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SPECIAL ISSUE

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A MATTER OF TIME

Time's Mysterious Physics

Building Time Machines

The Mind and Time

Ultimate Clocks

The Philosophy of Time

The Body's Clocks

Time and Culture

And more . . .

september 2002

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SPECIAL ISSUE: A MATTER OF TIME

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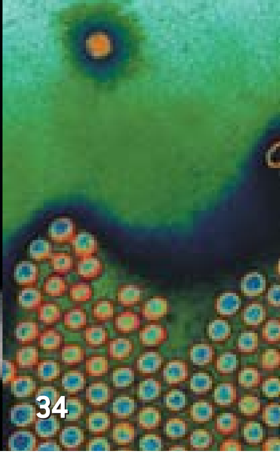

columns

Cover image by Tom Draper Design

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The Chronic Complaint

What time is it?

That simple question is probably asked more often today than ever. In our clock-studded society, the answer is never more than a glance away, and so we can blissfully partition our days into ever smaller increments for ever more tightly scheduled tasks, confident that we will always know it is 7:03 P.M.

Modern scientific revelations about time, however, make the question endlessly frustrating. If we seek a precise knowledge of the time, the elusive infinitesimal of "now" dissolves into a scattering flock of nanoseconds. Bound by the speed of light and the velocity of nerve impulses, our perceptions of the present sketch the world as it was an instant ago—for all that our consciousness pretends otherwise, we can never catch up. Even in principle, perfect synchronicity escapes us. Relativity dictates that, like a strange syrup, time flows slower on moving trains than in the stations and faster in the mountains than in the valleys. The time for our wristwatch is not exactly the same as the time for our head. It is roughly 7:04 P.M.

RON CHAPPLE *Getty Images*

Our intuitions are deeply paradoxical. Time heals all wounds, but it is also the great destroyer. Time is relative, but also relentless. There is time for every purpose under heaven, but there is never enough. Time flies, crawls and races. Seconds can be both split and stretched. Like the tide, time waits for no man, but in dramatic moments it also stands still. It is as personal as the pace of one's heartbeat but as public as the clock tower in the town square. We do our best to reconcile the contradictions. It seems like 7:05 P.M.

And of course, time is money. It is the partner of change, the antagonist of speed, the currency in which we pay attention. It is our most precious, irreplaceable commodity. Yet still we say we don't know where it goes, and we sleep away a third of it, and none of us really can account for how much we have left. We can find 100 ways to save time, but the amount remaining nonetheless diminishes steadily. It is already 7:06 P.M.

Time and memory shape our perceptions of our own identity. We may feel ourselves to be at history's mercy, but we also see ourselves as free-willed agents of the future. That conception is disturbingly at odds with the ideas of physicists and philosophers, however, because if time is a dimension like those of space, then yesterday, today and tomorrow are all equally concrete and determined. The future exists as much as the past does; it is just in a place that we have not yet visited. Somewhere, it is 7:07 P.M.

"Time is the substance from which I am made," Argentine writer Jorge Luis Borges wrote. "Time is a river which carries me along, but I am the river; it is a tiger that devours me, but I am the tiger; it is a fire that consumes me, but I am the fire." This special issue of *Scientific American* summarizes what science has discovered about how time permeates and guides both our physical world and our inner selves. That knowledge should enrich the imagination and provide practical advantages to anyone hoping to beat the clock or at least to stay in step with it. It is now 7:08 P.M. Synchronize your watches.

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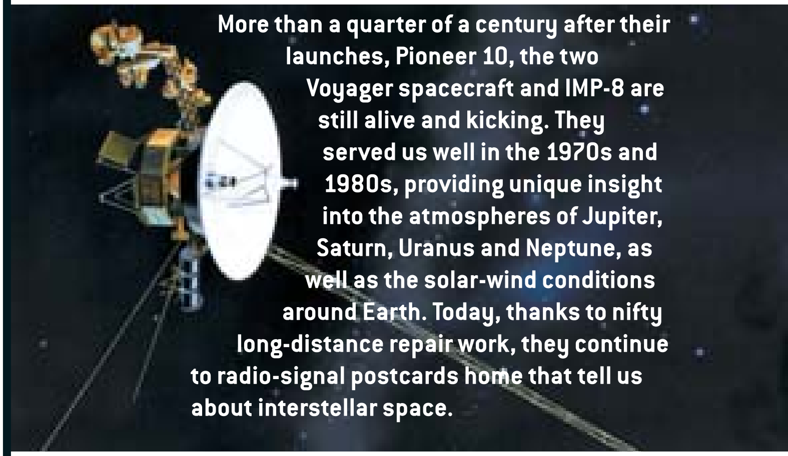
The Little Spacecraft That Could



More than a quarter of a century after their launches, Pioneer 10, the two Voyager spacecraft and IMP-8 are still alive and kicking. They served us well in the 1970s and 1980s, providing unique insight into the atmospheres of Jupiter, Saturn, Uranus and Neptune, as well as the solar-wind conditions around Earth. Today, thanks to nifty long-distance repair work, they continue to radio-signal postcards home that tell us about interstellar space.

Multilingual Machines

Sure, you can download free software from the Internet that will translate a document in, say, Italian, into English. But these programs are only 70 to 80 percent accurate. Moreover, they are generally available for only certain languages. Although it's relatively easy to get a translation from Italian into English, it's harder to get a translation from Swahili into English—or Swahili into Russian. Reliable translations have always required the services of a human.

Now the tide may be turning. A company called Fluent Machines has developed software that conducts a statistical analysis of large volumes of translated documents to improve the likelihood of correct translation. Is it a real solution? Only time will tell, but the idea seems promising.

ASK THE EXPERTS

Why do we yawn?

Mark A. W. Andrews, associate professor of physiology at the Lake Erie College of Osteopathic Medicine, provides an answer.

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Letters

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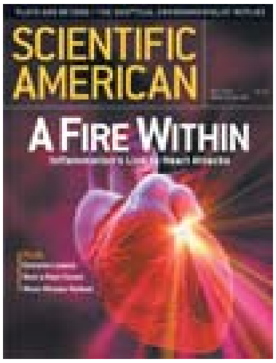
"AS AN IP PROFESSIONAL, I can accurately state that while Gary Stix may be correct regarding copyrights in 'IP Rights—and Wrongs' [Staking Claims, May 2002], he is mostly wrong about patents," writes Sheridan Neimark of Washington, D.C. "Rather than going 'too far in strengthening' patent rights, the Federal Circuit has weakened them considerably, enabling big companies to more easily take the innovations of private inventors and small companies without compensation. Further, the recent increase in patents can be attributed at least in part to government actions in the 1970s and 1980s to protect the value of patents. One example was the Bayh-Dole Act of 1980, which has largely resulted in the creation of the biotech industry.

"*The Patent Office Pony* tells of the opening of Japan in the 19th century. Japan's leaders sent an emissary to learn why the U.S. was so successful. His answer: the patent system."

As the following pages devoted to other topics in the May 2002 issue demonstrate, the marketplace of ideas is still strong.



ATHEROSCLEROSIS QUESTIONS

Regarding "Atherosclerosis: The New View," by Peter Libby: If LDLs' getting stuck in the arterial wall is the initiating factor in atherosclerosis, why would the resulting plaques not be system-wide? And why are not veins similarly vulnerable to such plaque formation? Why do veins harvested for bypass operations to replace diseased arteries sometimes develop plaques?

Richard C. Betancourt
New York City

Could hypertension be a cause of the inflammation cited as the initiator of atherosclerosis? Could excess strain on artery walls result in damage with an accompanying inflammation response? If so, might this lead to a vicious cycle, wherein the increased resistance caused by artery blockage could be overcome only by higher blood pressure? In turn, could this lead to more inflammation?

Greg Marlow
Warminster, Pa.

Although Libby writes that "the presence of C-reactive protein in the blood signifies that inflammation is occurring somewhere in the body," he never mentions the most frequent causes of chronic inflammations, such as gingivitis and the resulting periodontitis. You missed an opportunity to inform readers that if they are at risk for a cardiovascular disease, besides maintaining a healthful diet, exercising and refraining from smoking, they should consult a periodontologist or a dentist to check for gum and jawbone inflammation.

Daniel van Steenberghe
Leuven, Belgium

LIBBY REPLIES: Some areas of the arterial tree show more atherosclerosis than others in part because plaque formation requires not only cholesterol but also a biomechanical stimulus, such as disturbed blood flow (which occurs at the branch points of arteries). Lower pressure in veins rather than in arteries helps to explain why veins generally lack plaques. When veins are subjected to arterial pressures, they, too, can become diseased.

Abnormally high blood pressure (hypertension) can contribute to atherosclerosis by promoting some of the biomechanical changes that predispose vessels to plaque accumulation. In addition, certain hormones involved in hypertension appear to encourage arterial inflammation.

Epidemiologists have observed a correlation between periodontal disease and cardiovascular risk. But they have yet to determine whether periodontal disease is a cause of vascular disease or whether something else, such as smoking, typically has a hand in both problems. I do agree, though, that any program to prevent cardiovascular disease should include a healthful diet, regular physical activity and abandonment of smoking.

Letters

COMPLEXITIES OF CONSERVATION

"Rethinking Green Consumerism," by Jared Hardner and Richard Rice, makes a good case for environmental payments and "conservation concessions" as tools for conserving tropical forests and biodiversity. Yet such payments will rarely provide an incentive to retire plantations of valuable crops of bananas, cocoa, coffee and oil palm. Even with concessions, the industry may just move on and clear forests elsewhere.

In many tropical places, green marketing provides a strong local incentive for improved timber management. Brazil and Bolivia both now have more than one million hectares of forest certified by the Forest Stewardship Council, and 20 Brazilian retailers are creating domestic markets for certified products.

There are strong ethical and conservation arguments in favor of environmental payments. But they are still experimental, and even if successful they will be just one addition to the range of approaches that thoughtful conservation organizations will employ. National parks, community forestry, green consumerism and good old-fashioned law enforcement are all needed more than ever.

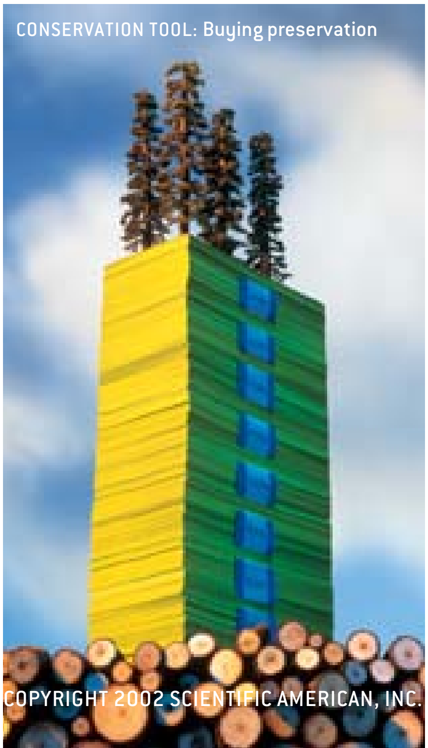
Chris Elliott, Director
Jeff Sayer, Senior Associate
World Wildlife Fund–International, Forests for Life Program, Gland, Switzerland
Bruce Cabarle, Director
Global Forest Program
Jason Clay, Senior Fellow
WWF-U.S., Washington, D.C.

HARDNER AND RICE REPLY: We agree that conservation is complex and requires a portfolio of approaches. We should clarify some points about our position, however. First, conservation concessions are not intended to substitute all land use in all places but rather specific priority sites identified as important for conservation. Second, those certain places are very often the target of agriculturalists and loggers operating on the economic margin, where profitability is low. Third, while we applaud efforts to reduce the ecological impact of agriculture and forestry, the cost of subsidizing these operations can be astronomical—in many cases, greater than the cost of a conservation concession. Conservationists should assess the range of strategies available to them at each site, and we expect that in a number of cases the financial logic of conservation concessions will make sense for local communities and conservationists alike.

WIRELESS WOES

Regarding "Wireless Data Blaster," by David G. Leeper: The wonderful metric of "spatial capacity" presented by Leeper needs to be enhanced to show the effects of multiple independent users. When that is done, UWB systems are not the best but perhaps the worst of the communications systems. If the playing field is leveled by imposing the real requirement of simultaneous high-speed communications among hundreds or thousands of independent users in the same small "spatial" area, while retaining the ability to receive hundreds of channels of "broadcast" information, UWB may take a seat in the broadcast realm, but I don't yet see it as a viable multiuser two-way point-to-point communications methodology.

John T. Armstrong
PROBE Science, Inc.
Pasadena, Calif.



CONSERVATION TOOL: Buying preservation

I saw no mention made of the danger of computer hackers getting into a person's wireless devices. What is being done to handle this problem?

Richard H. Smith
Burbank, Calif.

LEEPER REPLIES: UWB is more difficult to intercept than most wireless technologies. First, its range is so short: a high-speed UWB link beyond 10 meters is difficult to distinguish from background noise. Second, some forms of UWB modulation fire the pulses at pseudo-random time intervals, making it difficult for a receiver to lock on. Although these characteristics improve security, they are not enough. Data-encryption techniques can and should be used.

LONG LIVE D.I.Y.

As the onetime editor of *Scientific American*'s column the Amateur Scientist, I seldom disagree with my friend and former colleague George Musser, but he shouldn't be singing a requiem for D.I.Y. science just yet. He is right that today's amateur scientists build fewer of their own instruments than their predecessors did. But science has never been about making instruments. Rather science is about using instruments, as well as one's own eyes and ears, to learn more about how nature works and to share that knowledge.

A better measure of the health of D.I.Y. science is the number of ordinary people involved. The Society for Amateur Scientists supports hundreds who are pursuing their own research interests. Beyond us, hundreds of citizen scientists work paleontology digs every year. Tens of thousands monitor the health of their local waterways. Hundreds of thousands contribute data from bird-watching programs. Clearly, there's a lot of D.I.Y. science.

The "mentoring and serendipity" that Musser referred to has not been lost. These still attract young people to technical careers—more today, I suspect, than in the heyday of the Amateur Scientist column.

Shawn Carlson, Executive Director
Society for Amateur Scientists

PETE McARTHUR

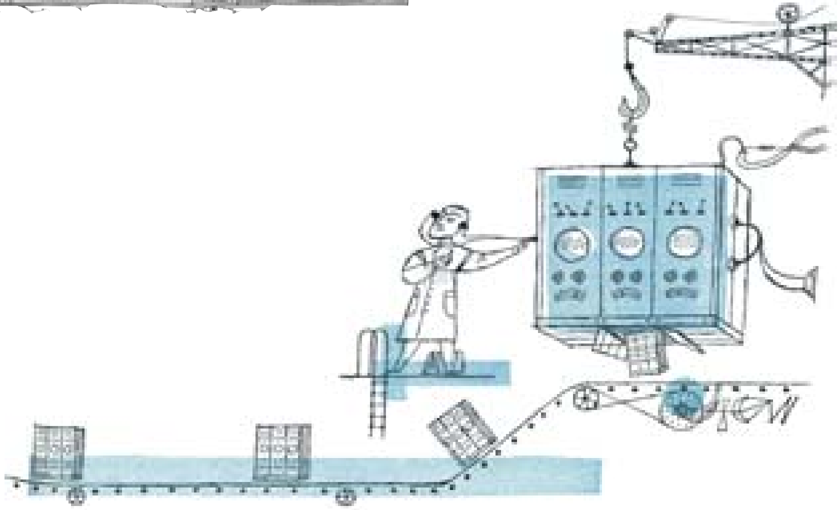
50, 100 & 150 Years Ago

FROM *SCIENTIFIC AMERICAN*

Evolving Machines ▪ Dammed Nile ▪ Shaky Stocks

SEPTEMBER 1952

SELF-REGULATION—"The title of this issue is 'Automatic Control.' The reader might well ask: 'Automatic control of what?' This issue is primarily concerned with the self-regulation of machines that do men's work. Many such machines exist today. What is more significant is that the tempo of their evolution is quickening [*see illustration*]. A new kind of engineer thinks not only of automatic machines but also of automatic factories. It is not beyond the bounds of reasonable imagination to think of automatic industries: even now large sectors of the communications industry control themselves. This acceleration of tempo amounts to a technological revolution that must powerfully influence the future of man."



FANCIFUL END POINT for machine evolution: self-reproduction, 1952

RUN, RABBIT, RUN—"During the past two years a great rabbit plague has run like a scared rodent across the length and breadth of Australia. The epidemic was man-made, and Australia thinks that it has finally found the answer to its century-long struggle with the fabulously prolific bunny. Myxomatosis is a virus disease that is fatal to rabbits but does not affect farm animals or people. Early attempts to plant it failed. But two years ago the Australians discovered that mosquitoes spread the disease from one animal to another. That was the key. The rabbit exterminators round up a large number of rabbits, inoculate them with the myxomatosis virus and shave their coats to provide bare patches on which mosquitoes can easily feed."

SEPTEMBER 1902

ASWAN DAM—"The new monumental dam at Assouan [*sic*], by far the greatest achievement of its kind in ancient or modern times, which will form a reservoir in the Nile Valley capable of storing 1,000,000,000 tons of water, will not only produce a revolution in the primitive and laborious methods of irrigation in Egypt, but will reclaim for the uses of the husbandman vast areas of land that hitherto have been accounted arid and worthless desert. The old system of irrigation was little more than a high Nile flooding of different areas of land or basins surrounded by embankments. Ship navigation is provided for by a 'ladder' of four locks, each 260 feet long by 32 feet wide."

SEPTEMBER 1852

A MYSTERIOUS FORCE—"The comet's tail is raised from the comet's body by the powers of sunshine, as mist is from damp ground. Not only a vapor-forming power, but also a vapor-drifting power, is evident in tail formation. This vapor-drifting force must be some occult agent of considerable interest from a scientific point of view, for it is a principle evidently antagonistic to the great prevailing attribute of gravitation. The comet's tail is the only substance known that is repelled instead of being attracted by the sun."

FETID WATER—"During the present season there has been a great number of cholera cases in the city of Rochester, N.Y., by which a great many of the citizens have been suddenly cut off. The 'Rochester American' believes that the present foul and stagnant condition of the Genesee River, consequent upon low water, may be one cause of the continued sickness. Some have asserted that the cholera is exclusively a geological disease; that is, it is never manifested in districts of primitive formations, such as the granite districts of New England. This theory is founded on very strong facts."

GOLDEN DREAMS—"It is exactly seven years since Mr. Rufus Porter's Flying Ship was illustrated and described in the Scientific American, and at that time it was represented to be a perfectly 'fixed fact.' We know that a scheme was established in 1849 to carry passengers to the gold fields of California by the Flying Ship, and some shares were taken up [sold]. The Flying Ship is a most useful invention, for it has been used to gull the people in our country for the past seven years." [*Editors' note: Porter founded this magazine in 1845 and sold it 10 months later.*]

news SCAN

[9/11: ONE YEAR LATER]

Unsettled Air

THE UNKNOWN HEALTH EFFECTS OF THE TOWERS' COLLAPSE

BY MARGUERITE HOLLOWAY

The site of the World Trade Center is now a flat, empty dirt expanse. But no one familiar with the devastation wrought on September 11 has forgotten the images of fire and smoke, the collapsing buildings, the sheets of dust that rushed through the streets of downtown Manhattan, and the smoldering piles of wreckage. For thousands of rescue workers and people who live in the vicinity, these dispersed vapors continue to menace. “One of the things that is clear is that the environmental sampling data does not fully explain what we are seeing,” says Robin Herbert of the Mount Sinai–Irving J. Selikoff Clinical Center for Occupational and Environmental Medicine in New York City. “You look at it and you would say that there shouldn’t be health problems, and yet we are seeing them.”

DANGEROUS DUST: Pollutants and particulates spewed from the destruction of the World Trade Center.

SUZANNE PLUNKETT *AP Photo*

Many studies are only just starting, but scientists do know what people were exposed to. Different agencies, universities and companies have sampled or analyzed the air and dust on-site and off. Although there are discrepancies among findings—and controversy surrounding some of the readings regarding asbestos and certain heavy metals—it is clear that the brew on-site was noxious. At various times, it included dioxins and other persistent organic pollutants, benzene, mercury, lead, fiberglass, sulfuric acid and particulate matter of varying sizes.

Thomas A. Cahill, an atmospheric scientist at the University of California at Davis, is most worried about the particulates. He found fine particles of silica in the samples he and his colleagues took about a mile north of the site, most of them 2.5 microns in diameter, a size that the Environmental Protection Agency regulates because it can cause heart and lung disease, respiratory problems and death. Cahill also found high concentrations of very fine particles, 0.26 micron in diameter, which he says may have worse heart and lung effects.

Taken together, the particulate matter and the other airborne compounds mark a medical mystery. “The whole issue of science looking at multiple effects is not robust,” notes Peter Iwanowicz of the American Lung Association of New York State. “We don’t have good data on fine particles and cement dust and then on what happens when someone breathes high levels of diesel exhaust”—as many workers and nearby residents did because of the ever present trucks carting away material. Or, Cahill asks, what happens when sulfuric acid damages the lungs, which are

PULVERIZED REMAINS of the towers coated apartment interiors nearby.

then exposed to microscopic particles? Many workers experienced the full force of those synergistic effects because they were working without respirators, contrary to Occupational Safety and Health Administration guidelines. The federal agency “stepped back from strict enforcement,” says lawyer Eric A. Goldstein of the Natural Resources Defense Council. “That increased risks to those who spent weeks and months at the trade center site.” Rescue workers have already reported respiratory health problems—among them nearly 5,000 firefighters, 500 of whom took medical leave. Herbert and her colleagues at Mount Sinai have patients with upper and lower respiratory problems, chronic sinusitis, irritation of the nasal passages, bronchitis and asthma. As of July, she says, “we have patients who have significant effects and a few who are disabled from work.”

Away from the site, the concentrations of particulates resulting from the months-long burning dispersed quickly. “We haven’t seen any evidence of exposure that would be likely to have long-term health effects,” says George D. Thurston of New York University’s Nelson Institute of Environmental Medicine. Thurston and his team collected air samples about four blocks away from Ground Zero, starting a few days after the attack until the end of December, when the fires were finally out. For the most part, people with respiratory ailments would have been affected, he says. And a small subset may still be sensitized to air pollution, Iwanowicz notes.

The complete medical legacy of the September 11 disaster may never be known, because groups of people continue to fall through the cracks. So far there is no comprehensive registry to follow everyone—only a series of registries and studies at universities and medical institutions. Moreover, some workers who were hired to clean up surrounding buildings have reported persistent respiratory problems, according to physician Steven Markowitz of Queens College. Many of them have no health coverage and are unlikely to find themselves in long-term studies. “There is no way we can provide intervention or care or track whether there are ongoing health problems until we know the population that was out there,” says Joel A. Shufro of the New York Committee for Occupational Safety and Health. “It is a real public health failure.”

INDOOR DUSTUP

People living around the twin towers report ongoing respiratory problems, and one of their largest concerns has been persistent indoor dust. After a long debate about jurisdiction, the Federal Emergency Management Agency gave the EPA funds to test and clean apartments—and their ventilation systems—below Canal Street (which is about a mile north of Ground Zero). As of mid-July, 3,000 requests had come in, according to EPA spokesperson Mary Mears. The cleanup, as well as studies of pregnant women and their infants and a pulmonary study of 10,000 residents, should provide a fuller picture of community health.

QUYEN TRAN *AP Photo*

SECURITY

Staying Open

UNIVERSITIES WORRY ABOUT THE STRAIN ON ACADEMIC FREEDOM IN THE FACE OF CLASSIFIED RESEARCH

BY DANIEL G. DUPONT

This past July, at a Capitol Hill reception sponsored by the Coalition for National Security Research and the Association of American Universities, researchers from academia and government laboratories mingled with members of Congress and their staffs. Several schools and labs showed off technologies developed for military customers interested in fresh thinking on biological and chemical warfare defense and other national security areas. The mood at the reception was upbeat, but the complex relations among universities, government-funded labs and national security agencies have been put under new strains since September 11. Research universities such as the Massachusetts Institute of Technology have undertaken reviews of their policies on classified research, and many in academia have openly complained of government restrictions on publishing unclassified results.

Charles M. Vest, the president of M.I.T., remarked in a June speech to college and university attorneys that three issues of enormous importance have led to significant debate on campuses: the government’s enhanced tracking of international students at U.S. schools; a mandate to define "sensitive areas of study" for which the government "should not grant visas to students from certain countries"; and the necessity of securing scientific materials and research results in an appropriate way.

CLASSIFIED RESEARCH at M.I.T. is conducted away from the main campus, at its Lincoln Laboratory. But not many universities have that option.

M.I.T. LINCOLN LABORATORY

According to Vest, universities are nearly united on the need to track basic information on international students and scholars, although some say better computer systems are needed for such a task. As for the second issue, Vest believes the government is moving toward modified rules for student visas "in a thoughtful and careful manner."

The third issue is more complicated. Last fall M.I.T. established an ad hoc committee to study the access to and the disclosure of scientific information in the current security environment. Chaired by M.I.T. aeronautics professor Sheila E. Widnall, former secretary of the U.S. Air Force, the panel stated in June that "restrictions on access to select biological agents, the application of export control provisions to university researchers, and a growing pressure to treat research results as sensitive create a new landscape for faculty, students and M.I.T. as an institution." Its solution was to continue to ban classified research on campus but to allow it at secure, off-campus facilities, such as its Lincoln Laboratory.

But few universities have the luxury of consigning classified work to a separate domain. So most ban classified research as a matter of policy and hold sacrosanct the concept of "basic research"—an official term delineating certain categories of government funding. Yet maintaining that kind of policy has become tricky. James N. Siedow, vice provost for research at Duke University, observes that there were problems with a number of post–September 11 research grants, for which the government wanted more insight into research results before publication. In most cases, he says, the wording of an agreement could be modified slightly to allow Duke to do the studies, but in one case the university rejected a grant that would have given the military the right to approve the release of research results.

Universities got a scare earlier this year when a draft of a proposed Pentagon research policy suggested that additional restrictions on basic research might be looming. Eva J. Pell, vice president for research at Pennsylvania State University, summed up the feeling on campuses nationwide by noting that "imprudent moves to regulate publication could further threaten our ability to educate students." The Pentagon has since issued public assurances that such research will be kept in the open realm, although the publication of results deemed sensitive by the government—even when the research itself is unclassified—may continue to raise red flags. Flare-ups seem inevitable: possible army missile defense testing at the University of Alaska–Fairbanks last year kicked off a heated—and still unresolved—debate between the faculty and the administration over the university's policies on classified and sensitive research.

For government lab officials such as Jim C. I. Chang, director of the Army Research Office, preserving an open atmosphere on campuses is key from the military's standpoint. Basic research, Chang says, must be conducted in the unclassified realm to ensure the kind of long-range innovation his organization and others prize. "We don't want to stifle research," he says.

The National Academy of Sciences, in a June report on science, technology and terrorism, noted that debates on the free exchange of ideas always arise during wartime. The solution, according to the NAS, is communication. The government, the report states, should not restrict who can perform research or share in its results "without first engaging in a thoughtful process that includes consultation with the universities and solid, case-by-case study of the risks vs. the benefits of open scientific investigation." Judging by the tone of the July Capitol Hill reception, no one seems to disagree.

Daniel G. Dupont writes about defense technology issues from Washington, D.C.

CAMPUS IN THE CROSSHAIRS

Complicating the issue of how best to maintain academic openness in a post–September 11 world is that universities themselves can be integral to terrorist plots. John H. Marburger III, the director of the president's Office of Science and Technology Policy, said in an April speech that universities and other research institutions "are not only sources of solutions and advice, they are also potential targets and means of exploitation for terrorism. . . . They cannot ignore their responsibility to society for limiting the opportunities for such perversions of their educational and research missions."

CIVIL ENGINEERING

After the Fall

NEW THINKING TO MAKE SKYSCRAPERS SAFER

BY STEVEN ASHLEY

One year after the devastating attacks on New York City's 110-story, 1,365-foot-high World Trade Center towers, questions linger concerning the future of skyscrapers. After all, who wants to work or live in a grand, iconic structure that stands out in a crowd and thus makes an inviting target? "Despite the tragedy of the World Trade Center collapse, the skyscraper is here to stay," asserts A. Eugene Kohn, senior partner of Kohn Pedersen Fox Associates, a leading architectural firm in New York City. "Although there could be a hiatus in the construction of skyscrapers in the U.S. lasting as long as a decade, ultimately I think it'll just be a sad interlude in the ongoing history of tall buildings."

Kohn notes that the reasons for building lofty towers haven't changed: high land costs in congested cities, demanding economic needs (especially in fast-growing Asia) and the developers' egos. "A lot of great buildings get erected because somebody wants to make their mark on the skyline," he says. Kohn points to a pair of projects his firm has under way—Union Square (Kowloon Station) in Hong Kong and the Shanghai World Financial Center, each of which will be more than 1,500 feet high (about 100 stories) when completed around 2007. Neither effort has been altered much since the September 11 assaults, he says, because of conservative building codes in China that make for strong structures.

The attack did, however, lead engineers, architects and safety specialists to rethink high-rise design. Builders now favor more highly reinforced structures that "keep damaged buildings standing longer, so more people can escape," states Charles H. Thornton, chairman of the New York–based firm Thornton-Tomasetti Engineers, which engineered Kuala Lumpur's Petronas Towers, the world's tallest at 1,483 feet. The focus is on halting chain reactions of failures set off by triggering events such as bombs, plane crashes or major fires.

Modern tall buildings are engineered so that the central core supports the weight or gravity load of the structure, whereas the surrounding exterior columns work like outriggers to keep the tower from overturning or sliding when exposed to hurricane-force winds or earthquakes. Meanwhile the floors tie the inner frame to the outer one, bracing the entire edifice.

In the case of the World Trade Center, which was a state-of-the-art design in the late 1960s, the steel-mesh exterior skeleton was highly robust, but the steel-truss floor framing turned out to be quite fragile, and the central core was not designed to handle significant lateral (sideways) loads, Thornton explains. When the planes hit the towers, they knocked out many internal and exterior support columns and dislodged much of the sprayed-on fire insulation that had protected the steel members. Although the remaining structure readily supported the new loads transferred to them when the columns were lost, it then had to contend with the insidious effects of the aviation-fuel fire that set all the flammable contents of the floors alight. "It was the intense fuel fire and the following inferno that led to the collapse," he says. The federally sponsored study of the disaster came to the same conclusion.

Thornton thinks that future mega-skyscraper designs are likely to make greater use of concrete. Reinforced with steel rods, it will be employed to make structural members. Concrete will also encase steel components, shoring them up and insulating them from fire. Strengthening the structure will raise construction costs, but not by much. "The reinforcement should add no more than 2 to 3 percent to the total job cost," the engineer says. And although concrete buildings tend to be markedly heavier and bulkier than steel ones, clever design can avoid the bunker look, according to architect Kohn.

Architects plan to incorporate other safety features as well. Floors may be compartmentalized like naval vessels to stop the spread of frame failures and fire. Extremely strong load-transfer trusses inserted every 30 stories or so can isolate structural damage and avoid free-fall collapses. The progress of fires could be blocked by fireproof partitions and by ventilation systems that pressurize the floors both above and below the flames to

BENDING BUT NOT BREAKING?

A federally funded study of the cause of the twin towers' collapse points to the intense fires as the primary cause. But one physicist thinks that the towers could have collapsed immediately once the planes struck. Frank Moscatelli of Swarthmore College contends that the report's authors erred by focusing solely on force and omitting torque effects. Moscatelli calculates that the 7.7 million foot-tons of torque applied to the structure on contact with the speeding planes actually exceeded the buildings' 7.4-million-foot-ton resistance to wind loads. He thinks the buildings could have toppled on impact if their frames had not flexed to absorb much of the shock.

EXTERIOR STEEL LATTICE of the twin towers was evident during their construction.

AP PHOTO

contain smoke and heat, which would be vented out through exhaust shafts. Large water tanks at the tops of buildings could act as mass dampers to counteract any swaying from extreme lateral loads and as reservoirs for deluging fires.

A greater number of wider staircases better protected against the encroachment of fire and smoke are also likely. Designers will separate fire stairs so that the destruction of one does not mean the loss of the others. Independently ventilated and reinforced refuge floors or zones, where occupants could go to wait out a blaze, can be positioned every 15 stories or so. High-speed lifts for firefighters that can rise to the top of a building in a minute could be installed as well.

Despite these measures, however, experts emphasize that there must be a first line of defense in protecting skyscrapers—namely, it must be to stop terrorist attacks from occurring at all.

CLIMATE

Dampened Swings

The air traffic shutdown following the September 11 attacks gave scientists an unexpected chance to measure the climatic effect of airplanes. Contrails, which develop when water vapor released in aircraft exhaust fumes spontaneously turns to ice, can form at altitudes and humidities that do not support normal clouds. The puffy trails cool the upper atmosphere by reflecting sunlight away and warm the lower atmosphere by trapping outgoing heat. Climatologists think that contrails exert a net warming influence, perhaps as large as 2 percent of the global warming resulting from greenhouse gases.

WISPY CONTRAILS hover over Maryland and nearby states in this false-color image taken in January 2001. Dark pink areas indicate snow-covered regions.

The three-day grounding of commercial aircraft last year has provided some insights on contrails' effects. Atmospheric scientist David J. Travis of the University of Wisconsin–Whitewater studied data from 4,000 weather stations covering the September 11–14 period. He saw an increase in the daily swing of high and low temperatures of 1 degree Celsius, suggesting that contrails dampen the diurnal temperature range. With air traffic expected to grow by 2 to 5 percent annually during the next 50 years, contrails could have significant climatic effects by 2050. Travis's work appears in the August 8 *Nature*. *—Zeeya Merali*

SECURITY

Science to the Rescue

"America's historical strength in science and engineering is perhaps its most critical asset in countering terrorism," says a recent report by the National Academies. It calls for more research into pathogens to fight bioterrorism, the development of blast-resistant buildings and the introduction of adaptive electrical grids to enable rapid power recovery. Its most important recommendation, according to report committee co-chair Lewis M. Branscomb, is to create "networks of new sensors that can detect explosives and other threats without requiring personal searches of our citizens." It also emphasizes the need for science-literate spokespeople to calm the public during crises. A proposed Homeland Security Institute, costing around $40 million a year, would coordinate the projects. With additional plans to strengthen the Internet, transport systems and telecommunications, the guidelines would also protect the nation against natural disasters, infectious diseases, hackers, and failures in public services. For a copy of the report, see http://books.nap.edu/html/stct/index.html *—Zeeya Merali*

DATA POINTS: CLOSURE

The largest forensic investigation in U.S. history continues in the aftermath of the September 11 attacks. Officials hope that with modern genetic analyses, half to two thirds of the victims at the World Trade Center site will be identified. Labs across the nation contribute to the effort; data funnel to the Office of the Chief Medical Examiner in New York City, which updates the figures twice daily. Numbers below are as of July 9, 2002.

Total number of dead or missing at World Trade Center:	2,823
Total identified:	1,215
Whole bodies recovered:	293
Body parts recovered:	19,693
Percent first identified by	
DNA:	41.7%
Dental x-rays:	27.8%
Fingerprints:	8.3%
All other (including visible remains and personal belongings):	22.1%

SOURCE: New York City Office of the Chief Medical Examiner. Total number of victims may drop as fraudulent claims are discovered. Dead or missing at the Pentagon: 184; at the Pennsylvania crash site: 40.

NASA

DEFENSE TECH

Training for Terror

IN CANADA, U.S. MARINES FIND A PLACE TO LEARN HOW TO HANDLE LIVE CHEMICAL AND BIOLOGICAL WARFARE AGENTS

BY MARTY KLINKENBERG

Marines dressed in hazmat suits stand at the edge of a prairie, pockmarked with gopher holes, in southern Alberta. Thirty yards away a 250-milliliter bottle of mustard agent—a cupful capable of spreading a quarter of a mile and affecting a few thousand people—is about to explode. A tentlike device called Blastguard has been placed over the bottle, and a substance similar to firefighting foam has been pumped into the tent to suppress the blast energy and to keep the mustard from dispersing. A few feet from the Blastguard stands a container marked "CDC." The U.S. Centers for Disease Control and Prevention sent the container, used to carry antidotes for a biological attack, to see if the tent could shield the contents from contamination.

TOXIC PRACTICE: Marines "rescue" a mannequin in a rubble pile tainted with live lethal agents.

Soon the mustard bottle is detonated, producing a muffled blast. Less than 20 minutes later the tent is opened, and the marines can find no trace of mustard, even with sophisticated detection equipment. "Witness paper" taped to the side of the CDC container comes up blank, too—if droplets of mustard gas were in the air, it would have visibly stained the dye in the paper. "This is totally amazing," says Lt. Col. Scott Graham, executive officer of the marines' unit, based in Indian Head, Md. "It's almost like something out of a science-fiction movie."

Elite forces and emergency response teams from all over the world train at the Canada Forces Base in Suffield. A half-hour's drive northwest of Medicine Hat, the base is one of the few places where live chemical agents can be tested outdoors. Environmental laws bar similar testing in the U.S., so military personnel have had to make do with mock agents—which results in an unrealistic experience. "No matter how hard you try to pretend" that a fake compound is real, says Chief Warrant Officer Robert A. Murphy, a 21-year veteran of the Marine Corps, "you know in the back of your head that it isn't."

So in the past two years the marines' response force to chemical-biological incidents has come to Canada to learn how to deal with live compounds. For a week in May, 73 marines handled an array of deadly nerve agents, including sarin, soman, tabun, cyclosarin (GF) and VX, as well as the blister agents mustard and lewisite. Directed by Graham, the marines raided a mock terrorist laboratory containing a lethal dose of sarin, extricated victims from contaminated rubble, swept through a mailroom after the detonation of a chemical bomb, and tested detection and decontamination equipment in tense lab exercises.

The field tests were orchestrated by NBC Team, Ltd., a firm based in Fort Erie, Ontario. It produces Blastguard and other counterterrorism products, including a broad-spectrum skin lotion that removes and destroys agents on contact. The latter invention, called reactive skin decontamination lotion, was developed primarily by J. Garfield Purdon of Defense Research and Development Canada in Suffield. Canadian soldiers used the lotion during the Gulf War, in Iraq and in the former Yugoslavia; U.S., British, Australian and NATO forces now pack it. It contains a potassium salt mixed with a solvent that encourages a reaction between potassium ions and the chemical agents.

To decontaminate vehicles, machinery and other bulky surfaces, Purdon worked with his colleague Andrew Burczyk to invent CASCAD (Canadian Aqueous System for Chemical-biological Agent Decontamination), which is a buffered hypochlorite solution combined with a surfactant and a solvent. CASCAD closes over the contaminants, thereby eliminating outgassing and associated downwind hazards.

NBC Team designed the Blastguard system using prototypes from ordinary tents purchased from Canadian Tire (Canada's answer to Sears). The proprietary material consists of three layers of ballistic felt that encapsulates shrapnel and absorbs its energy by stretching

MAINTAINING A CHEMICAL BASE

Horrific casualties inflicted during World War I and World War II prompted Canada to engage in aggressive research in chemical and biological defense that the country has maintained for more than 50 years. The base at Suffield, Alberta, is the headquarters for Defense Research and Development Canada's laboratories, where government scientists work to mitigate the effects of chemical and biological weapons and to support the efforts of private firms. It is also the principal high-intensity conflict training area for the British army and NATO forces.

DEDDEDA STEMLER

up to 900 percent. It works in conjunction with a foam that contains billions of tiny bubbles. When the blast wave expands, it breaks the bubbles and thereby loses energy.

"I am ecstatic," CWO Murphy states as the week of testing nears its end. "It was an opportunity to apply all the science and chemistry I had learned and to see how things work." More important, Murphy explains, the marines could handle the real stuff safely "and are confident they can do it again."

Marty Klinkenberg is a writer based in New York City.

TELECOM

Radio Space

A RENEGADE PLAN TO SHOW THAT SPECTRUM ISN'T SCARCE

BY WENDY M. GROSSMAN

It is a truth universally acknowledged that radio-frequency spectrum is scarce in the U.S. Increasingly, however, the contention is that spectrum is scarce the way diamonds are scarce: the supply isn't infinite, but the extreme scarcity is artificial. The policies under which the Federal Communications Commission has allocated spectrum space since 1927 are being challenged by the same combination of new technology and rebellious thinking that helped the Internet revolutionize telecommunications. Combining these approaches is Dewayne Hendricks, who is both chair of the spectrum management working group for the FCC's Technological Advisory Council and renegade leader of a scheme to get the FCC to change its policy.

In managing the spectrum, the FCC sells licenses to discrete portions of the airwaves. Buyers can use the spectrum for only a single purpose, and they may not subdivide, aggregate, buy or sell it. The upshot is that a broadcaster has more space than is needed to transmit a program. This management approach dates back to the 1920s, when a certain amount of wasted space was necessary for the technology of the time. But today computing power and software can get around the limitations. One such technology is spread spectrum, which is less prone to interference and uses bandwidth more efficiently. Transmissions are also more secure and difficult to jam.

Proponents of such dynamic systems point to the unlicensed 2.4-gigahertz band as an example of the potential innovation that could take place if the FCC were to unburden the airwaves. Several kinds of technologies already coexist at 2.4 GHz: wireless networks such as Bluetooth and 802.11, cordless telephones and ham radio. Having been involved in installing wireless links and Internet access in Mongolia and Tonga, Hendricks is currently working on setting up wireless broadband on existing radio frequencies (he won't be specific as to the exact technology). To avoid FCC regulations, he's taken his project to tribal nations. The legal theory: they have sovereignty not just on their lands but also over the airwaves. The policy theory: if tribal nations have it and the rest of the U.S. doesn't, the FCC will be embarrassed into changing its rules.

The FCC is responding to the pressure. In June it formed the Spectrum Policy Task Force, which has collected public comments and plans a final report by October. Hendricks is cautiously supportive: "It's positive, but I don't know whether there will be change. There are a lot of incumbents"—those now licensed to use the airwaves. And in a nod to government conspiracies, he thinks that the real power lies with the Interdepartment Radio Advisory Committee, made up of members of most federal agencies that use the radio spectrum and want to keep the status quo.

David J. Farber, chief technologist at the FCC, says that Hendricks's contribution "is very valuable, because it says what things could be like if we loosen up what we have. The question is whether we will." It's a case of entrenched interests, both political and economic, versus the promise of a more rational way to use a limited but potentially plentiful resource.

Wendy M. Grossman writes frequently about information technology from London.

MAKE WAY for more wireless?

SPREADING THE SPECTRUM

Spread-spectrum transmission—the breaking up of a signal to send the pieces along several frequencies simultaneously—has been around for a long time. Though used primarily by the military, it is now common in cordless telephones and some other wireless devices. Advanced software-defined radio, called cognitive radio, would be needed to take full advantage of digital spread-spectrum transmission. Significant computing power will be necessary for the millions of "smart" radios to analyze the airwaves, meaning that cognitive radios may be five years away.

BIOTECH

The Terminator's Back

CONTROVERSIAL SCHEME MIGHT PREVENT TRANSGENIC SPREAD

BY CHARLES CHOI

The "terminator" genes appeared to meet their end in 1999 amid a storm of controversy. Incorporated into bioengineered crops, the genes would make the plants infertile and thereby force farmers to buy seeds every year, rather than cultivate them from past harvests. Hence, biotech firms would have a guaranteed income stream and patent protection. The outcry over the genes led multinational Monsanto, which was at the time trying to buy the company that developed the technology, to declare that it would abandon commercial uses of the terminator. Advocates of genetically modified (GM) crops, however, think that such genes should come back—as a means to protect the environment.

Patented in 1998, the terminator genes make a cytotoxin ironically named RIP, for ribosome inhibitor protein, which renders the seed nonviable. Biotechnology watchdogs saw such genetic-use restriction technology as a tool to force farmers in developing nations into "bioserfdom." "The majority of the world uses their own seed, and the notion of the terminator gene giving a few people control of the world food supply incited an immense controversy," recounts Margaret Mellon, director of the food and environment program at the Union of Concerned Scientists in Washington, D.C.

In calling for the return of terminator genes, supporters of GM crops note that genetically enhanced plants have as much or more potential as exotic species to invade surrounding ecosystems and drive wild populations into extinction. "Terminator technology is a near perfect way of controlling unwanted GM spread," insists geneticist William M. Muir of Purdue University.

Terminator critics remain unconvinced. "What if these triggers aren't perfect?" Mellon asks of the means necessary to activate the terminator gene. For instance, the original design required GM seeds to be soaked in an antibiotic to activate the gene. "If the chemical doesn't penetrate completely, then you would let loose plants that weren't sterile," she says.

Considering that there are now 150 million acres of GM crops covering the U.S., Muir acknowledges that even if the terminator system's failure rate were one in a million, you would still have 150 acres of fertile plants out there. But having some containment "is a heck of a lot better" than none, a situation that the world currently faces, Muir observes. Besides, he adds, when exotic organisms escape into foreign environments, there is often a critical limit below which small releases do not result in long-term establishment. Of course, exceptions exist—the spread of Africanized "killer" bees from Brazil resulted from only three queens. Muir suggests that newer and more reliable terminator technology could "get failure rates of one in 10 billion, which is very acceptable." Based on recent patent filings, biotech giants, including Syngenta and DuPont, are continuing to tinker with and improve terminator systems.

Still, a terminator plant could spread its DNA around. Mellon points out that the genes could move through pollen to neighboring fields and inadvertently kill off nearby crops or wild cousins. Most research shows that the pollen doesn't get very far—99 percent of corn pollen travels just 30 feet, Muir says, unless a tornado or hurricane blows through. (Some research has found, however, that transgenic DNA has appeared miles away from its source.)

Scientists are also busy looking into other, arguably better ways to prevent DNA spread, states plant molecular biologist Henry Daniell of the University of Central Florida. One example is maternal inheritance technology, in which modified genes pass down to only the seeds (the maternal line), not to the pollen (the paternal side). The technology has actually been tested in tobacco, potato and tomato plants. "There is no one gene-containment strategy for all crops," Daniell remarks. It might take several to satisfy environmentalists and farmers alike.

Charles Choi is based in New York City.

READY ACCEPTANCE of transgenic crops is apparent in China's Hebei province.

GREG BAKER AP Photo

CONSPIRACY IN THE MAIZE?

In April, *Nature* stated that it should not have published the work of David Quist and Ignacio H. Chapela, which the journal now considers flawed. The researchers, both at the University of California at Berkeley, had reported that DNA from transgenic maize planted in Mexico found its way into native species as far off as 60 miles. The news was a public-relations disaster for biotech companies trying to persuade many nations to lift their embargoes on genetically modified crops.

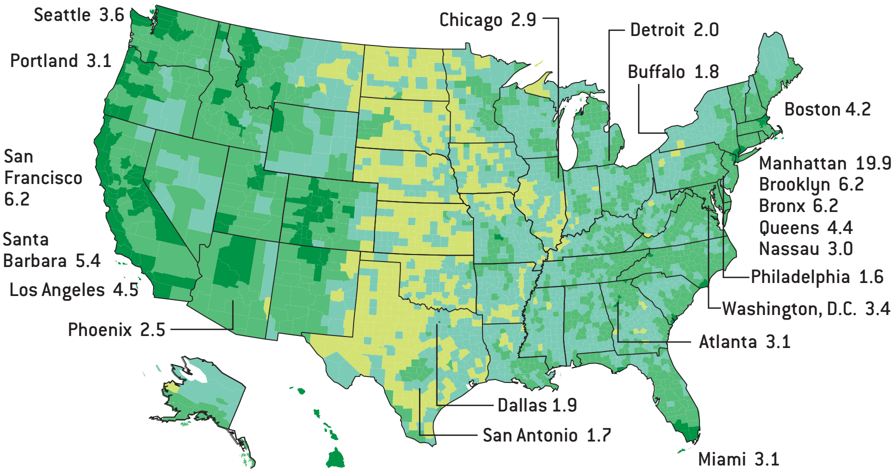
Soon messages on the server AgBioWorld started attacking the scientists. A story in the May 14 *Guardian,* a U.K. newspaper, suggested that these accusations were part of a smear campaign to align other scientists against Quist and Chapela. It indicated that "Mary Murphy" and "Andura Smetacek"—two of the first and most persistent message posters—are not real people and claims to have traced their e-mails to the Bivings Group, a Washington, D.C., firm that handles public relations for Monsanto. Bivings denies any connection to the postings.

BY THE NUMBERS

Affording a Home

WHAT DOES IT TAKE TO BUY A REASONABLY PRICED HOUSE? **BY RODGER DOYLE**

There are now about 107 million households and 122 million dwelling units in the U.S.—more than enough, it would seem, to place all 287 million Americans under a roof. Furthermore, the typical U.S. family can afford a house: according to the National Association of Realtors, a family with a median income of about $52,000 has 36 percent more than the minimum needed to qualify for a mortgage on a median-priced house.



Number of Years of Median Family Income Needed to Buy a Median-Priced House, by County

🟨 Less than 1.5 🟦 1.5 to 1.99 🟩 2 to 2.99 ■ 3 or more ☐ No data

SOURCE: U.S. Census 2000. Based on homeowners' estimates of the value of their house in 2000 and their income in 1999. The figures noted on the map apply to the home counties of cities.

NO PLACE LIKE HOME

Total housing units in 2001: 119,120,000

Total year-round housing units: 117,900,000

Occupied by owner: 61.8%

Occupied by renter: 29.1%

Vacant: 10%

SOURCE: U.S. Department of Housing and Urban Development, Office of Policy Development and Research

But many Americans are not housed adequately, and some are not housed at all. Part of the problem is that many live in places where housing costs are high in relation to income. This is illustrated by the map, which correlates median family income to median housing value, expressed as the number of years of income needed to obtain an existing home. As the map indicates, buyers have a relatively easy time purchasing in areas such as Buffalo, N.Y., where the median family income is about $49,500 and the median house valuation is about $91,000. Thus, it takes about 1.8 years of family income to buy a typical house there. But in places such as Santa Barbara, Calif., where the median income is $54,000, a family must spend 5.4 years' worth of income to buy a median-priced residence, valued at $293,000. The typical Buffalo family would have no problem obtaining a mortgage with a minimum down payment, whereas a similar family in Santa Barbara would be turned down. In certain other places, such as Brooklyn, N.Y., prospective buyers are at an even greater disadvantage: houses there are valued at an average of $224,000, but the average family income is only $36,000, or 6.2 years' income.

The Millennial Housing Commission, a bipartisan group appointed by Congress, concluded in a May report that affordable housing in the U.S. for low- and moderate-income renters—those with family incomes of up to 120 percent of the median income—is "being lost at alarming rates." In the prosperous Washington, D.C., region, for example, 114,000 new jobs were added in 2000, compared with only 35,000 new dwelling units. Using the rule of thumb of 1.6 workers per home, that is a shortage of about 36,000 homes.

Part of the problem in Washington and elsewhere is gentrification of older properties, which has led to a reduction in the number of units available to lower-income families. Other causes for the shortfall, according to the Millennial Commission, are a rise in housing production costs; inadequate public subsidies; and local regulations, including zoning laws that require at least five acres for each home or limit the construction of multifamily dwellings. Indeed, according to economist Edward L. Glaeser of Harvard University and policy analyst Joseph Gyourko of the University of Pennsylvania, zoning restrictions, rather than a shortage of land, may be the most important contributor, especially in places such as New York City, Washington, D.C., and Los Angeles.

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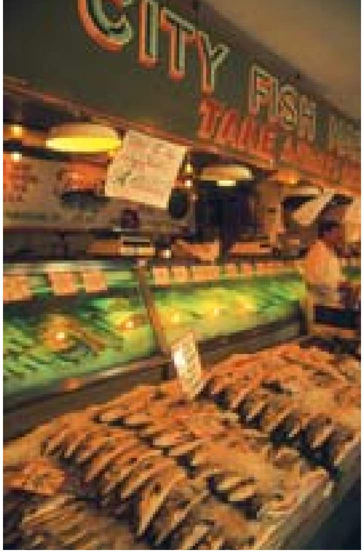
RODGER DOYLE

FISHERIES

Net Size



UNIFORM FISH SIZES are the result of regulations but could harm future catches.

Setting minimum sizes on fish destined for the dinner plate, as many regulations currently do, could one day mean a smaller dinner plate. Marine scientists David O. Conover and Stephan B. Munch of the State University of New York at Stony Brook stocked Atlantic silversides in laboratory tanks and then fished for certain types. Removing the largest individuals, which tend to be older and sexually mature, shrank the average size of the fish four generations later. In contrast, targeting the smaller ones led to descendants nearly twice the size of the other fourth-generation fish. Selective cullings, the researchers report in the July 5 *Science,* may be causing genetic changes that could ultimately reduce the populations of commercially valuable catches. Not all biologists think that the lab-based results apply to the wild, noting that some stocks adapt to heavy harvesting by maturing sooner.

—Philip Yam

SOFTWARE

Glitch in the Machine

Buggy software drains the U.S. economy to the tune of nearly $60 billion, according to a new study by the Research Triangle Institute in North Carolina. The study, funded by the National Institute of Standards and Technology, surveyed automotive and aerospace manufacturers and financial-service providers to assess their software woes, which included added labor, lost transactions and processing delays. Those who experienced major errors saw an average of 40 big bugs a year. Extrapolating from these software-dependent industries to the economy as a whole, the researchers projected that more than half of the total burden falls on users and the rest on vendors and software makers, who already spend an estimated 80 percent of their development costs ferreting out defects. The study concluded that better testing tools could cleave a net $22 billion from the collective burden.

—JR Minkel

BIOENGINEERING

Polio de Novo

Virologists have managed to synthesize the poliovirus using little more than the publicly available string of letters representing its genome and a test tube. The researchers, from the State University of New York at Stony Brook, ordered stretches of the viral DNA from a biotechnology company and strung them together to make the organism's 7,500 base pairs. They then mixed the genetic material with enzymes and biological molecules necessary to grow the virus. The resulting particles could infect and kill human cells, attract poliovirus-specific antibodies and induce polio in mice. The synthetic scourge, however, was at least 1,000 times less effective at paralyzing or killing the mice, possibly because of genetic markers introduced, the group explains in its report, published online on July 11 by *Science.* The technique probably isn't feasible yet for vastly more complex viruses, such as smallpox, says lead investigator Eckard Wimmer. The result suggests that we should hang on to polio vaccine stocks longer than we might have before, he adds.

—JR Minkel

POLIOVIRUS can now be made in the lab.

WOLFGANG KAEHLER *Corbis* (*top*); GELDERBLOM/EYE OF SCIENCE/PHOTO RESEARCHERS, INC. (*bottom*)

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Smart People Believe Weird Things

Rarely does anyone weigh facts before deciding what to believe By MICHAEL SHERMER

In April 1999, when I was on a lecture tour for my book *Why People Believe Weird Things,* the psychologist Robert Sternberg attended my presentation at Yale University. His response to the lecture was both enlightening and troubling. It is certainly entertaining to hear about other people's weird beliefs, Sternberg reflected, because we are confident that we would never be so foolish. But why do *smart* people fall for such things? Sternberg's challenge led to a second edition of my book, with a new chapter expounding on my answer to his question: Smart people believe weird things because they are skilled at defending beliefs they arrived at for nonsmart reasons.

Rarely do any of us sit down before a table of facts, weigh them pro and con, and choose the most logical and rational explanation, regardless of what we previously believed. Most of us, most of the time, come to our beliefs for a variety of reasons having little to do with empirical evidence and logical reasoning. Rather, such variables as genetic predisposition, parental predilection, sibling influence, peer pressure, educational experience and life impressions all shape the personality preferences that, in conjunction with numerous social and cultural influences, lead us to our beliefs. We then sort through the body of data and select those that most confirm what we already believe, and ignore or rationalize away those that do not.

This phenomenon, called the confirmation bias, helps to explain the findings published in the National Science Foundation's biennial report (April 2002) on the state of science understanding: 30 percent of adult Americans believe that UFOs are space vehicles from other civilizations; 60 percent believe in ESP; 40 percent think that astrology is scientific; 32 percent believe in lucky numbers; 70 percent accept magnetic therapy as scientific; and 88 percent accept alternative medicine.

Education by itself is no paranormal prophylactic. Although belief in ESP decreased from 65 percent among high school graduates to 60 percent among college graduates, and belief in magnetic therapy dropped from 71 percent among high school graduates to 55 percent among college graduates, that still leaves more than half fully endorsing such claims! And for embracing alternative medicine, the percentages actually increase, from 89 percent for high school grads to 92 percent for college grads.

We can glean a deeper cause of this problem in another statistic: 70 percent of Americans still do not understand the scientific process, defined in the study as comprehending probability, the experimental method and hypothesis testing. One solution is more and better science education, as indicated by the fact that 53 percent of Americans with a high level of science education (nine or more high school and college science/math courses) understand the scientific process, compared with 38 percent of those with a middle-level science education (six to eight such courses) and 17 percent with a low level (five or fewer courses).

The siren song of pseudoscience can be too alluring to resist.

The key here is teaching how science works, not just what science has discovered. We recently published an article in *Skeptic* (Vol. 9, No. 3) revealing the results of a study that found no correlation between science knowledge (facts about the world) and paranormal beliefs. The authors, W. Richard Walker, Steven J. Hoekstra and Rodney J. Vogl, concluded: "Students that scored well on these [science knowledge] tests were no more or less skeptical of pseudoscientific claims than students that scored very poorly. Apparently, the students were not able to apply their scientific knowledge to evaluate these pseudoscientific claims. We suggest that this inability stems in part from the way that science is traditionally presented to students: Students are taught what to think but not how to think."

To attenuate these paranormal belief statistics, we need to teach that science is not a database of unconnected factoids but a set of methods designed to describe and interpret phenomena, past or present, aimed at building a testable body of knowledge open to rejection or confirmation.

For those lacking a fundamental comprehension of how science works, the siren song of pseudoscience becomes too alluring to resist, no matter how smart you are. SA

Michael Shermer is publisher of Skeptic *magazine (www.skeptic.com) and author of* In Darwin's Shadow *and* Why People Believe Weird Things, *just reissued.*

BRAD HINES

KAREN BEARD *Image Bank*

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. This achievement relies on an ever progressing ability to measure time more precisely. Over the aeons, the capacity to

> The gods confound the man
> who first found out
> How to distinguish hours.
> Confound him, too,
> Who in this place set up
> a sundial,
> To cut and hack
> my days so wretchedly
> Into small portions!
> —Titus Maccius Plautus
> (254?–184 B.C.)

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.

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 76]. 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, 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 pseudopendulum 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 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 clock makers 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 86]. Researchers also continue to press ahead in slicing and dicing the second more finely. The need for speed has become a cornerstone of the information age. In the laboratory, transis-

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.

SWATCH

tors can switch faster than a picosecond, a thousandth of a billionth of a second [see "From Instantaneous to Eternal," on page 56].

A team from France and the Netherlands set a new speed record for subdividing the second, reporting last year that a laser strobe light had emitted pulses lasting 250 attoseconds—that's 250 billionths of a billionth of a second. The strobe may one day be fashioned into a camera that can track the movements of individual 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 50]. 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 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 try 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 40]. 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 48].

The Great Mandala

THE ESSENCE of time is an age-old conundrum that preoccupies not just the physicist and 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 74]. 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 when our time is up [see "Times of Our Lives," by Karen Wright, on page 58].

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 66].

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 is 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.

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

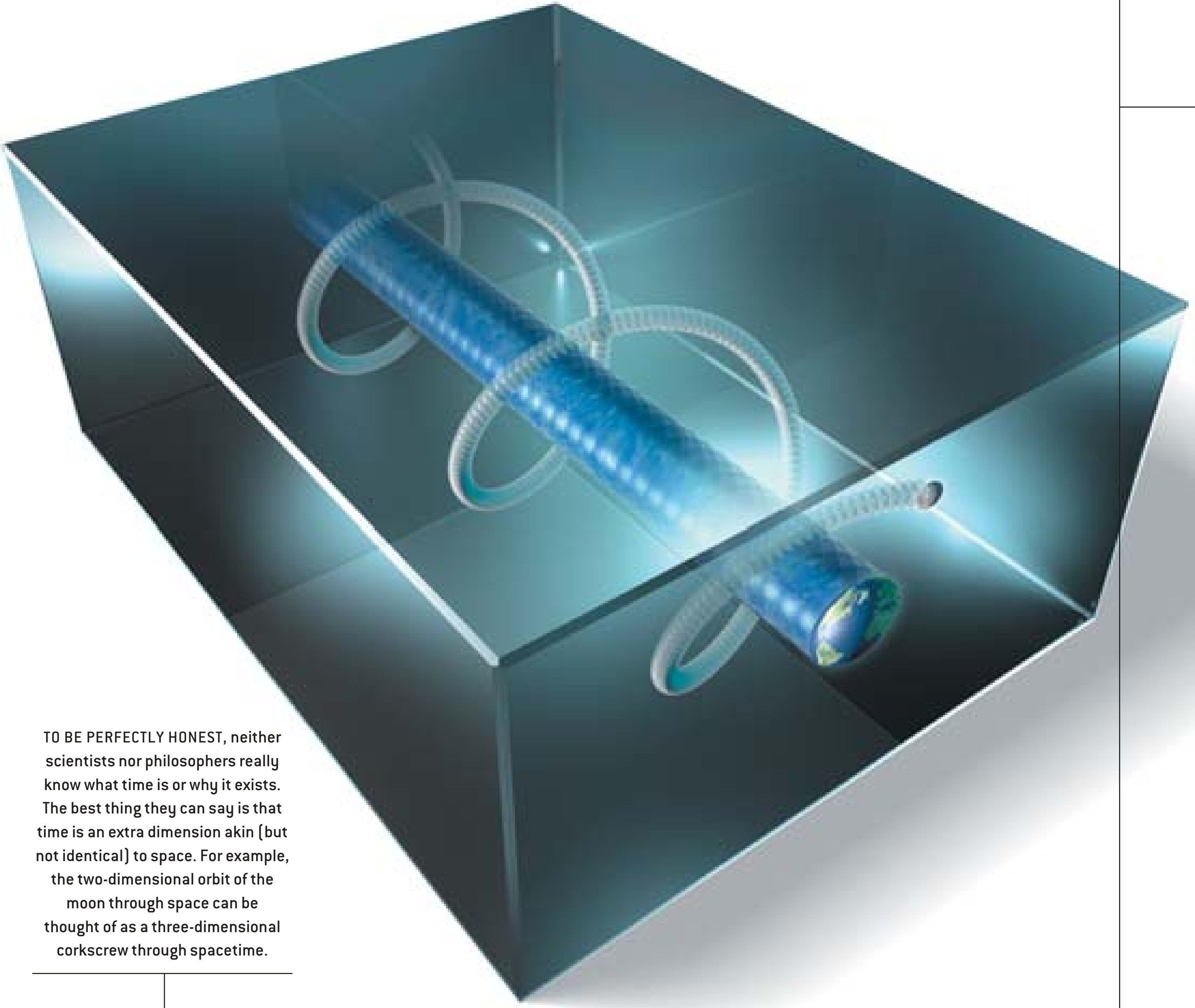
- Our senses tell us that time flows: namely, that the past is fixed, the future undetermined, and reality lived in the present. Yet various physical and philosophical arguments suggest otherwise.
- The passage of time is probably an illusion. Consciousness may involve thermodynamic or quantum processes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



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

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 illustration on page 46*]. 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.

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 how disordered it is—will tend to rise with time.

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.

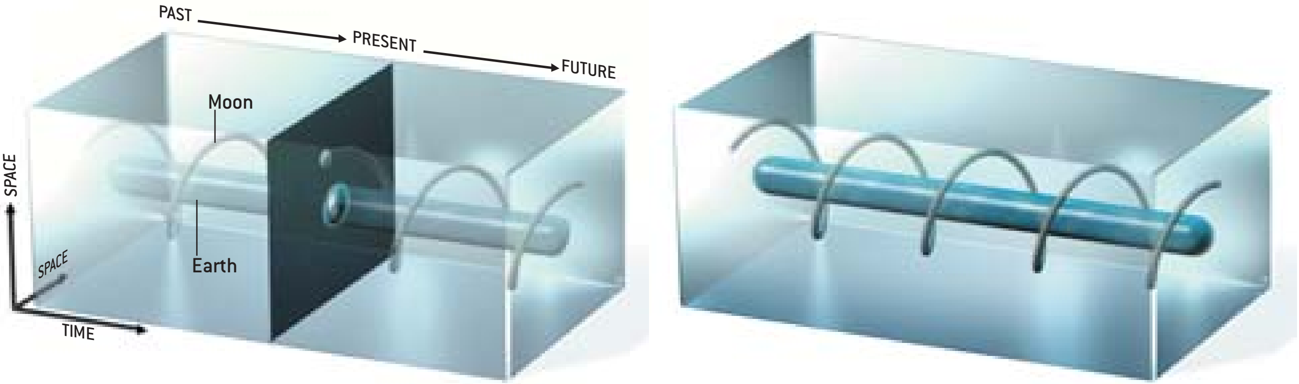
The fact that time may be treated as a fourth dimension does not mean that it is identical to the three dimensions of space. Time and space enter into daily experience and physical theory in distinct ways. For instance, the formula for calculating spacetime distances is not the same as the one for calculating 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.*

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 the 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

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 Nobel laureate chemist Ilya Prigogine, now at the University of Texas, have suggested 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 measures distances between places; it does

THE AUTHOR

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BRYAN CHRISTIE DESIGN

SIMULTANEITY

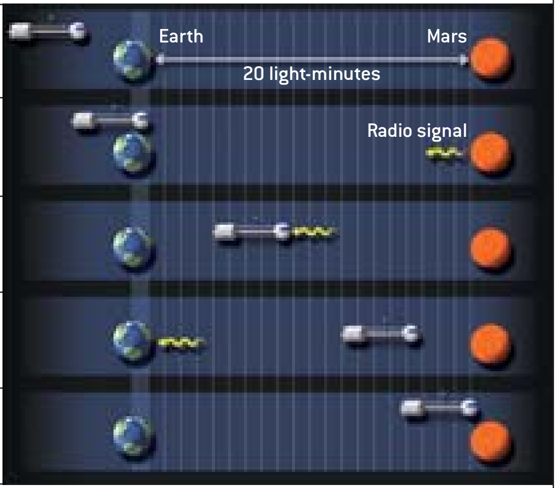
It's All Relative

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.

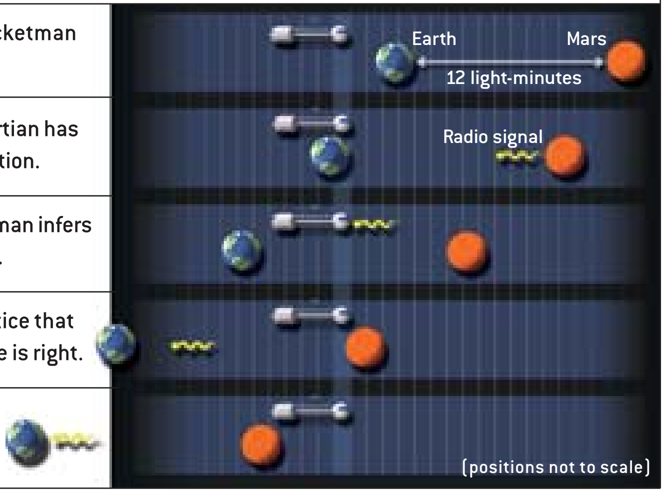
Before noon	By exchanging light signals, the Earthling and Martian measure the distance between them and synchronize their clocks.
12:00 P.M.	The Earthling hypothesizes that the Martian has begun to eat lunch. He prepares to wait 20 minutes for verification.
12:11 P.M.	Knowing the rocket's speed, the 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

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.

> Modern science has barely begun to consider the question of how we perceive the passage of time. We can only speculate about the answer.

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.

MORE TO EXPLORE

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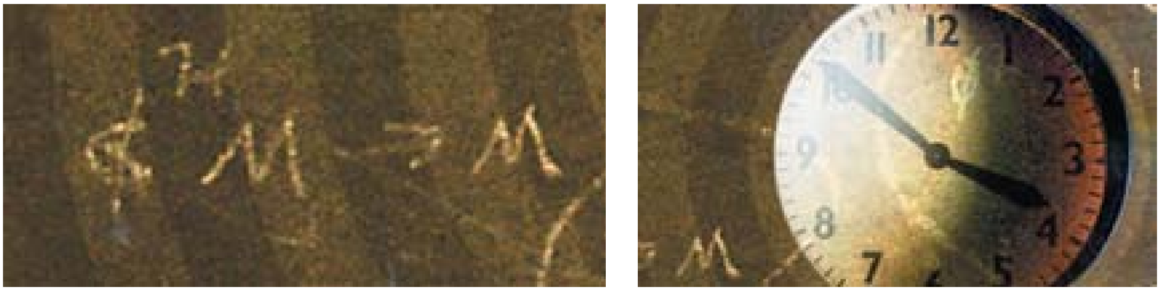


A HOLE AT THE HEART OF

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."

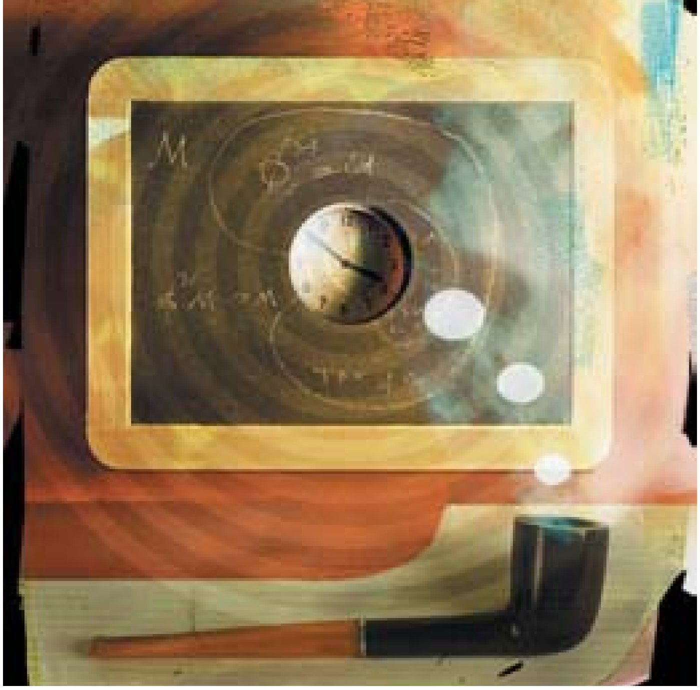
Two examples illustrate how physicists and philosophers have been pooling their resources. The first concerns the "problem of frozen time," also known simply as the "problem of time." It arises when theorists try to turn Einstein's general theory of relativity into a quantum theory using a procedure 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

STUART BRADFORD



PHYSICS

covariance has startling implications for an old metaphysical question: Do space and time exist independently of stars, galaxies 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 at 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. See also www.sciam.com/request.cfm?source=0902issue_moretoexplore

HOW TO BUILD A TIME MACHINE

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

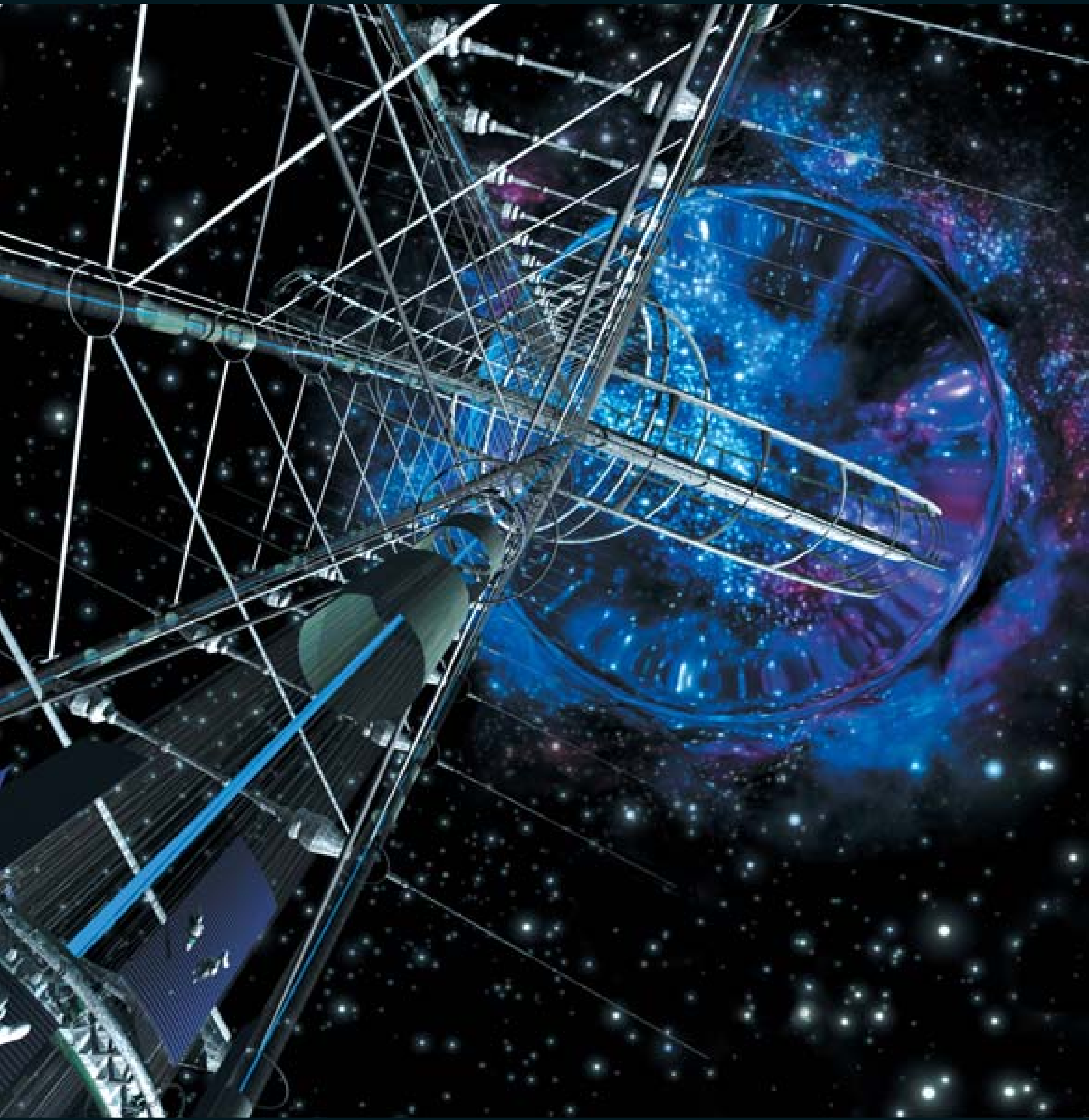
By Paul Davies

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.

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

THE AUTHOR

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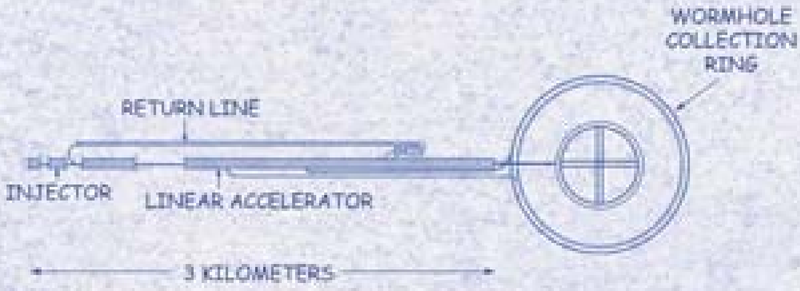
PETER BOLLINGER (*preceding page*); EVERETT COLLECTION (*above*)

WORMHOLE TRAVEL

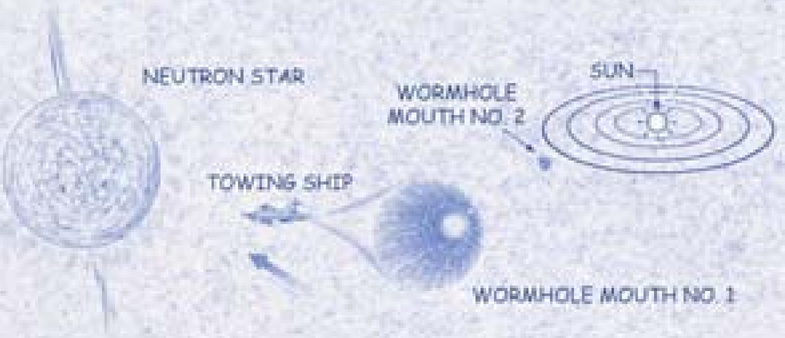
A Wormhole Time Machine in Three Not So Easy Steps

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.



PHILIP HOWE

nonetheless to demonstrate that going back in time was not forbidden by the 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.

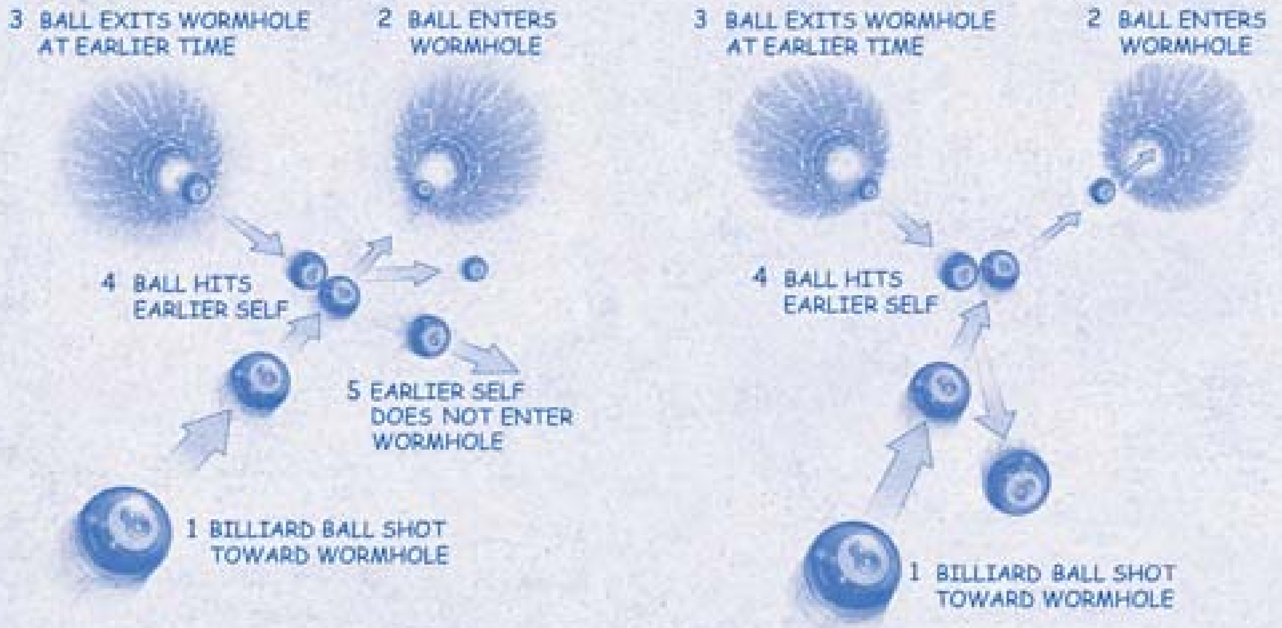
In science fiction, wormholes are sometimes called stargates; they offer a shortcut between two widely separated points in space. Jump through a hypothetical wormhole, and you might come out moments later on the other side of the galaxy. Wormholes naturally fit into the general theory of rel-

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.



PHILIP HOWE

ativity, whereby gravity warps not only time but also space. The theory allows the analogue of alternative road and tunnel routes connecting two points in space. Mathematicians refer to such a space as multiply connected. Just as a tunnel passing 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

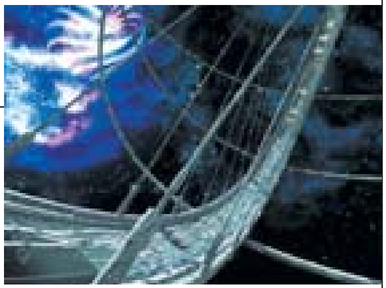
FOR THE WORMHOLE to be traversable, it must contain what Thorne termed exotic matter. In effect, this is something that will generate antigravity to combat the natural tendency of a massive system to implode into a black hole under its intense weight. Antigravity, or gravitational repulsion, can be generated 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 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.



PETER BOLLINGER

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. 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. SA

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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.

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

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. 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.

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.

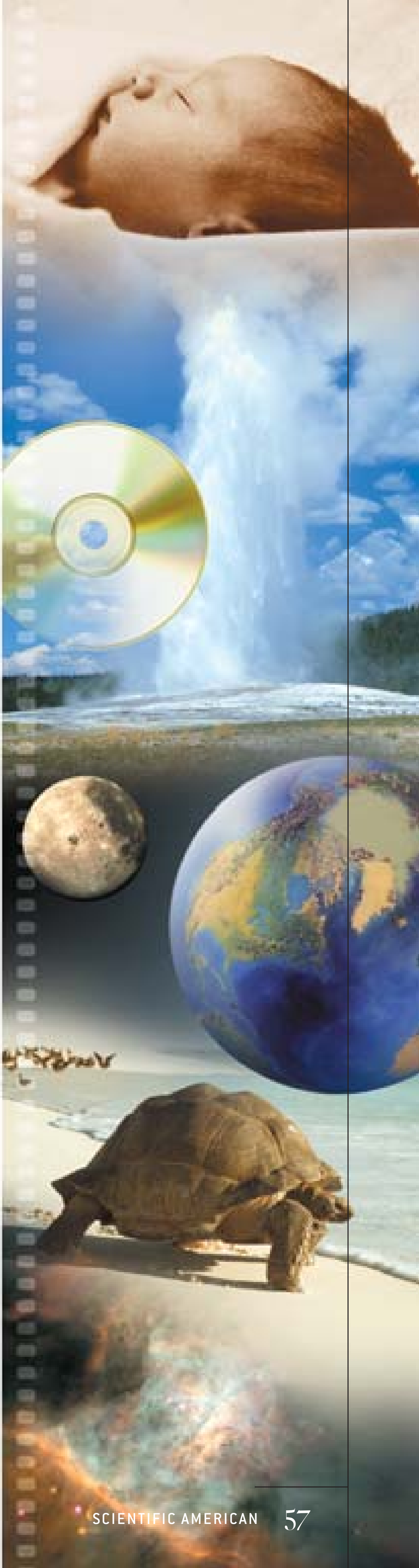
ONE MILLION YEARS

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

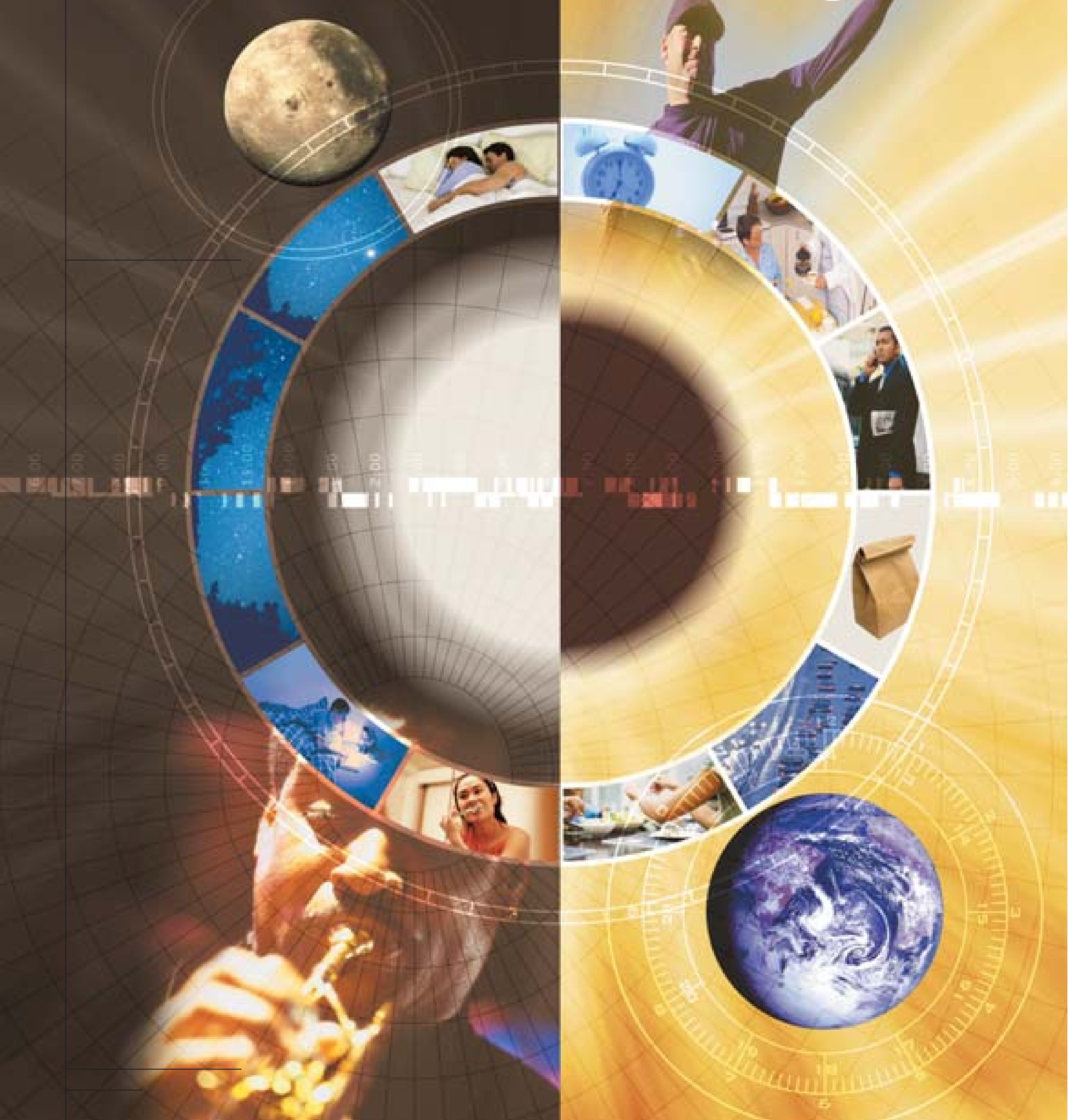
It took approximately this long for the newly formed Earth to cool, develop oceans, give birth to single-celled life and exchange its carbon dioxide–rich early atmosphere for an oxygen-rich one. Meanwhile the sun orbited four times around the center of the galaxy. Because the universe is 12 billion to 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 Reseachers, 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 oxygen than those that are not involved, and the fMRI scan records changes in blood flow and oxygenation

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.

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*)

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 recently 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.

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 last year. 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 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."

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

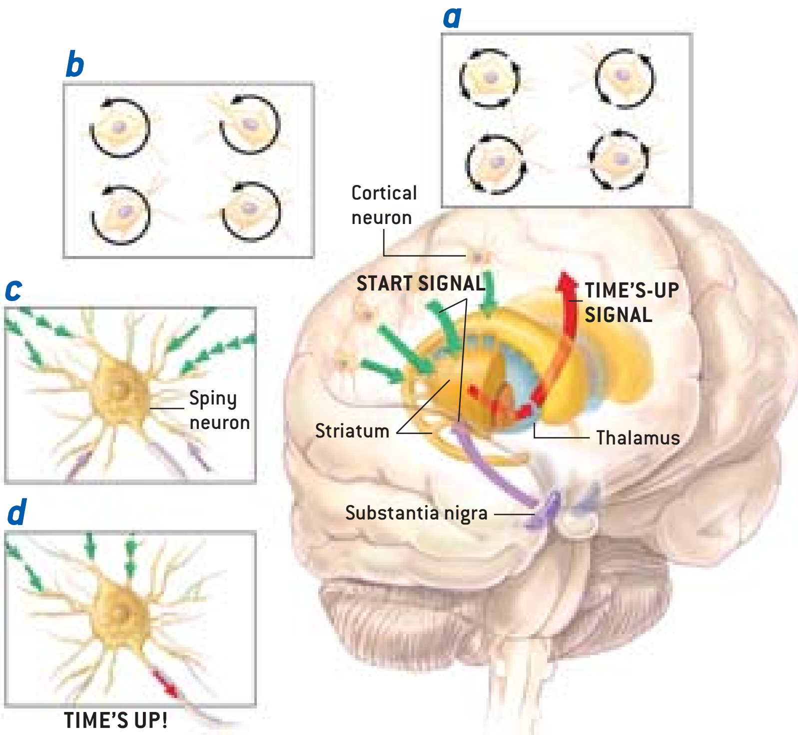
The Somatic Sundial

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

MECHANISMS

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.*

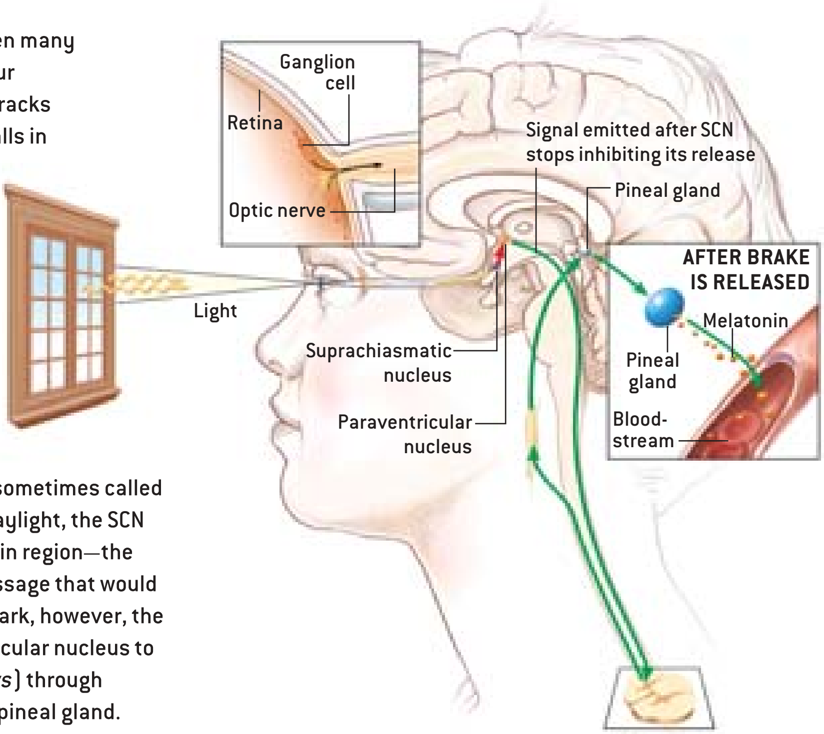


The Interval Timer

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 influence 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.

Earlier this year 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. Until recently, scientists 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 this year 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 recently 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 of those different drummers 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.

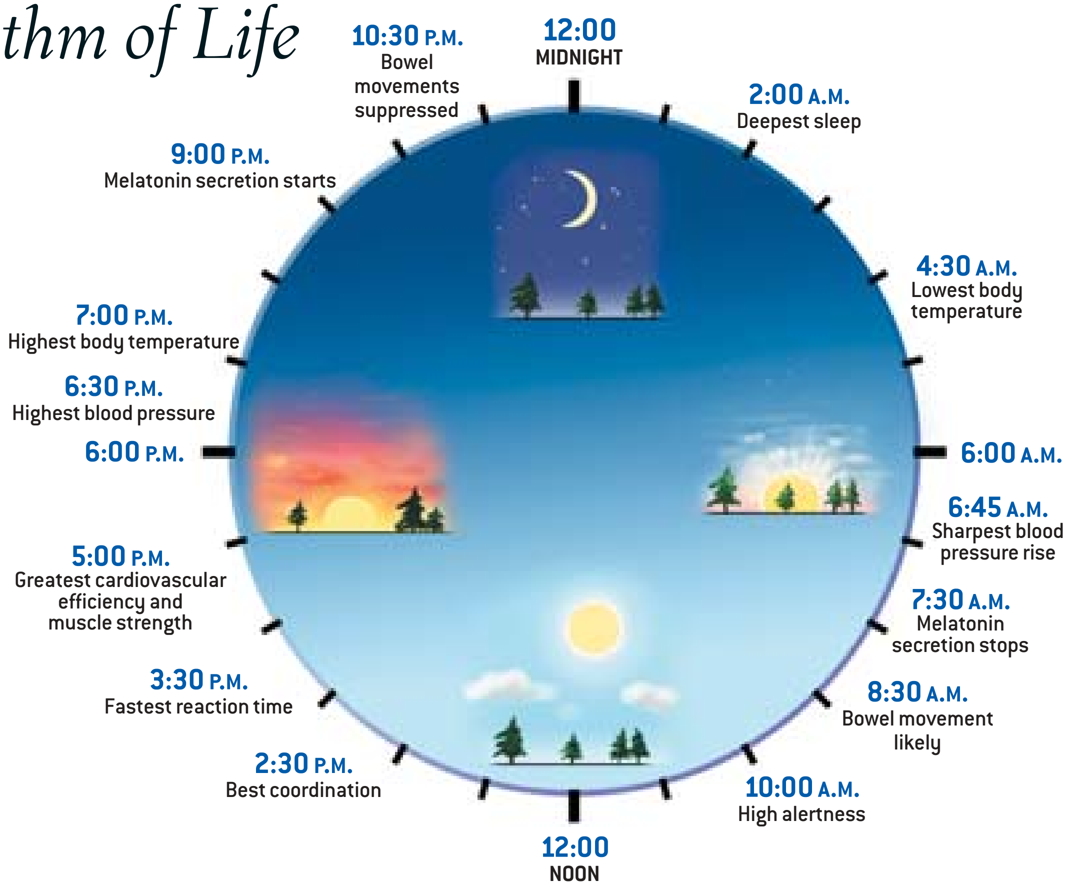
The mismatch between day length and daily life could explain the syndrome known as seasonal affective disorder, or SAD. In the U.S., SAD afflicts as many as one in 20 adults with depressive symptoms such as weight gain, apathy and fatigue between October and March. The condition is 10 times more common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

CYCLIC EVENTS

The 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, 2000*

TERESE WINSLOW

seasonal rhythms, it's partly because 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.

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, 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.*

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

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 recent 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 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."

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

Cultured cells usually reach this state of senescence in a few months. Fortunately, most cells in the body divide much, much more slowly than cultured cells. 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 1997 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. Recently Titia de Lange of the Rockefeller University 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.

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

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 58].

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.

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.

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

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.

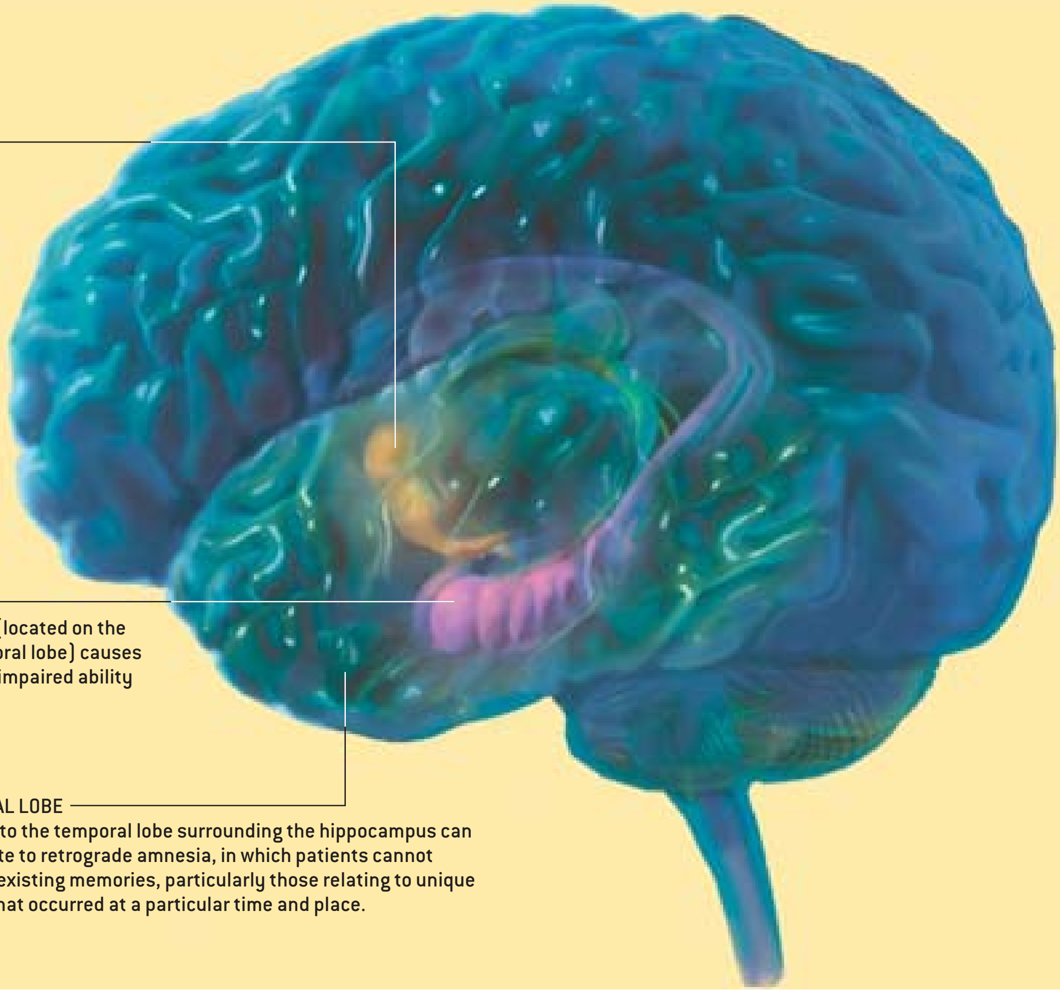
The association between amnesia and time can be seen most dramatically in cases of permanent brain damage to the hippocampus, a region of the brain important to memory, and to the nearby temporal lobe, the region through which the hippocampus holds a two-way communication with the rest of the cerebral 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 marriage—carries no such date with it. The temporal lobe that surrounds the

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

hippocampus is critical in the making and recalling of such memories.

In patients with 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 1942 and 2013. He guesses 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 clock of body time is of no help. This patient cannot state his age, either. He can

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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 unique work that was shot in continuous, unedited 10-minute takes; no other feature has ever been produced in its 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 none as long as those 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 away from each character. Yet to join each segment to 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 places that event in a chronological sequence—or in the case of my patient, fails to do so—is 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, my University of Iowa 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 about parents, siblings and various relatives, schools, friendships and professional activities, and then we verified the answers with relatives and records. We also established what the participants remembered of key public events, such as the

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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.

the next, Hitchcock finished every take 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.*

election of officials, wars and other 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 not unlike that of playing the board game Life. For the investigators, the setup permitted a measurement of the accuracy of time placement.

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.

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

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 at 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

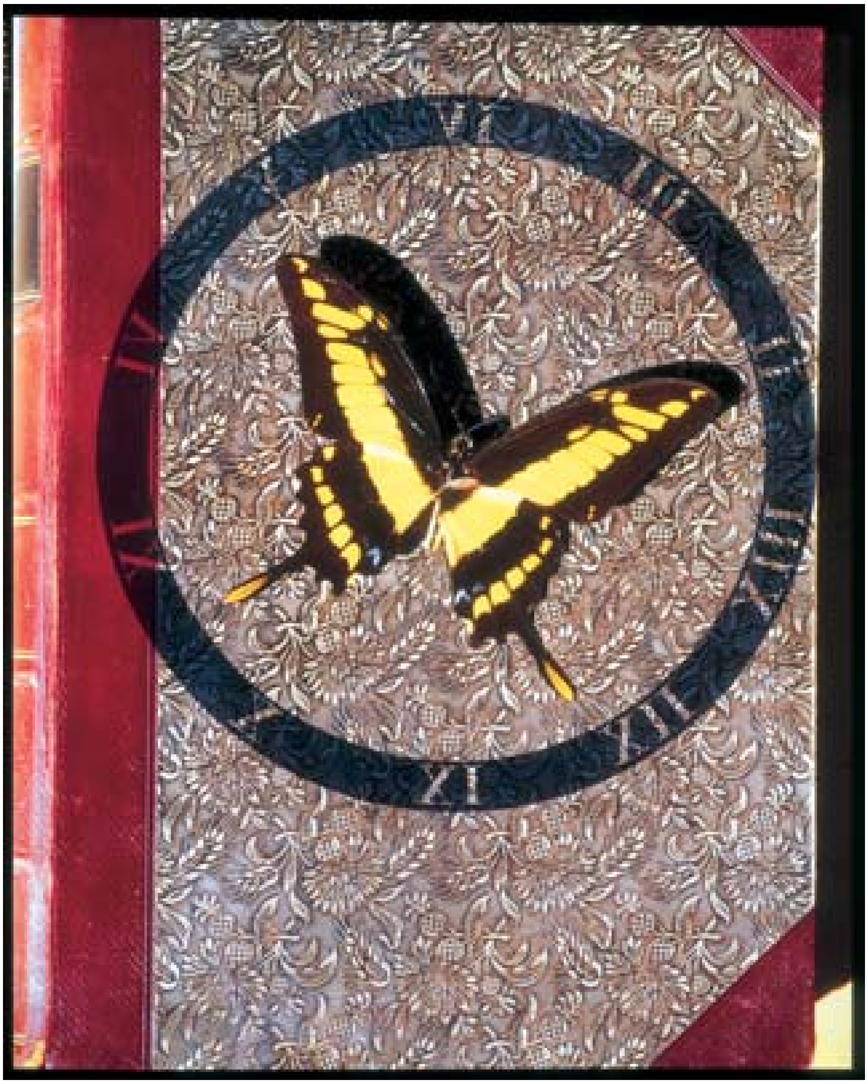
IRAIDA ICAZA

lag exists between the beginning of the neural events leading to consciousness and the moment one actually experiences the consequence of those neural 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 from one target to another during a saccade. 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.



IRAIDA ICAZA

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

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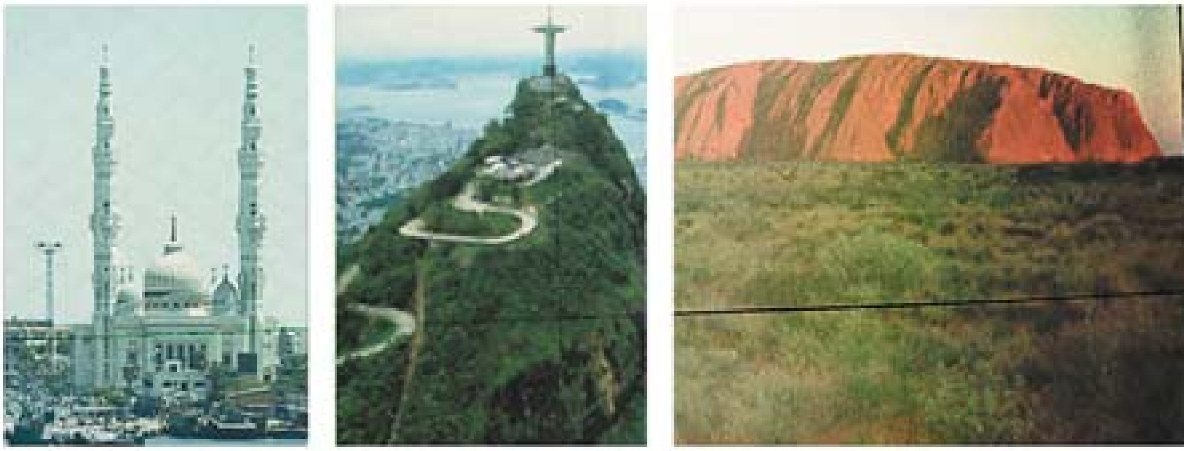


CLOCKING CULTURES

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 New York City 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.

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 at Fresno. "You get answers on what cultures value and believe in.

STUART BRADFORD

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, 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 makes it hard 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 they 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

Carol Ezzell is a staff editor and writer.

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 calendars to organize and coordinate communal activities and public events, to schedule the shipment of goods and, in particular, to regulate 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

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

CORBIS

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.

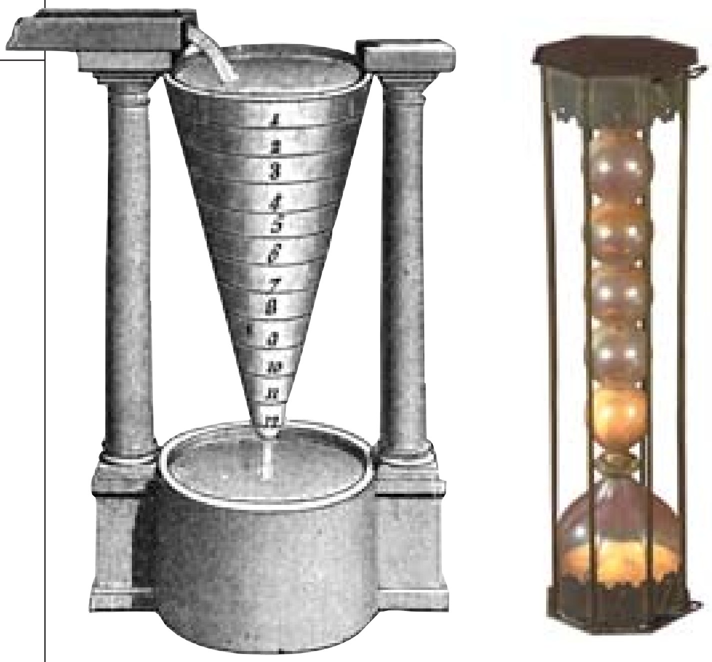
Before the invention of artificial light, the moon had greater social impact. And, for those living near the equator in particular, its waxing and waning was more conspicuous than the passing of the seasons. Hence, the calendars developed at the lower latitudes were influenced more by the lunar cycle 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 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 Eu-



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.

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

rope 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 illustration on page 80*]. 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 clock makers 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 on page 80*]. 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.

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 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 clock maker Salomon Coster in 1657. Coster collaborated with Christiaan Huygens, the Dutch scientist who first applied the pendulum to the mechanical clock.

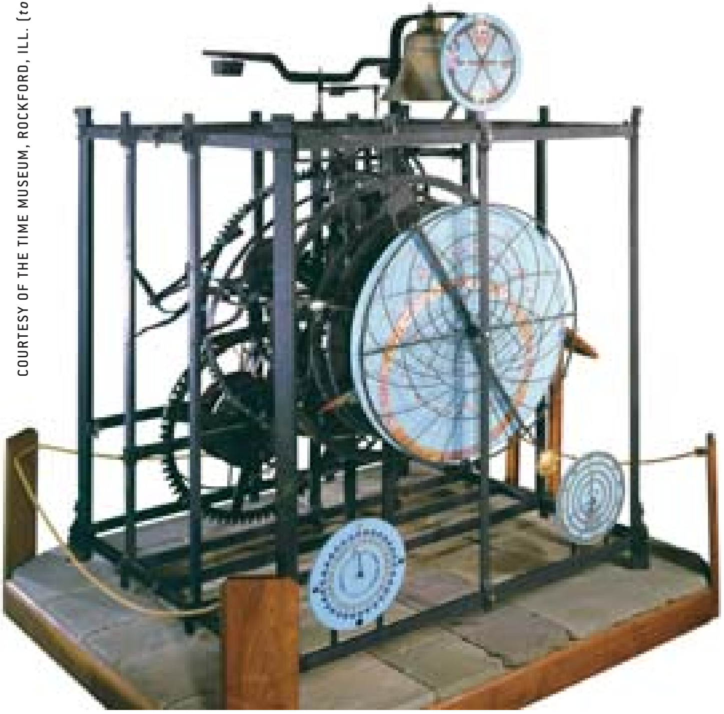
The advent of the pendulum not only heightened demand for clocks but also resulted in their development as furniture. National styles soon began to emerge: English makers designed the case to fit around the clock movement; in contrast, the French placed greater emphasis on the shape and decoration of 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. 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 on page 81*]. 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

THE AUTHOR

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



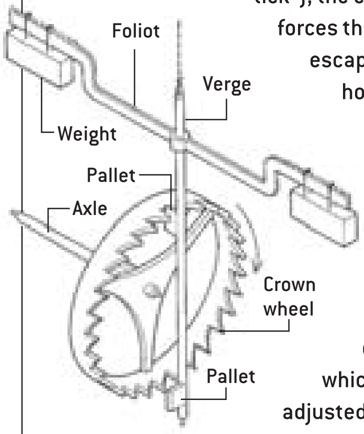
EARLY MECHANICAL CLOCK, commissioned by Richard of Wallingford, English mathematician and abbot of St. Alban's Abbey, was built between 1327 and 1336 to help his monks maintain their daily routines.

COURTESY OF THE TIME MUSEUM, ROCKFORD, ILL. [*top and bottom*]

DEVELOPMENT OF EARLY MECHANICAL CLOCKWORKS

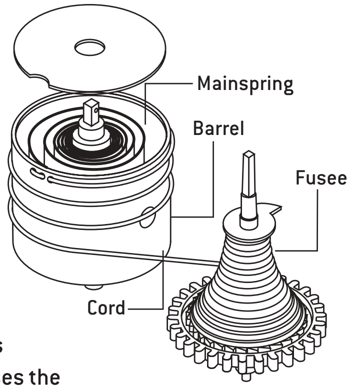
1 *Verge and Foliot Escapement*

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).



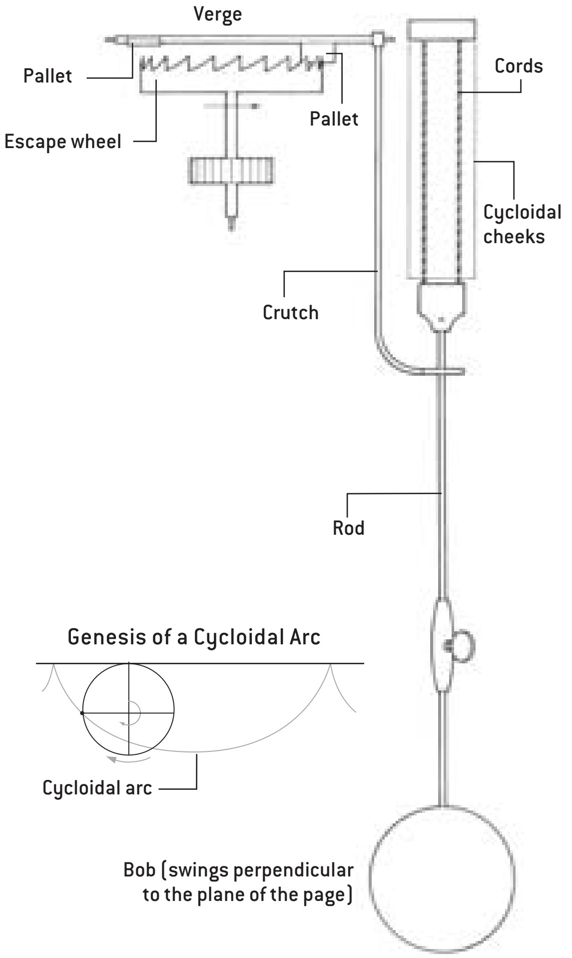
2 *Fusee*

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.



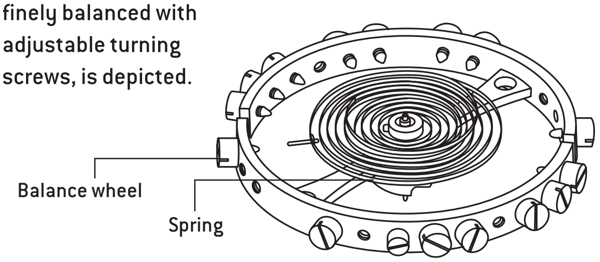
3 *Pendulum Clock*

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.



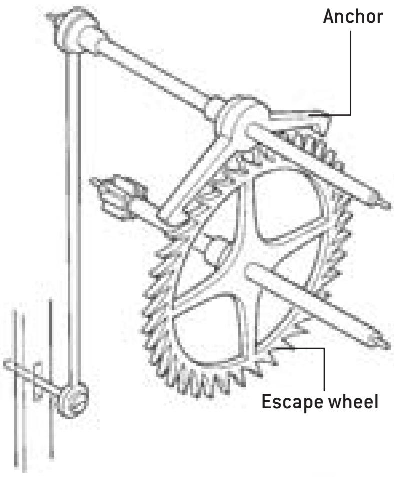
4 *Spiral Balance Spring*

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. Here a modern version, finely balanced with adjustable turning screws, is depicted.



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 grandfather clock.



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

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 clock maker 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.

Solving the Problem of Longitude

WHEN THE ROYAL OBSERVATORY at Greenwich, England, was founded in 1675, part of its charter was to

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.

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.

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 some 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 $18 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

SHELF CLOCK with its revolutionary wooden movement was developed by Eli Terry, a Connecticut clock maker 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*)

by correcting 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 clock maker 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 clock-making industry.

Standard Time

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*) 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 CLOCK MAKERS 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 that 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

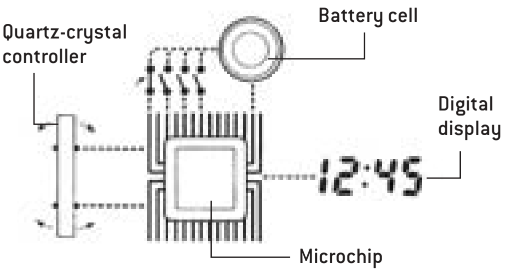
AT THE END of the 19th century, Siegmund Riefler of Munich developed a radical new design of regulator—a highly accurate timekeeper that served as a standard for controlling others. Housed in a partial vacuum to minimize the effects of barometric pressure and equipped with a pendulum largely unaffected 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 an English railroad engineer named 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

TWO MODERN PRECISION TIMEKEEPERS

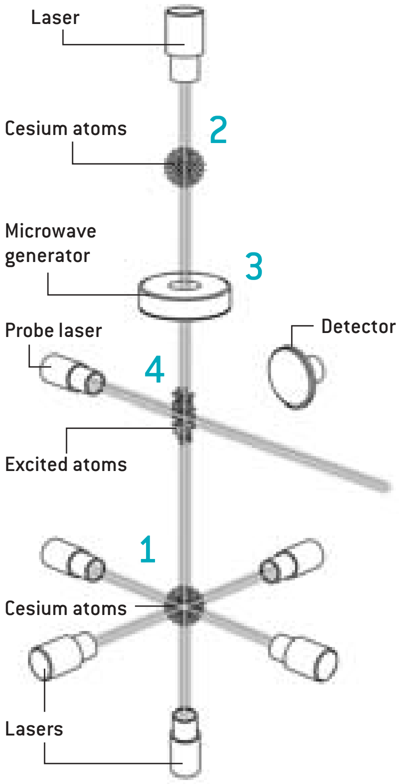
1 *Quartz Movement*

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, up through a magnetically shielded cavity (*2*). As gravity pulls the cloud back down through the cavity, the electrons in the atoms are bombarded by a microwave generator (*3*) whose emissions are set to the predetermined frequency of a piezoelectric-crystal oscillator (*not shown*). 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*); THE NATIONAL TIME MUSEUM (*right*)

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 observatory 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 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 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 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. 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 86].

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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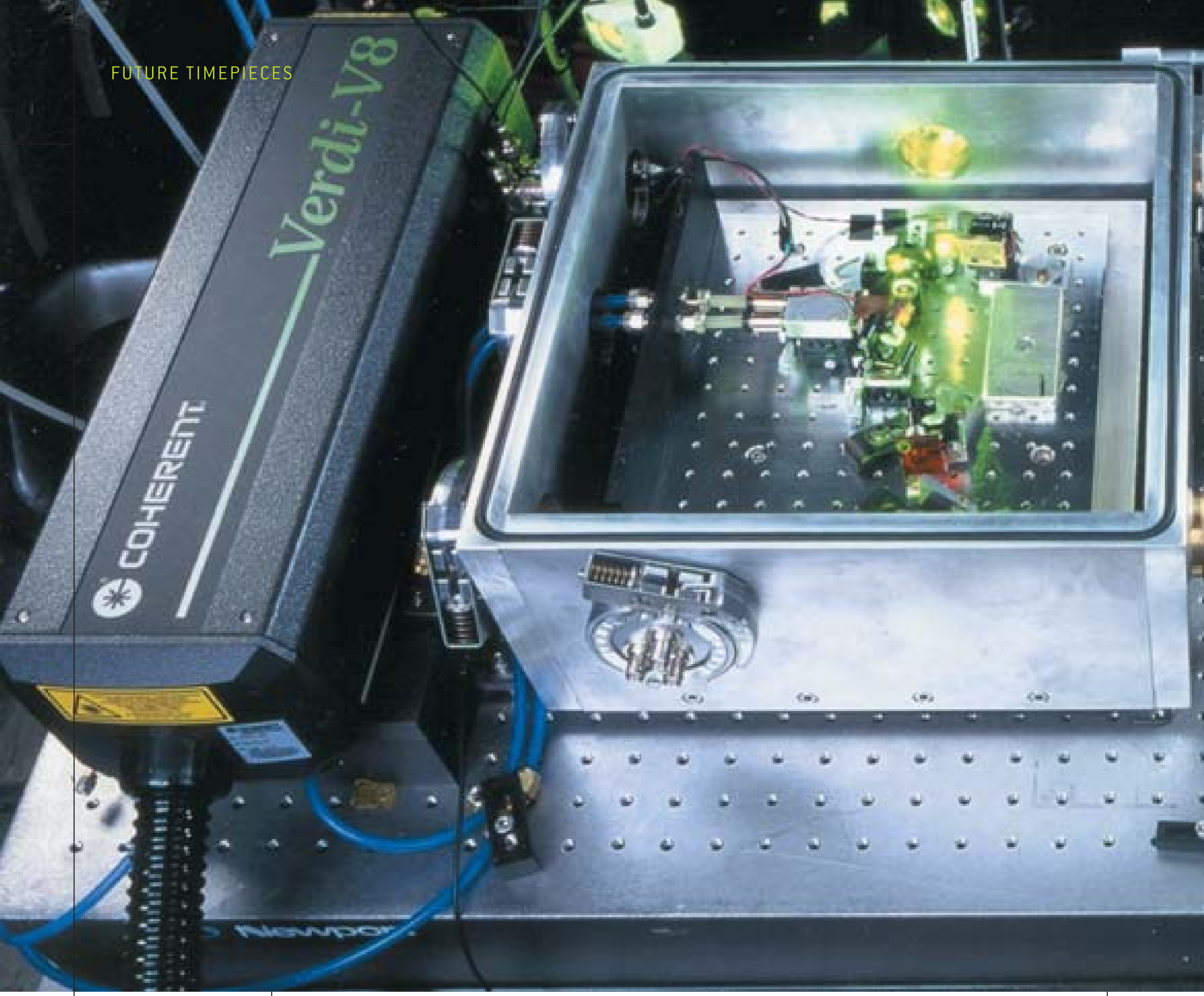


ULTIMATE CLOCKS

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

By W. Wayt Gibbs

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.

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

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

Dozens of the top clock makers in the world convened in New Orleans one muggy week this past May 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 Agilent sells for $63,000, 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 one part in 10^{15} (usually written simply as 10^{-15}). That is 500 times the accuracy of NIST's best clock in 1975. But space-based clocks set to fly on the International Space Station by 2005 are expected to tick with uncertainties better than 10^{-16}. 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 within three years, accuracy will 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 clock makers face.

Further down the road lies a more fundamental limitation: as 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 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 wristwatch 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 15-cubic-centimeter prototype in 1999 (*below*). Their latest design is 95 percent smaller. If atomic wristwatches ever arrive, they won't be for telling time to the nearest nanosecond—but they might help keep our wrist-phone 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.

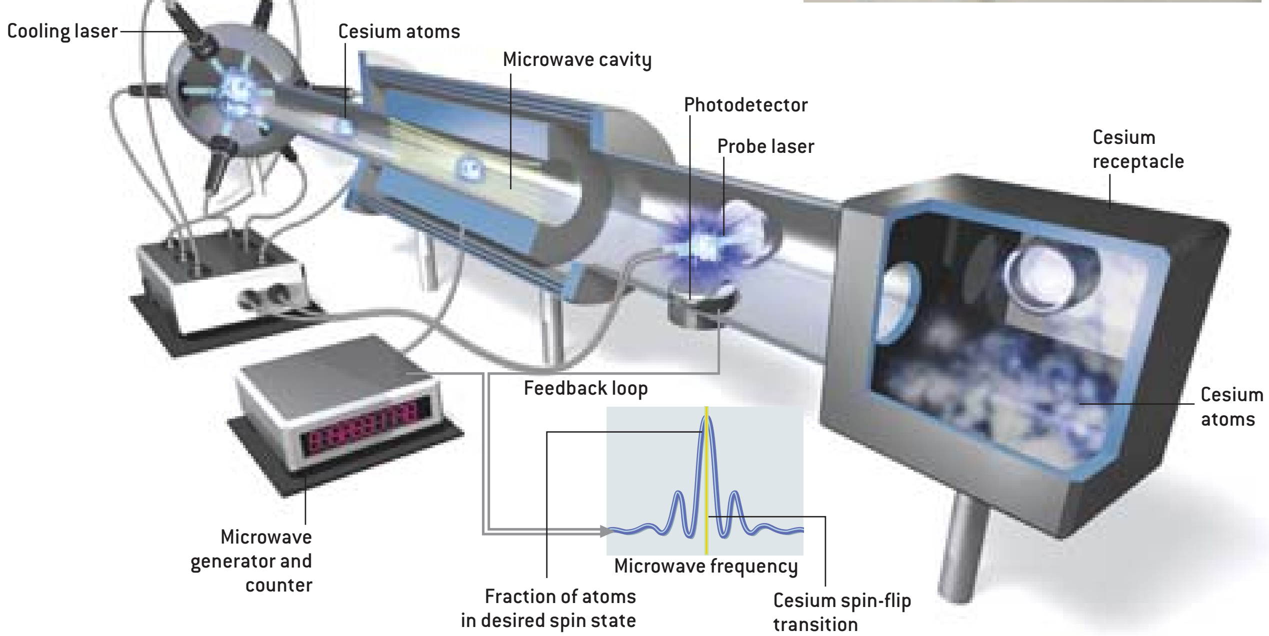
Of course, nothing in quantum physics is really that simple. Complicating things, as usual, is the Heisenberg indeterminacy principle, which puts strict limits on how precisely one can measure the frequency of a single photon. The best clocks now scan a one-hertz-wide sweet spot to find its exact center, 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 will 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. The

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 2005. 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*)

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 clock makers 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 84*]. 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 fountain-like 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 in late 2005 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

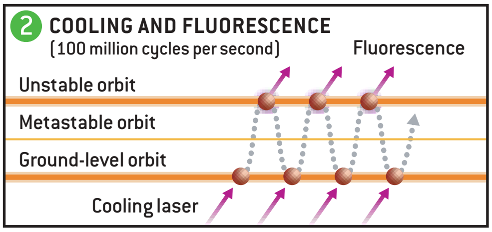
HOW AN ADVANCED ATOMIC CLOCK WORKS

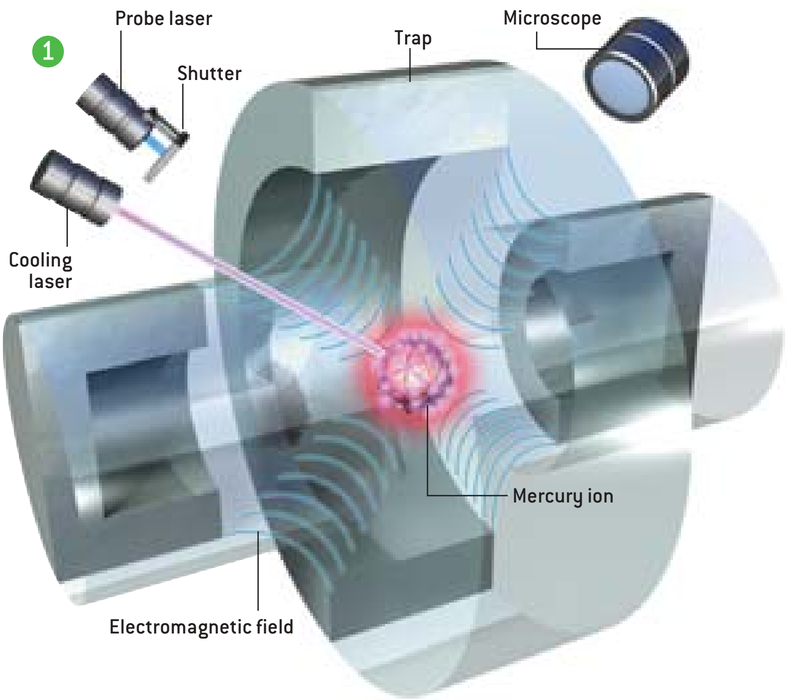
Extracting Time from an Atom

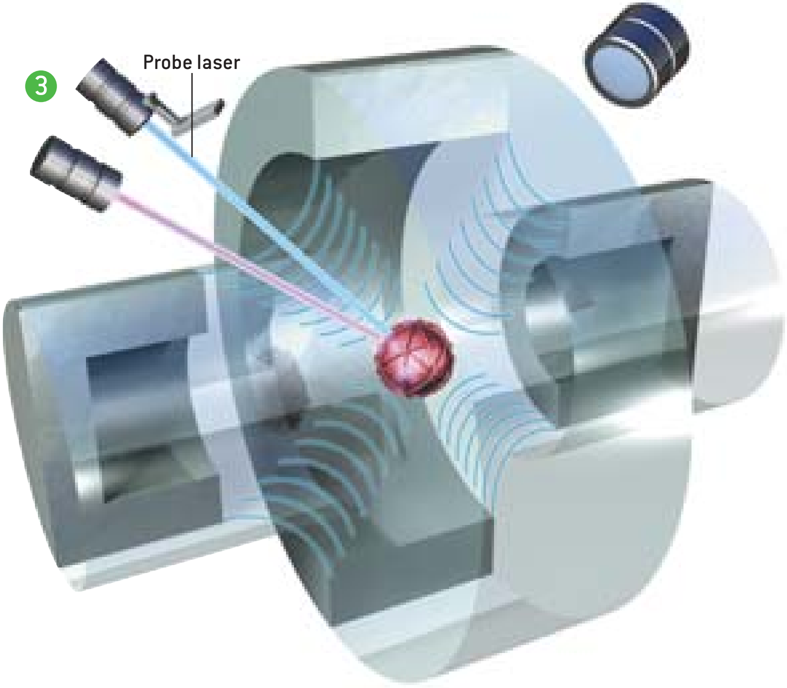
EVERY CLOCK has at least two basic components, an oscillator and a counter. An atomic clock is so accurate because it includes a third element: a feedback system that periodically checks an atomic reference to keep the oscillator ticking with near perfect regularity. In a state-of-the-art optical ion 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.

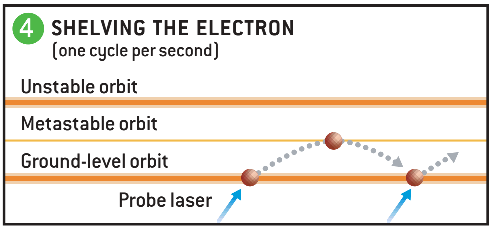






Probed and Shelved

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 hasn't 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.



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 in 2008, although Gibble, who directs the project, hopes it might fly sooner. As its name suggests, RACE will replace the cesium so familiar to clock makers with a different alkali element. "In the best cesium fountains the largest source of error are so-called cold collisions," Gibble explained. 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 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

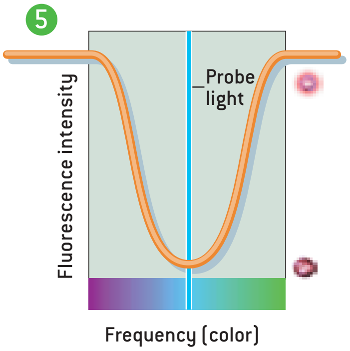
ASIDE FROM ITS REPLACEMENT of cesium with rubidium, RACE will be a fairly standard fountain clock, with lasers cooling the atoms but microwaves kicking the electrons around and ticking off the time. That is a proven and reliable design. But it will soon be obsolete.

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.

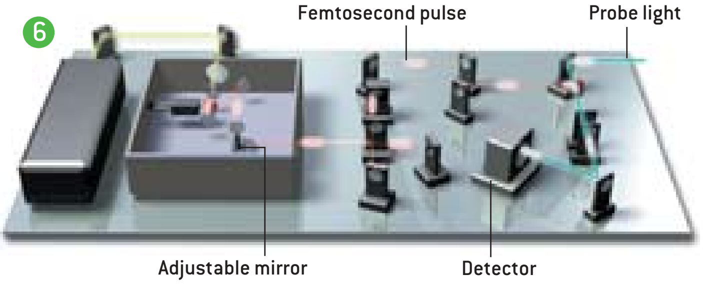
"Nobody knows how to count 10^{16} cycles per second," observes Eric A. Burt of the Jet Propulsion Laboratory in Pasadena, Calif. "We needed a bridge to the microwave regime, where we do have electronic counters."

Matched and Metered

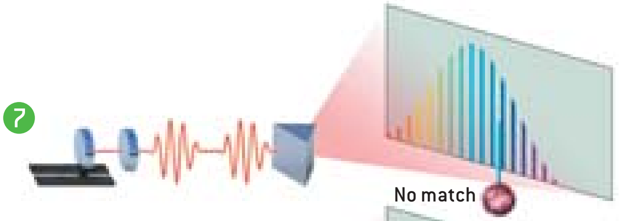
A FEEDBACK SYSTEM adjusts the laser color until the fluorescence is at a minimum (*5*). The probe light, now rock steady, is next passed via optical fiber to a counter. The probe light oscillates about a quadrillion times a second, far too fast to count directly. A third laser acts like a reducing gear to translate the time signal from a quadrillion cycles a second to about a billion cycles a second.

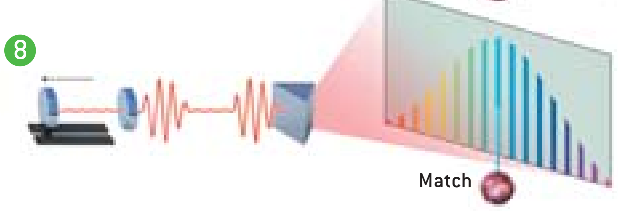


This third laser emits infrared pulses just a few femtoseconds long, with stretches of darkness between them (*6*).



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.





BRYAN CHRISTIE DESIGN

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."

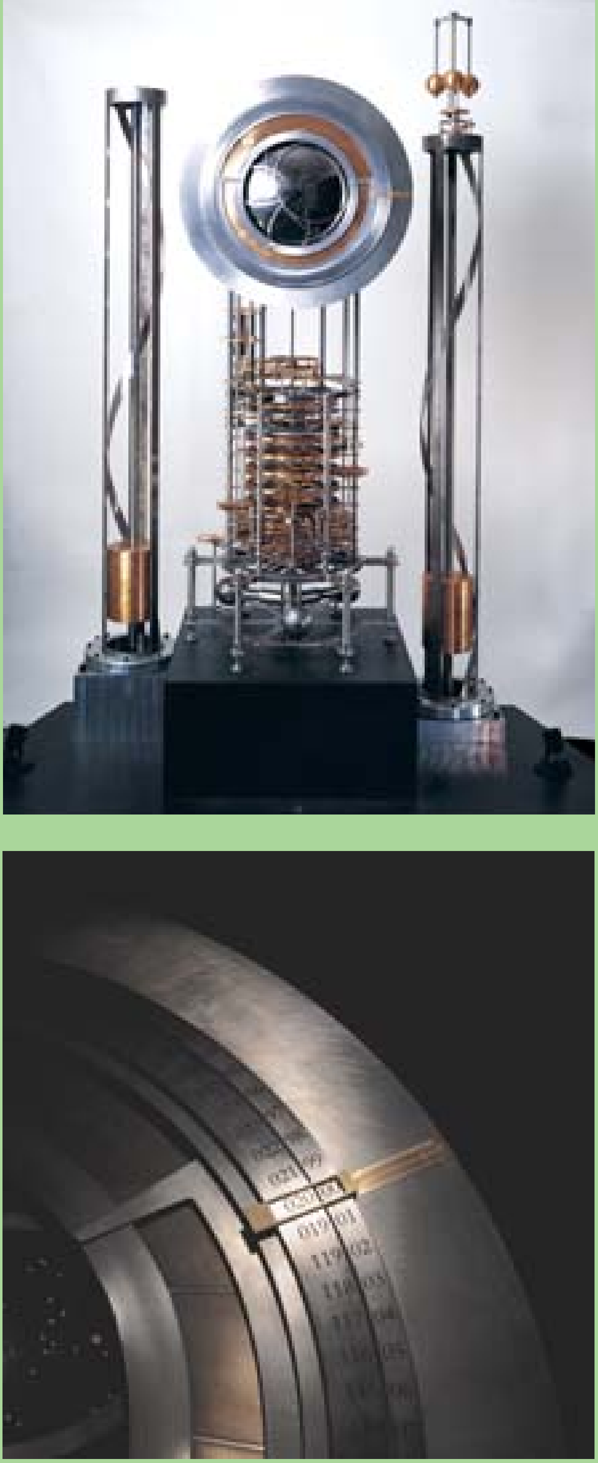
Hillis may seem like an unlikely leader of a movement to reverse society's preoccupation with the fast and soon. In the 1980s he designed supercomputers; in the 1990s, theme park rides. Today he can spare an hour for an interview only if half of it is done on the trip to Silicon Valley for his next meeting.

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 recently 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 in 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 30 inches 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*).

ROLFE HORN, COURTESY OF THE LONG NOW FOUNDATION

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

Enter the optical ruler. In 1999 Thomas Udem, Theodor W. Hänsch and others at the Max Planck Institute for Quantum Optics in Garching 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 illustration on page 90*]. Because each atom is missing an electron, the ions carry a positive charge. They repel each other, 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 puts 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? SA

W. Wayt Gibbs is senior writer.

MORE TO EXPLORE

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Ultrashort-Pulse Lasers. John-Mark Hopkins and Wilson Sibbett in *Scientific American*, Vol. 283, No. 3, pages 72–79; September 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: **boulder.nist.gov/timefreq/**

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

A Promenade with Prosimians

VISITING LEMURS AND THEIR NEXT OF KIN AT THE DUKE PRIMATE CENTER **BY MARGUERITE HOLLOWAY**

"Keep your voices down," cautions Lincoln Larson, "because if you get into a shouting match with the lemurs, they will win every time." We are standing beside a series of spacious outdoor cages at the Duke Primate Center in Durham, N.C., staring at three female red-ruffed lemurs and a black-and-white-ruffed male that is housed with them. It is midday in June, and the primates in question are sluggish and for the most part staying in the shade of their sleeping boxes. But soon, as if to prove our guide Larson right, they begin to cry out, something between a growl, a hoot and a chirp. The crescendo of calls is quite loud but subsides quickly before the rest of the lemurs get going.

There are currently 250 or so prosimians—the roots of the term mean "pre-ape" or "pre-monkey"—at the Duke center, mostly lemurs from Madagascar but also bushbabies and lorises from Africa and Asia. Prosimians appeared about 55 million years ago. Because they branched off the line leading to humans and retain some of the characteristics of that common ancestor, they are fascinating to primatologists and other scientists interested in our origins. But they are equally fascinating to those not snooping around the family tree. The 50 or so species—which all evolved from one ancestral lemur that most likely traveled the 250 watery miles from Africa to Madagascar on a tangle of vegetation—are beautiful with their various colors and almost canine faces, intriguing because of their amazing specialization to narrow ecological niches, and highly endangered because of intense deforestation.

BLACK-AND-WHITE ruffed lemurs from the Duke Primate Center have been reintroduced to Madagascar with mixed success. Many species of lemur are threatened by deforestation on the island, which has only about 13 percent of its original forests.

PHOTOGRAPHS BY DAVID HARING *Duke Primate Center*

Fifteen kinds of lemur live at the center, which sits on 80 acres of forest, and visitors can see many of the species. Housed next to the ruffed lemurs is a common brown lemur, and next to it a sifaka named Drusilla with her new infant. Of all the lemurs, sifakas are perhaps the best known because they can leap fantastic distances in trees but when on the ground jump awkwardly on two legs, their skinny bodies stretched tall as they careen sideways. Drusilla is having nothing to do with anything as strenuous as that, however, and stays in the back of the cage with her tiny baby. In with Drusilla is Nigel, the 30-year-old, bald-kneed sire of many of the sifakas at the center. "You can tell when lemurs are old because they lose the hair on the top of their knees," Larson says.

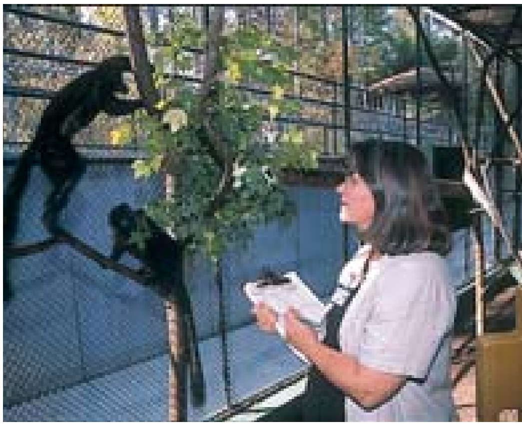
Next we see a ring-tailed lemur, its long black-and-white tail arching far overhead. The tour group—about 17 of us—traipses past the adjacent outdoor cages and then around several free-standing circular ones. Many of the enclosures look like day-care center playgrounds: they have brightly colored plastic jungle gyms. None of the lemurs are cavorting on the climbing equipment at the moment, though. It is too hot. So over the course of the tour we catch glimpses of napping red-bellied lemurs, bamboo lemurs, crowned lemurs, blue-eyed black lemurs, mongoose lemurs, as well as more sifakas and ring-tails. Some inside their boxes, some in the shade, a few stalking about, one leaping.

After about half an hour of wandering by cages, we reach Romeo, a 12-pound diademed sifaka, one of the largest of the lemurs. He is the only diademed in captivity in the world, and just a few thousand remain in Madagascar. The center has had no luck finding a Juliet for him, Larson says. Romeo leaps across to examine us and then goes indoors as we do. He settles in the threshold between the inner and outer sections of his cage, keeping an eye on us as we peer at him, one leg held close to his body, the other stretched out, as if he were sitting in the door of a railway car, voyaging alone. "Sort of sad to name him Romeo when he is the only one of his kind here," a visitor remarks.

The center has had more success breeding and reintroducing black-and-white ruffs. Over the past few years, three groups of these lemurs—from Duke and from various zoos—have been released in Madagascar. (A hilarious PBS documentary, *Lemurs with John Cleese,* chronicles the story of the first set of lemurs, called the Carolina Five.) According to David Haring, the center's registrar and photographer, the lemurs that had experienced living wild for a time in Duke's forest fared much better than those that knew only cages. Of the 13 that have been released, only six have not been eaten by fossas—a big catlike creature that is the lemurs' primary predator—died from other causes or been recaptured because they were not thriving. Most of the research at the Duke center, however, does not revolve around conservation. Current projects, Haring says, include looking at lemur locomotion and jaw strength and at aye-aye foraging behavior.

The strange-looking aye-ayes are the sole nocturnal prosimians that visitors get to see (although there is talk of opening the nocturnal building housing the diminutive bushbabies and lorises, says Heather Thomas, the center's tour coordinator). Before Larson lets the group into the darkened room in the building that also houses Romeo, he shows us a brass lock that one of the aye-ayes bit with its extremely sharp, strong and quickly growing teeth: it is gouged with deep marks. Inside the room there are several green-lit cages, and we can see aye-ayes creeping around in the branches. They weigh about six pounds and have huge, hairless ears and enormously long fingers—especially the third finger, used to root in deep holes for grubs and other prey.

We emerge from the dim room back into the Carolina sun and the dry aroma of the surrounding pine forest. We don't get a glimpse of the free-ranging lemurs in the nearby trees, but it is nice to know they are out there, perhaps being readied for a trip home.

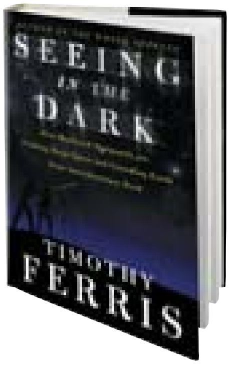


RING-TAILED LEMURS (*left*) use their tails to fight scent wars. The animals rub secretions onto their tails and then flick them at opponents. Blue-eyed blacks (*above*) do not fight olfactory battles; only the ring-tail and bamboo lemurs do.

The Duke Primate Center is open from 8:30 A.M. until 4:30 P.M. Monday through Friday and from 8:30 A.M. until around 1 P.M. on Saturdays. Visitors—of which there are about 15,000 a year—must call beforehand to make reservations: 919-489-3364. The tours cost $6 for adults and $3 for children (infants are free) and take an hour or so. The center is located on Lemur Lane, at 3705 Erwin Road, and is easily accessible from either Interstate 85 or 40 (good directions can be found at www.durham-nc.com/planners/group_tours/nature_primate.php and at map.duke.edu). As you drive down Lemur Lane, go past the signs saying RESTRICTED RESEARCH AREA: DON'T ENTER. Check out www.duke.edu/web/primate for further information.

Amateurs Take On the Universe

A LOOK BACK DOWN THE TELESCOPE AT CITIZEN ASTRONOMERS **BY SHAWN CARLSON**



SEEING IN THE DARK: HOW BACKYARD STARGAZERS ARE PROBING DEEP SPACE AND GUARDING EARTH FROM INTERPLANETARY PERIL
by Timothy Ferris
Simon & Schuster, 2002
($26)

If you've never heard of Stephen James O'Meara or Don Parker, then you've missed some of the most fascinating adventures in 20th-century astronomy. O'Meara was the first person to measure the length of a day on Uranus and to see radial "spokes" in Saturn's rings. (Most astronomers dismissed that discovery as illusionary, until Voyager got close enough to photograph them.) What's more remarkable, in an age of computer-enhanced CCD images, O'Meara made these observations visually, using only a small telescope and his own eyes. Parker went in a different direction. After improving the technique of CCD-based astrophotography, he amassed what might be the world's most extensive and scientifically valuable digital archive of planetary portraits. Despite their passion for astronomy, both hold more down-to-earth day jobs.

They are not alone. Today, equipped with low-cost telescopes and high-tech imaging systems, a small army of dedicated amateur sky watchers struggles every night to advance our understanding of the cosmos. While that's no secret, tales from the trenches are seldom told, so these passionate citizen scientists and their extraordinary achievements have remained undeservedly obscure.

Happily, amateur astronomy is about to receive a whole new type of exposure. *Seeing in the Dark,* Timothy Ferris's latest sojourn into matters astronomical, presents a delightful look back down the telescopes of some of the world's most accomplished citizen astronomers.

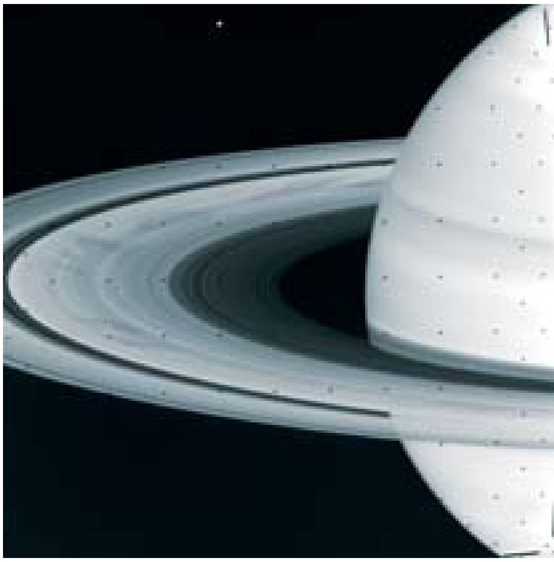
Ferris knows this community well. A lifelong amateur astronomer, he has an intimate connection to his subject. He isn't bashful about sharing his own experiences. In one passage, Ferris regresses to 1959, when he was a young man, strapped inside the cockpit of a "raw, street-legal racer" while it screeched headlong down the Florida interstate. A self-described "white boy" in the segregated South, Ferris was haunted by his forbidden love of authentic African-American blues. But the radio stations that played it were hundreds of miles away. So he took to the road near midnight, when the ionosphere firmed up and reflected those prized AM waves from their faraway source to his car radio.

As he describes how he mentally connected the stars with those distant radio signals, he makes it clear why some people wonder incessantly about life on other planets. It's a refreshing perspective because it presents the situation as astronomers often see it: one cosmos in which the great questions of existence are inextricably intertwined with the mundane. It's what turns thousands of otherwise ordinary folks into night owls who tirelessly prowl the skies for new insights into ancient mysteries.

Ferris profiles some of the stars of amateur astronomy, such as comet hunter extraordinaire David Levy (best known for co-discovering Comet Shoemaker-Levy, which plummeted into Jupiter in 1994). But he also meanders about the community's charming backroads, where you never know whom you are going to meet. The introductions include a roly-poly Houston housewife and master observer who casually chases alligators away from her observatory with a rake, and a sculptor who converted the caldera of an extinct volcano into an enduring work of modern astronomical art. We even get to meet Brian May of the rock

"SPOKES" in Saturn's rings (the shadows lying across the rings in this image) were discovered by an amateur astronomer.

NASA



group Queen. It turns out that the fellow who wrote "We Will Rock You" also did postgraduate work in infrared astronomy and still observes as an amateur.

To provide context for the profiles, Ferris has also written an excellent introduction to basic astronomy. Actually, it may be a bit too good. Anyone who wishes to plumb the depths of planetary astronomy, or to contemplate catastrophic cosmic collisions, can buy bushels of best-selling books on those subjects. But here, where the main course is the community itself, astronomy should be treated like a rich dessert. The chef needs to present enough to complement the meal, but too much richness can detract from the experience. In an era when publishers impose strict page limits on their authors, more science means less of the stuff that makes *Seeing in the Dark* such a joy to read.

Also, the book eats up 30 pages with astronomical tables and viewing tips, apparently so the publisher can position it as an observer's guide. This must be the work of an overzealous marketing department. Ferris surely knows this small space can't present enough information to be of much use and that many excellent observing guides can already be found in bookstores and on the Internet. My advice to Simon & Schuster would have been to keep the "Further Reading" section and let Ferris substitute the rest with another profile or two. Then this great book would be near perfect.

In the end, *Seeing in the Dark* teaches an important lesson for any nonprofessional interested in science. Amateurs may not have access to all the toys the professionals do. But they always seem to enjoy their research tremendously—and many make discoveries, some of them of immense value to our understanding of the universe. SA

Shawn Carlson wrote this magazine's Amateur Scientist column from 1995 to 2001. He is the founder of the Society for Amateur Scientists and a MacArthur Fellow.

SCIENTIFIC AMERICAN Help Desk

For your convenience, we have summarized the answers to often-asked customer service questions and how to get in touch with us.

Scientific American Frontiers

The magazine's PBS television series, Scientific American Frontiers, is hosted by actor and life long science buff, Alan Alda. There are now 10 one-hour episodes each season , with Frontiers becoming an integral part of a new PBS science programming initiative. Visit the Scientific American Frontiers Web site at www.pbs.org/saf

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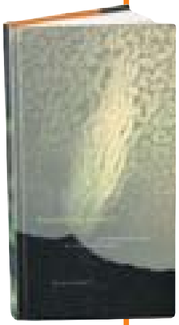
THE EDITORS **RECOMMEND**

ENVISIONING SCIENCE: THE DESIGN AND CRAFT OF THE SCIENCE IMAGE

by Felice Frankel. MIT Press, Cambridge, Mass., 2002 ($55)



Frankel, a science photographer and research scientist at the Massachusetts Institute of Technology, presents "a guide to photographing science material." As that alone, it would be of limited interest. But two other attributes give the book a far broader appeal. One is her goal of encouraging science workers "to find a place in your research for a new way of seeing and presenting your work" so as to see "the potential of using your images to communicate to those outside the research community." The other is the pictures, a stunning array that will communicate with any reader. Open the book at random, and your eye will be dazzled: a three-centimeter drop of ferrofluid, gold on gold (one-centimeter patterned chips on a gold wafer), or a flowerlike yeast colony illuminated by daylight from a window.

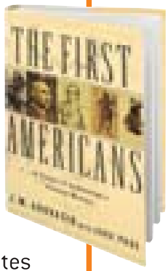
UNLOCKING THE SKY: GLENN HAMMOND CURTISS AND THE RACE TO INVENT THE AIRPLANE

by Seth Shulman. HarperCollins, New York, 2002 ($25.95)

The list of Glenn Hammond Curtiss's achievements as a major figure in the early history of aviation is long and impressive. He was, journalist Shulman writes, "the first to make a public flight in the United States, the first to sell a commercial airplane, the first to fly from one American city to another, and the first to receive a U.S. pilot license, to name just a few of his accomplishments." Shulman makes his biography a suspense story by tracing Curtiss's long and bitter legal battle with Orville Wright, who charged Curtiss (and many others) with patent infringement. "Ultimately, the case would cripple the development of the youthful aviation industry, especially in the United States." Now, however, one can see that a number of Curtiss's "seminal contributions are still in use in airplanes today, including everything from wing flaps and retractable landing gear to the enclosed cockpit and the design of the pontoons used on seaplanes," whereas "virtually none of the Wright brothers' aeronautical designs has stood the test of time."

THE FIRST AMERICANS: IN PURSUIT OF ARCHAEOLOGY'S GREATEST MYSTERY

by J. M. Adovasio, with Jake Page. Random House, New York, 2002 ($26.95)



When did the first humans reach North America? Archaeologist Adovasio's answer is, thousands of years earlier than the Clovis people of 11,200 to 10,500 years ago (9200 to 8500 B.C.), who are held by "a tenet of archaeology" to have been the pioneers. He first advanced that argument in 1974, after charcoal taken from two fire pits in a shallow cave at Meadowcroft Rockshelter in western Pennsylvania revealed through radiocarbon dating "that humans had been there using these two hearths in about 13,000 B.C.," some 4,000 years "before any human being was supposed to have set foot anywhere in this hemisphere." Now five pre-Clovis sites are known in the Americas, all displaying very different technologies. The existence of so much cultural diversity "strongly suggests that there were multiple incursions into this hemisphere by people who were probably diverse genetically." In telling this story, Adovasio—founder and director of the Mercyhurst Archaeological Institute—and science writer Page give the general reader a fine grounding in what is known of human migration.

All the books reviewed are available for purchase through www.sciam.com

PUZZLINGADVENTURES

Venture Bets

BY DENNIS E. SHASHA

Suppose you're the manager of a venture capital fund. You've identified 11 hot companies, each of which has a decent chance of striking it rich, providing your fund with returns 10 times as great as your original investment in the company. Your investors, however, want a safe road to riches. Can you use your mathematical knowledge to increase the probability of financial success?

Here's a warm-up problem. Let's say that your fund has $17 million to invest. Each of the 11 companies has a 40 percent chance of yielding 10-fold returns and a 60 percent chance of going bust. Your investors want at least a 60 percent probability that the fund will grow to a minimum of $60 million. How should you allocate the $17 million among the companies?

Obviously, putting all the money in one company won't work, because the probability of success is only 40 percent. But if you invest in two companies, the chance that at least one of them will succeed is 64 percent (because the probability that both will fail is 0.6 × 0.6 = 0.36). So if you put $6 million in each of two companies, you will meet the required probability for a $60-million return and still have $5 million left in reserve in case an even better investment comes along. Spreading your bets further is not a good strategy. For example, if you invest $3 million in each of four companies, hoping that two or more will reap a windfall, your probability of success is barely over 50 percent.

Now let's suppose that the economy has suddenly improved. Each of the 11 hot companies now has an 85 percent chance of yielding 10-fold returns. But the demands of your investors have grown correspondingly. They want a 95 percent chance that their fund will grow from $17 million to $100 million. Again, investing all the money in one company won't work. And giving two companies $8.5 million each won't work either: although there's a 97.75 percent chance that at least one company will succeed, a 10-fold return on $8.5 million is only $85 million. Can you find a way to achieve your investors' goals while keeping as much money as possible in reserve?

Answer to Last Month's Puzzle

The smallest circumference of the repellanoid cylinder is 14. The composition of the stacked rings is: emerald (8), crimson (6); aqua (4), blue (5), blue (5); yellow (7), yellow (7); and crimson (6), aqua (4), aqua (4). For mini repellanoids, let the strand lengths be A = 2, B = 3, C = 4, D = 5 and E = 7. The circumference can then be 7. Here is the composition of the rings: E, DA, AAB and BC.

Web Solution

For a peek at the answer to this month's problem, visit www.sciam.com

SARA CHEN

Einstein's Hot Time

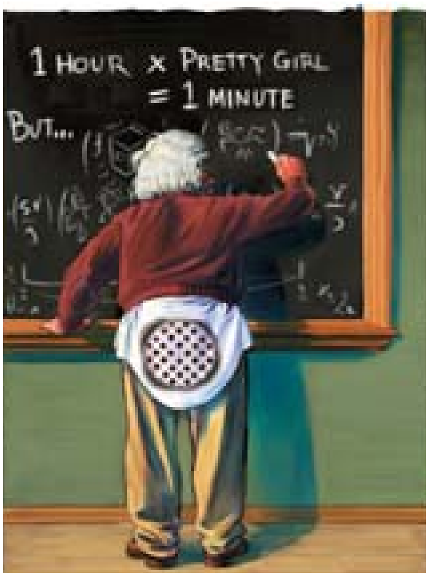
GREAT THEORETICIANS KNOW THAT HYPOTHESIS MUST BE CONFIRMED WITH EXPERIMENT

BY STEVE MIRSKY

A well-known quote from Albert Einstein, a member of the all-time time team, is his attempt to make relativity more accessible to the layperson: "When a man sits with a pretty girl for an hour, it seems like a minute. But let him sit on a hot stove for a minute and it's longer than any hour. That's relativity."

Some serendipitous research shows that the pretty girl/hot stove line turns out to be more than just a clever musing. On a recent troll through exceedingly dusty stacks at the local library, I stumbled upon the statement in its original form. Amazingly, the pretty girl/hot stove quote is actually the abstract from a short paper written by Einstein that appeared in the now defunct *Journal of Exothermic Science and Technology* (*JEST*, Vol. 1, No. 9; 1938). Apparently, the great theoretician tried his hand, and other body parts, at experimentation to derive his simple explanation for relativity. Here now, in its entirety, is that paper.

> "On the Effects of External Sensory Input on Time Dilation." A. Einstein, Institute for Advanced Study, Princeton, N.J.
>
> Abstract: When a man sits with a pretty girl for an hour, it seems like a minute. But let him sit on a hot stove for a minute and it's longer than any hour. That's relativity.
>
> As the observer's reference frame is crucial to the observer's perception of the flow of time, the state of mind of the observer may be an additional factor in that perception. I therefore endeavored to study the apparent flow of time under two distinct sets of mental states.
>
> Methods: I sought to acquire a hot stove and a pretty girl. Unfortunately, getting a hot stove was prohibitive, as the woman who cooks for me has forbidden me from getting anywhere near the kitchen. However, I did manage to surreptitiously obtain a 1924 Manning-Bowman and Co. chrome waffle iron, which is a reasonable equivalent of a hot stove for this experiment, as it can attain a temperature of a very high degree. Finding the pretty girl presented more of a problem, as I now live in New Jersey. I know Charlie Chaplin, having attended the opening of his 1931 film *City Lights* in his company, and so I requested that he set up a meeting with his wife, movie star Paulette Goddard, the possessor of a *shayna punim,* or pretty face, of a very high degree.



> Discussion: I took the train to New York City to meet with Miss Goddard at the Oyster Bar in Grand Central Terminal. She was radiant and delightful. When it felt to me as if a minute had passed, I checked my watch to discover that a full 57 minutes had actually transpired, which I rounded up to one hour. Upon returning to my home, I plugged in the waffle iron and allowed it to heat up. I then sat on it, wearing trousers and a long white shirt, untucked. When it seemed that over an hour had gone by, I stood up and checked my watch to discover that less than one second had in fact passed. To maintain unit consistency for the descriptions of the two circumstances, I rounded up to one minute, after which I called a physician.
>
> Conclusion: The state of mind of the observer plays a crucial role in the perception of time.

Einstein scholars disagree, but the pretty girl/hot stove experiment also may have led to another of his pithy remarks, namely: "If we knew what it was we were doing, it would not be called research, would it?" Then again, Einstein was a bit of a wag. Consider his explanation of wireless communication: "The wireless telegraph is not difficult to understand. The ordinary telegraph is like a very long cat. You pull the tail in New York, and it meows in Los Angeles. The wireless is the same, only without the cat." This quote reportedly kept Schrödinger awake well past his bedtime.

ILLUSTRATION BY MATT COLLINS; PHOTOGRAPH BY FRANK VERONSKY

ASK THE EXPERTS

What exactly is déjà vu?

—Ayako Tsuchida, Ube, Japan

James M. Lampinen, assistant professor of psychology at the University of Arkansas, supplies this answer:

Most people experience déjà vu—the feeling that an entire event has happened before, despite the knowledge that it is unique. We don't yet have a definitive answer about what produces déjà vu, but several theories have been advanced.

One early theory, proposed by Sigmund Freud, is that déjà vu takes place when a person is spontaneously reminded of an unconscious fantasy. In 1990 Herman Sno, a psychiatrist at Hospital de Heel in Zaandam, the Netherlands, suggested that memories are stored in a format similar to holograms. Unlike a photograph, each section of a hologram contains all the information needed to reproduce the entire picture. But the smaller the fragment, the fuzzier the resultant image. According to Sno, déjà vu occurs when some small detail in one's current situation closely matches a memory fragment, conjuring up a blurry image of that former experience.

Déjà vu can also be explained in terms of what psychologists call global matching models. A situation may seem familiar either because it is similar to a single event stored in memory or because it is moderately similar to a large number of stored events. For instance, imagine you are shown pictures of various people in my family. Afterward, you happen to bump into me and think, "Hey, that guy looks familiar." Although nobody in my family looks just like me, they all look somewhat like me, and according to global matching models the similarity tends to summate.

Progress toward understanding déjà vu has also been made in cognitive psychology and the neurosciences. Researchers have distinguished between two types of memories. Some are based on conscious recollection; for example, most of us can consciously recall our first kiss. Other memories, such as those stimulated when we meet someone we seem to recognize but can't quite place, are based on familiarity. Researchers believe that conscious recollection is mediated by the prefrontal cortex and the hippocampus at the front of the brain, whereas the part housed behind it, which includes the parahippocampal gyrus and its cortical connections, mediates feelings of familiarity. Josef Spatt of the NKH Rosenhügel in Vienna, Austria, has argued that déjà vu experiences occur when the parahippocampal gyrus and associated areas become temporarily activated in the presence of normal functioning in the prefrontal cortex and hippocampus, producing a strong feeling of familiarity but without the experience of conscious recollection.

As you can tell, this is an area still ripe for research.

How can graphite and diamond be so different if they are both composed of pure carbon?

—M. Hurley, North Attleboro, Mass.

Miriam Rossi, professor of chemistry at Vassar College, provides an explanation:

The distinct arrangement of atoms in diamond and carbon makes all the difference to their properties. In a diamond, the carbon atoms are organized tetrahedrally. Each carbon atom is attached to four others, forming a rigid three-dimensional network. This accounts for diamond's extraordinary strength, durability and other properties. Diamond, the hardest material known, can scratch all other materials. It conducts more than copper does, but it's also an electrical insulator. The gemstone disperses light into a rainbow of colors, giving rise to the "fire" of diamonds.

In comparison, the carbon atoms in graphite are arranged in layers. The atoms have two types of interactions with one another. First, each is bonded to three others and arranged at the corner of a network of hexagons. These planar arrangements extend in two dimensions to form a horizontal, hexagonal "chicken-wire" array. Second, these arrays are held together weakly in layers. Graphite is soft and slippery and can be used as a lubricant or in pencils because its layers cleave readily. The planar structure allows electrons to move easily within the planes, permitting graphite to conduct electricity and heat as well as to absorb light so that it appears black in color.

For a complete text of these and other answers from scientists in diverse fields, visit www.sciam.com/askexpert

SARA CHEN

FUZZY LOGIC

AN EXTREMELY BRIEF HISTORY OF TIME

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