the wavelength. For visible light, this ratio is smaller than 10^{-28}; even for the most powerful cosmic rays ever observed, it is about one billionth. For any radiation we can observe, the effects of the granular structure of space are very small. What the young researchers spotted is that these effects accumulate when light travels a long distance. And we detect light and particles that come from billions of light years away, from events such as gamma-ray bursts [see "The Brightest Explosions in the Universe," by Neil Gehrels, Luigi Piro and Peter J. T. Leonard; Scientific American, December 2002].

A gamma-ray burst spews out photons in a range of energies in a very brief explosion. Calculations in loop quantum gravity, by Rodolfo Gambini of the University of the Republic in Uruguay, Jorge Pullin of Louisiana State University and others, predict that photons of different energies should travel at slightly different speeds and therefore arrive at slightly different times [*see box above*]. We can look for this effect in data from satellite observations of gamma-ray bursts. So far the precision is about a factor of 1,000 below what is needed, but a new satellite observatory called GLAST, planned for 2007, will have the precision required.

The reader may ask if this result would mean that Einstein's theory of special relativity is wrong when it predicts a universal speed of light. Several people, including Giovanni Amelino-Camelia of the University of Rome "La Sapienza" and João Magueijo of Imperial College London, as well as myself, have developed modified versions of

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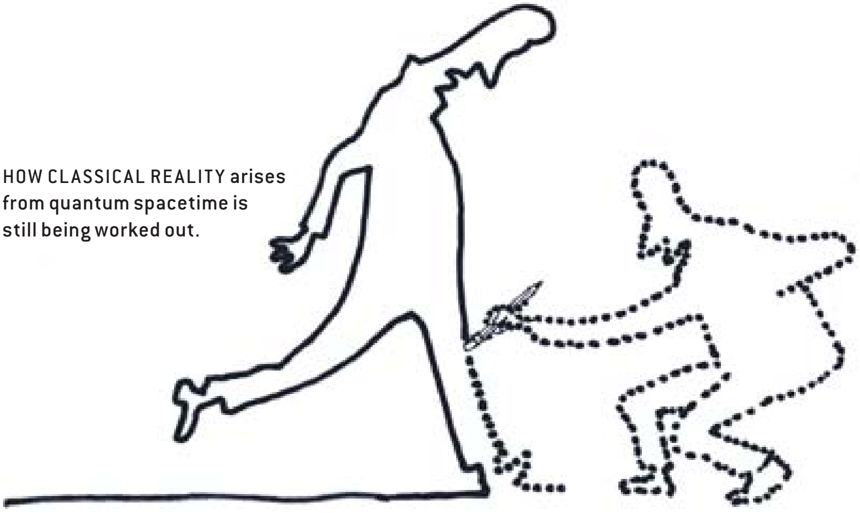
Einstein's theory that will accommodate high-energy photons traveling at different speeds. Our theories propose that the universal speed is the speed of very low energy photons or, equivalently, long-wavelength light.

Another possible effect of discrete spacetime involves very high energy cosmic rays. More than 30 years ago researchers predicted that cosmic-ray protons with an energy greater than 3×10^{19} electron volts would scatter off the cosmic microwave background that fills space and should therefore never reach the earth. Puzzlingly, a Japanese experiment called AGASA has detected more than 10 cosmic rays with an energy over this limit. But it turns out that the discrete structure of space can raise the energy required for the scattering reaction, allowing higher-energy cosmic-ray protons to reach the earth. If the AGASA observations hold up, and if no other explanation is found, then it may turn out that we have already detected the discreteness of space.



HOW CLASSICAL REALITY arises from quantum spacetime is still being worked out.

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The Cosmos

IN ADDITION to making predictions about specific phenomena such as high-energy cosmic rays, loop quantum gravity has opened up a new window through which we can study 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, but this conclusion ignores quantum physics (because general relativity is not a quantum theory). Recent loop quantum gravity calculations by Martin Bojowald of the Max Planck Institute for Gravitational Physics in Golm, Germany, 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. It is not impossible that in our lifetime we could see evidence of the time before the big bang.

A question of similar profundity concerns the cosmological constant—a positive or negative energy density that could permeate "empty" space. Recent observations of distant supernovae and the cosmic microwave background strongly indicate that this energy does exist and is positive, which accelerates the universe's expansion [see "The Quintessential Universe," by Jeremiah P. Ostriker and Paul J. Steinhardt; SCIENTIFIC AMERICAN, January 2001]. Loop quantum gravity has no trouble incorporating the positive energy density. This fact was demonstrated in 1990, when Hideo Kodama of Kyoto University wrote down equations describing an exact quantum state of a universe having a positive cosmological constant.

Many open questions remain to be answered in loop quantum gravity. Some are technical matters that need to be clarified. We would also like to understand how, if at all, special relativity must be modified at extremely high energies. So far our speculations on this topic are not solidly linked to loop quantum gravity calculations. In addition, we would like to know that classical general relativity is a good approximate description of the theory for distances much larger than the Planck length, in all circumstances. (At present we know only that the approximation is good for certain states that describe rather weak gravitational waves propagating on an otherwise flat spacetime.) Finally, we would like to understand whether or not loop quantum gravity has anything to say about unification: Are the different forces, including gravity, all aspects of a single, fundamental force? String theory is based on a particular idea about unification, but we also have ideas for achieving unification with loop quantum gravity.

Loop quantum gravity occupies a very important place in the development of physics. It is arguably *the* quantum theory of general relativity, because it makes no extra assumptions beyond the basic principles of quantum theory and relativity theory. The remarkable departure that it makes—proposing a discontinuous spacetime described by spin networks and spin foams—emerges from the mathematics of the theory itself, rather than being inserted as an ad hoc postulate.

Still, everything I have discussed is theoretical. It could be that in spite of all I have described here, space really is continuous, no matter how small the scale we probe. Then physicists would have to turn to more radical postulates, such as those of string theory. Because this is science, in the end experiment will decide. The good news is that the decision may come soon.

MORE TO EXPLORE

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