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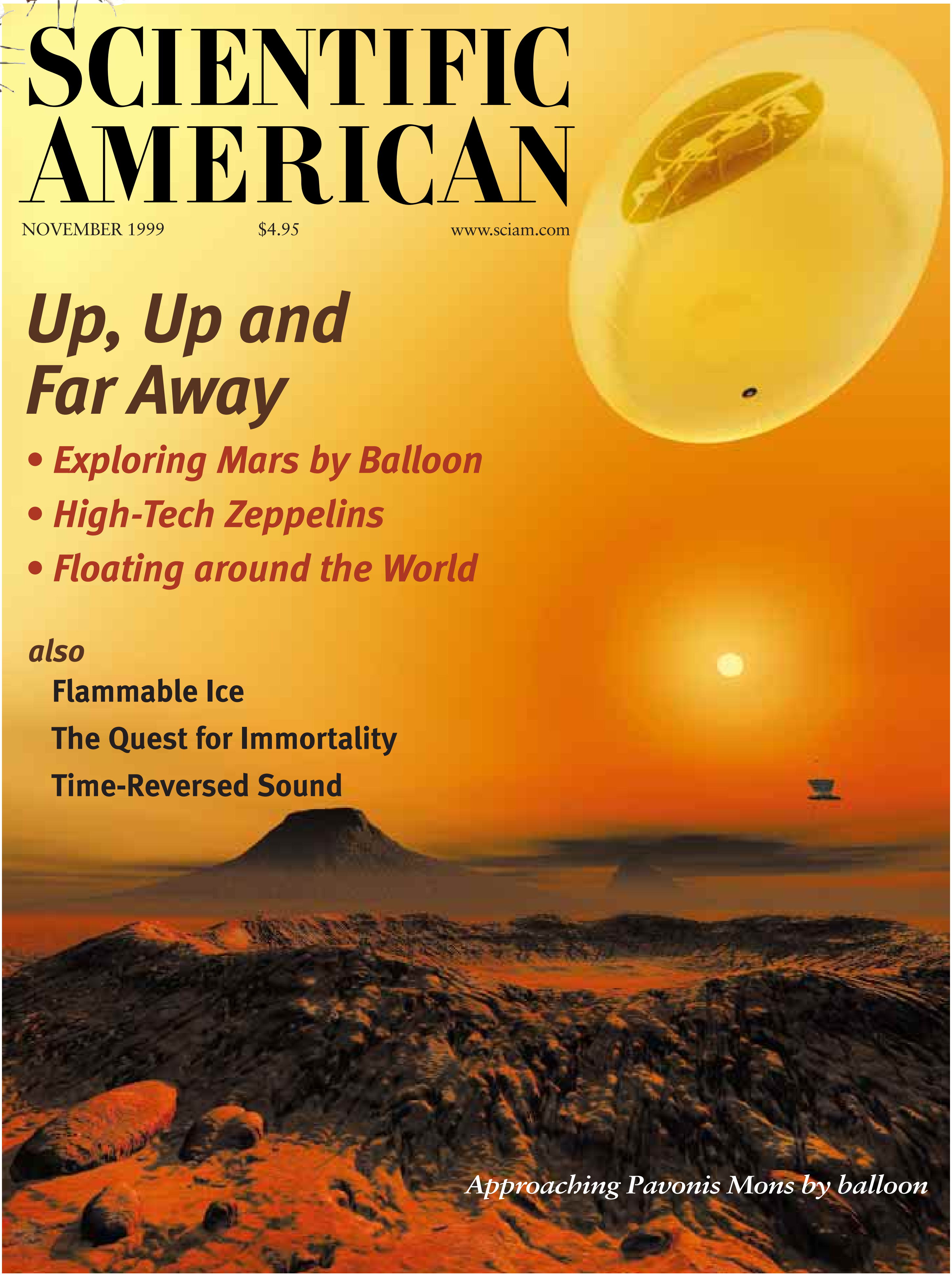

Approaching Pavonis Mons by balloon

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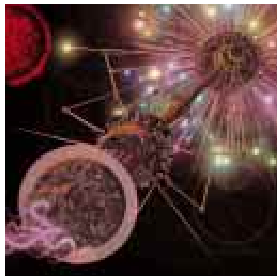

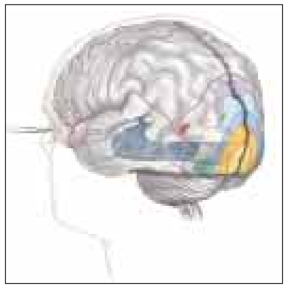

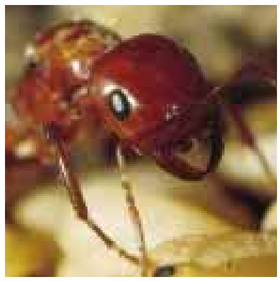

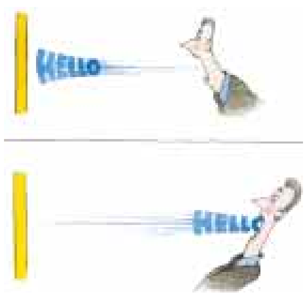

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About the Cover
Floating over the Martian surface, this balloon-borne NASA probe studies the area around the mountain Pavonis Mons. Digital Art by Space Channel/Philip Saunders.

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From the Editors

Who Wants to Live Forever?

Ponce de León looked for the Fountain of Youth. More modern dreamers place their hopes in cryonics and nanotechnology. The wish for physical immortality grows naturally out of our fear of death. Who wouldn't want a long, happy life? And yet how many of us are prepared to face what true immortality would mean?

Jorge Luis Borges dealt with eternal life, and other concepts of infinity, perhaps more provocatively and entertainingly than any other writer. In his short story "The Immortal," he described a people whose attainment of immortality has destroyed their individuality. They accept that over an infinite expanse of time, everything that can happen will, in every permutation and to everyone, over and over again. It leaves them without hope or desire, only fleetingly roused from emotional torpor by sensual experience. "To be immortal is commonplace; except for man, all creatures are immortal, because they are ignorant of death," the narrator observes, "what is divine, terrible, incomprehensible, is to know that one is immortal."

ERICA LANSNER

If you die when the universe is a cold, stagnant void, at least you won't be missing much.

Lawrence M. Krauss and Glenn D. Starkman, on page 58 of this issue, analyze whether eternal life is even theoretically possible. Being astrophysicists, they don't do things halfway. They aren't talking about living for a mere few million years, or billions, or trillions. They're not talking about living for 10^{100} years. They mean *forever.*

The good news, if I can put it this way, is that physics won't stop you from living an inconceivably long time, a number of years so great that calling it astronomical does it injustice. The bad news is that barring time travel or escape to other universes, that dismal truism of economics still applies: in the long run, we are all dead. If it's any consolation, when you die after 10^{37} years, you won't be missing much, because the universe will have thinned to a cold, stagnant void dotted with black holes. But the fact remains that every living thing in existence will eventually perish, and the universe will again be absolutely sterile. Despite your having fought successfully to survive for eons, it will still be as though you had never lived. And the fleeting fraction of eternity during which the universe will have known life and heat and order will be infinitesimally, insignificantly minute.

May I venture the opinion that this bleak vision is what comes of wrangling with an unforgiving eternity? Transience and limits are at the core of our nature, and you can consider that a curse or a blessing. Our lives are less than atomic flickers on the scale of the cosmos, but they would be equally infinitesimal if they lasted 10 million times longer, and they would still be infinitely precious to us. You have the chance to enjoy some morsel of the 10^{14} years that the sun and stars will last. You should.

JOHN RENNIE, *Editor in Chief*
editors@sciam.com

Readers responded in large numbers to “Life’s Far-Flung Raw Materials,” by Max P. Bernstein, Scott A. Sandford and Louis J. Allamandola, in the July issue. Many demanded to know why the authors didn’t discuss the efforts of certain researchers who have promoted panspermia—the theory that extraterrestrial organisms hitched a ride to Earth on comets and meteors and colonized our planet. Conversely, antipanspermia readers felt that the article represented irresponsible advocacy for a far-fetched notion.

In reply we might point out that this article discussed the possibility of life’s raw materials—complex organic molecules—arriving on Earth in this manner. This, of course, is rather a different idea than living organisms arriving from outer space and colonizing life here—a distinction that was made in a sidebar that appeared with the article. Still, we were curious about Bernstein’s thoughts on panspermia. “I am as confident as I can be that life on Earth was not the result of interstellar bacteria that floated their way here, because modern observations are simply not consistent with this idea,” he asserts. “Until that evidence is presented, I’ll stick with life starting here, since that’s the best theory we have so far.” Additional reader comments regarding this article and others in the July issue follow.

LIFE’S INTERSTELLAR INGREDIENTS

I read with interest “Life’s Far-Flung Raw Materials,” by Max P. Bernstein, Scott A. Sandford and Louis J. Allamandola. The article states that life on the earth is made up of left-handed amino acids, which correlates with a tendency toward left-handedness in extraterrestrial molecules. Are there any explanations for why left-handedness is favored over right-handedness? If life on our planet took off after a series of false starts, is it possible that any of those might have led to life based on right-handed amino acids?

DAVID LESBERG
via e-mail

COVER STORY of the July issue elicited a variety of responses.

I was fascinated by the speculation in “Life’s Far-Flung Materials.” I counted four coulds, two mays, and one each might, probably, presumably and implies. Wow—what conviction! My real reason for writing, however, concerns meteorite ALH 84001. What evidence is there for its purportedly Martian origin?

DANIEL Y. MESCHTER
via e-mail

Bernstein replies:

Recent research has shown that there is an excess of left-handed amino acids in two carbon-rich meteorites, which, as Lesberg notes, suggests that the left-handedness of the amino acids in our bodies was determined by extraterrestrial input. Because it always seems to be left-handed amino acids that are favored, it is unlikely that this occurred by chance; thus, earlier “false starts” were also most likely left-handed. But why? One proposal is that left-handed amino acids should be slightly more stable because of the weak force, but this effect seems far too small to account for the observed excess. It has also been theorized that if the material from which our solar system was made was exposed to circularly polarized radiation, that might have resulted in molecules of one-handedness being favored. This idea has received attention recently because circularly polarized radiation has been detected in the interstellar medium. Assuming there is life elsewhere, in another region of space the radiation might well have had the other polarization, thus giving rise to organisms with right-handed amino acids.

Regarding Meschter’s question, the origin of ALH 84001 is not controversial. ALH 84001 is one of a group of Martian meteorites called SNCs. The gases trapped inside these rocks match the Martian atmosphere very well, indicating that they came from Mars.

As for the frequency of could, may, might and probably in our article, ongoing scientific inquiry can rarely be related honestly without these words. You should worry more about the scientists who don’t use conditionals than the ones who do.

FUEL CELLS FOR CARS

In “The Electrochemical Engine for Vehicles,” A. John Appleby provides a useful summary, but he catalogues many problems that have already been resolved—namely, the $50-per-kilowatt stack-cost requirement, low system efficiency, limited catalyst supply, excessive hydrogen tank size and lack of hydrogen infrastructure. Correcting two common assumptions—that cars are too heavy and inefficient to get a decent driving range out of a compact, compressed-hydrogen-gas fuel tank and that fuel cells must be designed and deployed separately for buildings and vehicles—eliminates unnecessary and uneconomic constraints and makes all the pieces of technology, policy and market opportunity fall neatly into place.

AMORY B. LOVINS
Rocky Mountain Institute and
Hypercar, Inc.
Old Snowmass, Colo.

SUPPORTING CYBER SCHOOL

With regard to Wendy M. Grossman’s Cyber View piece “On-Line U,” at 37 years old I happily pay my monthly Internet fee and surf each week for low-cost, on-line universities. There

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was no money to send me to college, and despite my 4.0 grade point average, I was denied scholarships. Currently I take one to three courses—both on-site and via the Internet—annually, as time allows. Middle-income people soon stand to have the opportunity to obtain degrees in their own time (working around their two jobs and child-rearing) by utilizing the resources afforded by the Internet. I rather resent Grossman's comments on the quality issues those universities will be facing by allowing themselves to become on-line learning centers. It smacks of the same classism that permeates our society and keeps a lower-income person working in a truck stop when the same brain could have helped find a cure for HIV had he or she the opportunity of a higher socioeconomic birth.

BONNIE WHITE
via e-mail

REBUILDING EDUCATION

I appreciated "Make Science, Not War" [News and Analysis], by George Musser. The article describes the work of the World University Service in the reconstruction of higher education in Bosnia and Herzegovina. We are undertaking similar efforts in Kosovo. The University of Pristina was devastated in recent months but has since reopened. Students of all nationalities are welcome in hopes of overcoming the separation of the past.

WOLFGANG BENEDEK
Graz, Austria

Letters to the editors should be sent by e-mail to editors@sciam.com or by post to Scientific American, 415 Madison Ave., New York, NY 10017.

ERRATUM

Several readers have pointed out a potential problem with the solar projector described in the Amateur Scientist column ["Sun of a Gun," August]. Schmidt-Cassegrain telescopes may overheat and become damaged when used for such an apparatus. Although the designer of the project, Bruce Hegerberg, reports that his Schmidt-Cassegrain has suffered no ill effects thus far, readers should recognize the possible risk to their instruments.

50, 100 AND 150 YEARS AGO

NOVEMBER 1949

SOVIETS ENTER THE ARMS RACE—“At 11 A.M. on September 23, President Truman announced the end of the U.S. monopoly in atomic bombs. His announcement that the U.S.S.R. had produced an atomic explosion was based on a careful evaluation by scientists of certain unspecified evidence. The official U.S.S.R. comment broadcast two days later by Tass, the Soviet news agency, says in part: ‘As for the alarm that is being spread on this account by certain foreign circles, there are not the slightest grounds for alarm. It should be pointed out that the Soviet Government, despite the existence in its country of an atomic weapon, adopts and intends adopting in the future its former position in favor of the absolute prohibition of the use of the atomic weapon.’”

NOVEMBER 1899

THE ELECTRON—“At the recent meeting of the British Association for the Advancement of Science Prof. J. J. Thomson gave an interesting account of recent researches on the existence of masses smaller than atoms. His investigations led to a determination of the ratio of the mass of an atom to the electric charge conveyed to it. His experiments indicated that the charge carried by an atom in cathode discharges is apparently 1,000 times greater than in ordinary electrolysis. It would appear that electrification seems to consist in the removal from an atom of a small corpuscle, the latter consisting of a very small portion of the mass with a negative charge, while the remainder of the atom possesses a positive charge.”

LOUSY PEAS—“The injury by the new pea louse in many places has been complete, and has not been confined to the pea-growing areas of Maryland, where $3,000,000 worth of peas has been lost. So far as I can ascertain, this is the first season it has been abundant enough to attract attention from the economic standpoint. Talking with some of our largest growers, I find that the louse was present in some sections last season, although it was not reported. That this enormous loss should have been attributed to a single species, especially one new to science, hardly seems possible.”

The great telescope as it will appear at the Paris Exposition

ZEPPELIN PROTOTYPE—“Hitherto no trustworthy description has been published of the huge airship which Count von Zeppelin is building on a float anchored in the Lake of Constance in southern Germany. The inventor has at last overcome his reticence enough to enable us to form some conception of this contrivance. The airship now in the course of erection is 410 feet long. The supporting body is a cylinder 39 feet in diameter, the ends being tapered, the skeleton frame of which is composed of aluminum. The balloons are made of a cotton fabric covered with a gas-tight rubber composition. Count von Zeppelin will drive his airship by four aluminum propellers connected to a pair of benzene motors.”

PARIS EXPO—“Among the scientific exhibits at the Paris Exposition of 1900 the great telescope will undoubtedly be the most interesting and important object shown (*below*). Herewith we present views showing how the telescope will look upon completion. It consists of a horizontal tube 197 feet long provided with an objective 4.1 feet in diameter. The image of the moon or stars will be sent through this tube by the aid of a Foucault sidérostat, which is a movable plane mirror of diameter 6.56 feet, mounted in a large cast-iron frame.”

NOVEMBER 1849

THE FEEBLE AMERICAN—“Sir Charles Lyell in his ‘A Second Visit to the United States’ says—‘I suspect that the principal different aspect of the Anglo Saxon race in England and America is the climate. Even so cosmopolite a being as man may demand more than two centuries and a quarter before successive generations of parents can acquire and transmit to their offspring the new and requisite physiological peculiarities. English travelers often ascribe the more delicate health of the inhabitants here to their in-door habits and want of exercise. An Englishman is usually recognized at once in a party by a more robust look, and greater clearness and ruddiness of complexion.’”[*Editors’ note: Lyell is better known for his pioneering work in geology.*]

ABC & SA—“The question of Free Schools in New York is to be decided at the coming election. We have conversed with thousands of our mechanics and yeomen upon this subject, and in general they are in favor of it. No man can be a fit citizen of the Republic, unless he reads the opinions of our Statesmen upon different questions. We want all the boys and girls to learn to read, write and cypher, at least, so that when they grow up they will be able to read the Scientific American.”

NEWS AND ANALYSIS

IN FOCUS

THE INVISIBLE EPIDEMIC

Asthma is on the rise, especially in poor urban areas, and scientists don't know why

The Mott Haven section of New York City's South Bronx has long been one of the poorest neighborhoods in the nation. The median household income of its residents, most of whom are African-American or Hispanic, is less than one third of the U.S. median. As if the burden of poverty were not enough, however, the neighborhood has now earned a new and terrible distinction. A recent study conducted by researchers at the Mount Sinai School of Medicine showed that Mott Haven has one of the highest hospitalization rates for asthma in the U.S.—three times higher than the average rate for New York City and eight times higher than the national rate.

The neighborhood's children have been particularly hard hit. In the Bronx as a whole an estimated 13 percent of those under the age of 17 suffer from the disease. Yolanda Garcia, executive director of a community group called We Stay/*Nos Quedamos,* says that in some of Mott Haven's schools as many as half of the children carry inhalers for treating asthma attacks. "Children are dying of asthma here, but no one is paying any attention," says Garcia, whose own son died at the age of 25 after an 11-year struggle with the disease. "Anywhere else in the country, it would be called an epidemic."

Asthma is a chronic inflammation of the airways in the lungs, marked by attacks of wheezing and shortness of breath. In 1980 about 3.1 percent of the U.S. population suffered from it, according to the National Health Interview

ERICA LANSNER

***INNER-CITY CHILDREN** are developing asthma at an alarming rate. Nine-year-old Alex Guerra of New York City's East Harlem has asthma so severe he requires an oxygen tank.*

Survey; by 1994 the prevalence had risen to 5.4 percent. Among children between the ages of five and 14, the prevalence jumped from 4.3 to 7.4 percent. Asthma is now the most common chronic illness among children and the leading cause of school absences. Even more disturbing, the number of deaths from asthma in the U.S. has nearly tripled over the past two decades, to more than 5,000 a year. What makes this trend especially hard to understand is that the medications for treating the illness have greatly improved over the same period.

Epidemiologists say the statistics may be skewed somewhat by detection bias—that is, doctors may now be doing a better job of diagnosing asthma—but most are convinced that the numbers reflect a genuine increase in prevalence. In fact, asthma rates are climbing in many developed countries besides the U.S., including Finland, New Zealand and the U.K. Scientists are at a loss, though, to explain why the disease is on the rise or why the increase has been so steep in the inner cities. “We’ve done a lot of research on asthma, but we’re still scratching our heads,” says Jonathan M. Samet, chairman of the department of epidemiology at the Johns Hopkins School of Hygiene and Public Health. “We’ve been humbled.”

The difficulty lies in the fact that so many risk factors have been linked to the onset of asthma. First, susceptibility to the disease may be inherited: the children of asthmatics are three to six times more likely to develop it than other children are. Second, asthma has been associated with exposure to a wide variety of allergens, such as dust mites, mold spores and cat dander. Allergies often lead to asthma; over time, a child can become so sensitized to an allergen that inhaling even a small amount can trigger an attack. Third, an asthmatic’s lungs can be further irritated by pollutants such as secondhand tobacco smoke.

ERICA LANSNER

DIESEL FUMES from truck traffic in the South Bronx may be worsening the symptoms of asthmatic children in the area.

In the past few years researchers have tried to winnow this list of risk factors. For example, the National Cooperative Inner-City Asthma Study compared the effects of various allergens on asthmatic children living in poor urban areas. The results, published in 1997 in the *New England Journal of Medicine,* suggested that cockroaches may be the chief culprits. Nearly 40 percent of the asthmatic children were found to be allergic to the insects’ droppings and body parts. What is more, high levels of these allergens were detected in about half of the children’s bedrooms.

The study was widely reported and subsequently spurred the funding of several programs designed to rid cockroaches from the homes of asthmatic children. It failed to explain, however, why asthma rates have climbed so much in urban areas since 1980. Cockroaches, after all, are not newcomers to the inner cities. And roach allergies certainly could not have caused the sharp rise in asthma in Finland and other places where the bugs are uncommon.

Some scientists believe widespread social changes may have set off the asthma epidemic. “There appears to be something associated with a modern Western lifestyle that promotes allergies and asthma,” says David L. Rosenstreich, director of the allergy and immunology division of the Albert Einstein College of Medicine. One hypothesis is that children are breathing in more allergens because they are spending more time indoors than children did in the past. The effect would be particularly pronounced in the inner cities, where many parents are afraid to let their kids outside because of safety concerns. Other lifestyle changes may have aggravated the problem; for instance, the levels of allergens in indoor air may be higher now than in past decades because most homes are insulated better. Perhaps the most intriguing idea, advanced by Thomas Platts-Mills of the University of Virginia, is that asthma rates have risen because children are exercising less. “Most allergic kids live in homes where they get exposed to dust mites or roaches or cats,” Platts-Mills says. “But previously they didn’t develop asthma, because something was protecting their lungs. Could that something be physical exercise?”

Or perhaps the answer lies in exercise for the body’s immune system. Allergic reactions occur when specialized white blood cells called lymphocytes respond aggressively to a harmless foreign organism. Some epidemiologists have theorized that because most children in developed countries are now growing up in relatively germ-free environments, the microbe-fighting lymphocytes are not getting a proper workout. This could throw the immune system out of balance and make children more prone to allergies. Several studies have shown higher asthma and allergy rates in certain groups of children who were exposed to few infections in their early years. More evidence is needed, however, to shore up this hypothesis. And although it might explain the general rise in asthma, it cannot account for the disproportionate jump in poor communities.

Some leaders in those communities are convinced that pollutants in outdoor air, rather than allergens in indoor air, are the real problem. Air quality has improved nationwide since 1980, but polluting facilities such as sewage treatment plants and bus depots tend to be concentrated in poor urban areas. In Mott Haven, streams of trucks rumble through the local streets; volunteers for We Stay/*Nos Quedamos* counted 550 passing by one intersection over a 90-minute period. “And that wasn’t even rush hour,” Garcia says. “Our kids have to breathe those diesel fumes every day on their way to school.”

New research indicates that vehicle exhaust can indeed exacerbate asthma’s symptoms, even if it is not the underlying cause of the disease. This could partly elucidate why asthma cases tend to be so severe in the inner cities. Another possible explanation is that asthmatic children in poor areas don’t have proper access to health care that would help them control the disease.

In all likelihood, the asthma mystery will not be solved anytime soon. The Clinton administration has made asthma research a priority for federal funding, but epidemiologists say more resources should be directed toward comprehensive, long-term studies similar to the ones that identified the leading risk factors for heart disease and lung cancer. “We need to go back to the basics and do a real surveillance,” Samet argues. “There will be no quick, easy answers.” *—Mark Alpert*

CREATIONISM

SPEAKING UP FOR SCIENCE

The Kansas decision against evolution suggests that more scientists need to become local activists

But for the want of the votes of a midsize biology department, the Kansas debacle on evolution would probably never have happened. In August 1998 conservative John W. Bacon beat moderate Dan Neuenswander by a mere 15 votes in the Kansas 3rd District Republican primary election for the state board of education, tipping the scales to the religious conservatives. In a 6–4 vote, that extra weight succeeded in removing evolution and other basic scientific principles from the state's high school science standards.

Voting is just one way citizens, including scientists, can make a difference. But some scientists are doing more to reverse creationist tendencies in the U.S. through participation, activism and education. Most of them say the need for involvement has never been greater—especially considering that many of next year's presidential candidates, including science-savvy Al Gore, support local boards' power to set slippery standards on evolution. "These are the kinds of problems that, while they may be fought out locally with local school boards, are ultimately at the core of the quality of the scientific workforce we're going to have," says M.R.C. Greenwood, chancellor of the University of California at Santa Cruz and past president of the American Association for the Advancement of Science. The Kansas decision "should make people think very hard about whether they're doing everything they can possibly do to ensure that this doesn't happen in their district and their state."

That's because testimony of trained scientists before local boards tends to go unheeded. "It didn't matter how much support we mustered," says Marshall Berman, a Sandia National Laboratories manager and founding president of the Coalition for Excellence in Science and Math Education (CESE), a grassroots advocacy group—founded after New Mexico's own creationist coup in 1996—that served as a model for the just-formed Kansas Citizens for Science. "I got so upset with the whole political process that I felt that we—scientists and people who think science is important—needed to take some action."

So last year Berman ran for the New Mexico State Board of Education. He received well-promoted endorsements from prominent scientists and clergy and criticized his opponent, a 20-year incumbent, for supporting state science standards that he said didn't clearly uphold the teaching of evolution. Berman won the election by a 2-to-1 margin, and two other evolutionists also won seats on the board. The trio is now helping to rewrite policies and science standards.

Stephen Angel, an assistant professor of chemistry at Washburn University, has served on the Auburn-Washburn school board in Topeka for the past five years. Willingness to put in the time is the major requirement, he says—about 20 hours a month in his case. It took a while to establish his credibility. "When we scientists step down to the community, we expect the same sort of respect that we receive in a university environment, even though we haven't put in the time in the community to earn that respect," he found.

"The majority of the members of the state board just don't understand the nature of science," adds Angel, one of the 27 authors of the rejected Kansas science standards. Nor does the culture of science, involving strenuous but fair debate, always translate into effective politics. Comments are often heard that scientists appear dogmatic and arrogant in creationism-evolution debates.

Reluctance to get involved comes from several quarters. Rarely does local activism factor into tenure decisions, and scientists are as busy as anyone. And the chance to go toe-to-toe with a biblical literalist isn't really why anyone goes to graduate school. Moreover, science's answers are usually incomplete or complex, and many researchers hang back from speaking out on an issue. But they may be missing valuable opportunities to educate the public, says William Spitzer, director of education at the New England Aquarium in Boston. "If you really care about an issue, being accurate isn't always the way to be most effective."

As an example, Spitzer cites the 1998 "Give Swordfish a Break" campaign, in which some chefs removed swordfish from their pricey menus in an effort to revive stocks of North Atlantic swordfish. Despite not directly addressing the complexity of the problem—Pacific swordfish stocks, for example, are fine—the boycott captured the public's attention. "If you're really trying to make a change in public attitudes, sometimes you have to adopt a different strategy," Spitzer explains.

Although nearly every national science organization issued a statement following the Kansas decision, most of them lack a strong presence at the local level. "They just are not at all set up to do the kind of grassroots grunt work that has to be done," says Eugenie C. Scott, executive director of the National

CHRIS OEHSNER *Topeka Capital-Journal*

***KANSAS STATE BOARD OF EDUCATION** meeting in Topeka on August 11 was soon followed by a 6–4 vote to remove the requirement that evolution be taught.*

Center for Science Education, an organization created explicitly to promote the role of evolution in science education.

Several national organizations are attempting to address this shortcoming. The American Geophysical Union targets e-mail updates and bulletins to members in a particular state, often urging them to contact their state representatives. The American Chemical Society began sponsoring a State Capital Day program last year, whereby local chapter members spend a day in dialogue with state legislators. Six such meetings have taken place this year in states pursuing education reform, and about five will be held next year.

To paraphrase physicist Luis Alvarez, "there is no democracy in science." But there is democracy in science funding, which lax participation in public issues may ultimately affect. "It's made me think how vulnerable the sciences are in a democracy," Angel remarks. "We depend heavily on public opinion of the sciences." *—David Appell*

DAVID APPELL, who has a Ph.D. in physics, is a freelance journalist based in Gilford, N.H.

INVADING SPECIES

FLORAL FIEND

The Old World climbing fern speeds its assault on Florida

From a few hundred yards away, an emerald cloak gives the cypress trees I'm approaching an unfocused, impressionistic look. At a few dozen yards, individual fronds of the cloak resolve themselves: the trees now look as if they're dripping with green sequins. Up close, however, these fanciful images give way to a harsh reality: I'm in the midst of botanical carnage. Most of the vegetation beneath the verdant surface is dead, and the spongy ground underfoot chiefly comprises a disorderly tangle of brownish, dried strands of the very stuff that elegantly drapes everything in sight. This cypress stand at Jonathan Dickinson State Park in Hobe Sound, just north of West Palm Beach, Fla., has been taken over by an alien invader: *Lygodium microphyllum,* a.k.a. Old World climbing fern.

Michael Lott, a graduate student at Florida Atlantic University (F.A.U.), is showing me around, like a combat vet escorting a reporter through a war zone. The fern chokes off its victims from their light supply, and it has additional nefarious talents. "Fire gets in," Lott explains, "and just explodes the dry material"—the stuff underfoot—"into the tree canopy." Controlled burns can become uncontrolled infernos.

The fern is only one of a number of invading species that are wreaking havoc around the U.S. Zebra mussels and brown tree snakes get most of the ink, but some plant species are also a menace. A recent study by Cornell University researchers pegs the cost of invading species at about $123 billion annually.

Florida has its share of botanical invaders, which often thrive in the absence of competitors and herbivorous feeders from their original habitats. Old World climbing fern, the latest to hit the radar, has scrambled the fighters. "We're rather markedly concerned about it," understates Daniel F. Austin, Lott's mentor and the director of F.A.U.'s environmental sciences programs. That concern is based on the fern's spread. Thirty years ago it was unknown at Dickinson and limited to a small outbreak on the Atlantic coast. A 1993 survey found 11 percent of the park infected, and the fern now stretches across southern Florida from the Atlantic Ocean to the Gulf of Mexico, its spores probably blown across by the prevailing winds.

Perhaps most frighteningly, the fern, which probably got here as part of the nursery trade, is encroaching on the Everglades. In 1990 Loxahatchee National Wildlife Refuge, the northern remnant of the historical Everglades ecosystem, appeared to be fern-free; by 1995 12 percent of the refuge, 17,000 acres, harbored the weed. "I thought Dickinson was impressive until I flew over Everglades tree islands," says Robert W. Pemberton, a researcher with the U.S. Department of Agriculture in Fort Lauderdale. "You're looking at vast landscapes from about 500 feet [altitude], and the whole landscape is covered by this plant."

STEVE MIRSKY

CYPRESS TREE is virtually smothered in Old World climbing fern.

To avoid large-scale herbicide spraying, which would kill local vegetation, Pemberton is attempting to find biocontrols, insects that dine on *L. microphyllum* in its native habitat. He first had to reconstruct the weed's home turf—which includes tropical Africa, east India, southeast Asia and China, Indonesia and Pacific Australia—through analysis of museum specimens. For the past few years, he has been traveling to these regions, searching for finicky eaters. "When we do biocontrol, we need to employ extreme specialists that coevolved with the plant," he notes. Such specialists would chew the fern but eschew all native vegetation. Although his search is in its early phase, a moth from Australia and a sawfly from Thailand both show fern-fighting promise and will be exhaustively tested for specificity.

Lott has begun studies aimed at understanding the plant's basic physiology, and he has come to Dickinson this hot, steamy day to collect samples. "If you get an idea of how fast it grows," he says, "you can hopefully give [land] managers an idea of how much time they have to control it." That kind of data might lead to better choices about what battles are worth fighting. "You might say we can't do anything here, so let's get to areas of light infestation before they get out of hand," Lott remarks.

The fern's presence likely leads to a cascade of floral and faunal consequences. Because it displaces local vegetation, insects that make their living on that vegetation may decline. And species relying on those insects will probably move out as well. "Chances are that if you examined the animal diversity, it would be altered compared with a more natural system," Lott notes. Suddenly, we are struck by the silence. "I just don't hear any birds here," he says.

—Steve Mirsky in Hobe Sound, Fla.

FIELD NOTES

A TASTE OF WEIGHTLESSNESS

Our reporter flies on NASA's zero-g-simulating "Vomit Comet"

Flush and excited in Houston's late-summer heat, some of the visiting collegians are dreaming of becoming astronauts, and others are bent on publishing their first scientific paper. Just about all of them are quietly hoping they won't throw up. They are a select group, their proposals having won them a chance to carry out an experiment in the intermittently weightless cargo bay of the National Aeronautics and Space Administration's gravity-beating KC-135A aircraft.

The airplane, a military version of Boeing's 707 jetliner, is the world-renowned "Vomit Comet." Twice a year the space agency makes it available for a couple of weeks to undergraduate researchers under a program administered by the Texas Space Grant Consortium. On each flight about 15 students and half a dozen journalists get a taste (perhaps literally) of weightlessness.

The team I have been assigned to, from the University of Alabama at Birmingham, will study heat convection in artificial gravity. The team's five mechanical engineering majors have built a spinning assembly that produces centrifugal force in a test cell. Thermoelectric devices will heat and cool air in the cell while temperature sensors record how the heat is conducted through it.

Before we can fly, we'll have to make it through a quick course on gas laws, atmospheric science, physiological principles of balance and motion sickness, and emergency oxygen equipment. To make sure we could cope if the aircraft cabin suddenly lost pressure, we will also be decompressed in a hypobaric chamber to gain thin-air experience.

As might be expected, we're never too far from the issue of vomiting. It comes up again and again. "Of three first-time fliers, one gets violently sick, one gets mildly sick and a third doesn't get sick at all," says John Yaniec, who as lead test director has logged 353 flights.

Thus, crew members and instructors have developed a rich epistemology of motion sickness that rivals a geologist's knowledge of volcanoes. "If someone seems sick, get away from him," advises Charles Shannon, a speaker from NASA's manned test support group. "In zero-g, it sprays real well." No one laughs.

It is the trajectory of the aircraft, like a huge roller coaster in the sky, that causes the nausea. "Your body will be going through some stuff it's never gone through before," explains Sharon Sands, another lecturer. "Your visual system is saying you're not moving, but your vestibular system is out in left field." The plane flies a series of parabolas, with weightlessness induced for about 25 seconds around the top of each. Peaking at around 34,000 feet (10,400 meters), the airplane then dives about 10,000 feet, its fuselage pitched down at 40 degrees. Coming out of the dive and beginning its next ascent, the plane pitches upward at 50 degrees and subjects the passengers and itself to forces up to 1.8 times that of gravity. The entire cycle takes roughly a minute.

When we go into weightlessness, five million years of evolution go down the drain, and I am an ape who has lost his balance in a tree. For about three seconds, and just as Sands had promised, panic reigns. But by the time a rational thought enters my head—dismay that the panic might persist throughout all the weightless periods—the fear is gone, replaced by euphoria. My brain has somehow decided that I am floating, not falling. To call the perceptual shift strange wouldn't do it justice.

By the fifth or sixth parabola there is no initial flash of panic at all, just joy. The students have begun running their experiments in earnest. Some time after parabola 10, however, motion sickness begins claiming some fliers.

Around parabola 25, I stop wondering if I'll get sick, and I celebrate with a few back flips and other gyrations. Then, after floating to the cockpit, I see blue sky through the windshield as we climb. In simulated lunar gravity near the top of the parabola, I watch the grinning flight engineer drop his pen repeatedly to the little shelf in front of him. The implement falls in surreal slow motion.

Through the cockpit glass I see clouds and horizon shoot upward as we nose over the top of the parabola. Then I see the deeper blue of the Gulf of Mexico as we nose-dive toward it. I look at the altimeter: a hand is literally spinning as we plunge oceanward. For sheer exhilaration, not much can compare.

In all, 10 of 21 fliers became physically ill. Unfortunately, one of the afflicted went into shock and was carried off the plane on a pallet. Such a reaction is uncommon, a NASA crew member says.

My teammates Michael Bell and Richard Shunnarah were fine, but their experimental setup has unaccountably failed to record any intelligible data from the thermal sensors. Even with the failure, the flight was still "a dream come true," Bell says. Adds Shunnarah: "If I could do it again tomorrow and the day after, I would."

—Glenn Zorpette in Houston

For an enhanced version of this article, go to the Scientific American *Web site at www.sciam.com*

RICHARD SHUNNARAH

FLOATING REPORTER Glenn Zorpette tries a flip in between photographer Crystal Embrey (left) *and student Michael Bell* (right), *who straddles his experiment.*

IN BRIEF

Neural Fountain of Youth
Age-related changes to the brain may be physically reversible, say Mark Tuszynski of the University of California at San Diego and his colleagues. Using rhesus monkeys, they targeted cholinergic neurons, which regulate cortical and hippocampal areas—the main sites of cognitive functions. Grafted with neural tissue that had been genetically modified to produce nerve growth factor, the cholinergic neurons, which normally shrivel with age and lose function, nearly returned to normal size; 92 percent of the old neurons began functioning again. The team, which reported the study in the *Proceedings of the National Academy of Sciences,* is now examining whether the grafts produced behavioral and functional changes.

Planet of the Grapes
Sixteen venerable wine grapes, including chardonnay, aligoté and gamay noir, had at one point in their ancestry a variety called gouais blanc—considered so poor that it is no longer planted in France and was a target of a medieval ban. A U.S.–French collaborative describes in the September 3 *Science* how it took leaf samples from 300 grape varieties and generated DNA profiles for each to determine that the 16 types originally descended from pinot, a noble red grape of Burgundy and Champagne, and gouais blanc. The genetic diversity of the two may explain the quality of the resulting offspring, and knowing the lineage should help grape breeders avoid bad hybrids.

J. P. BRUNO INRA Domaine de Vassal

Gouais grapes

Dry Strike
On July 31 the spacecraft Lunar Prospector crashed into a permanently shadowed crater near the moon's south pole. The hope was that the impact would kick up material visible to the earth—and provide definitive evidence of water on the moon. But, true to expectations, no dust was seen, and no sign of water vapor was evident. Researchers, however, are still analyzing data from the Hubble Space Telescope and other instruments, which may have recorded signals of water vapor released from the crash.

More "In Brief" on page 30

ANTI GRAVITY

Down in Front

James Madison was a pivotal player in American history, one of the giants who created this country. He co-wrote the *Federalist Papers*. He was the key figure in the writing and ratification of the Constitution. After a stint as Thomas Jefferson's secretary of state, he became the fourth president of the U.S. *Boy, could we use a guy like that today,* you may be thinking. Except that today Madison would probably have to take a tour to get into the White House, as Americans no longer elect presidents who need help reaching their cabinet's top shelf. At 5′ 4″, Madison was, in the words of Washington Irving, "a withered little apple-John."

Now it turns out that Madison, in addition to being a political visionary, may have been physically ahead of his time, too. Some downsizing, to Madisonian proportions or even less, may be in order. That's the thinking of Thomas Samaras, an engineer and systems analyst in the medium-size city of San Diego. For 25 years Samaras, at 5′10″, has been on a mission to convince people that Randy Newman was woefully small-minded when he sang, "Short people got no reason to live." According to Samaras, a world of people fit for the titles of Louisa May Alcott novels would not only live longer but would be more environmentally friendly at the same time.

MICHAEL CRAWFORD

Samaras's conclusions are based on his entropy theory of aging. From a thermodynamic viewpoint, it holds that bigger people, being more energetic systems overall than smaller fry, are more likely to suffer from entropic increases in disorder that translate to disease and death. His most recent paper, published this year in the Swedish pediatrics journal *Acta Paediatrica,* spells out some of the advantages the human race could enjoy if "short, dark and handsome" became the ideal.

A long-lived short life seems to be one benefit. Numerous studies indicate that healthy small people outlive their larger counterparts. Samaras points out that a six-foot-tall man has about 100 trillion cells, whereas a five-footer has only about 60 trillion. "The tall man has 40 trillion more potential sites for cancer to be initiated from free radicals, cosmic rays, high-energy photons, or mutagens from the air, food and water," he and his co-authors write. All else being proportional, tall people's hearts have to work harder, pumping blood farther. And most damning to the lanky is the contention that "when a 20 percent taller person trips, he or she hits the ground with 210 percent more kinetic energy than a shorter person." This calculation is thus the first quantitative statement I've ever seen in a scientific journal for exactly how much harder they fall the bigger they come.

Samaras goes on to compare two hypothetical U.S. populations that differ in height by 10 percent. The big lugs would need some 80 million more acres of farmland just to feed themselves. They would also produce an extra, large mountain of garbage, some 36 million additional tons annually. Small people are just more efficient.

The same high-calorie, high-fat diets that promote chronic disease are also probably at least partly behind the rise in height (about an inch every generation this century) in the U.S. One key to reversing the trend toward superfluous height would be a nutritious diet, starting in childhood, that did not promote the kind of showy bigness that saunters down fashion show runways. The average person then eventually might be six to eight inches less inelegantly tall than are today's big shots.

Will humanity get down? Cultural imperatives will probably prevent it in the short term. For now, Samaras makes do with his recommendation for "scientists and medical professionals to educate their patients, students and the public about the advantages of shorter human size." His quest seems to have a worthwhile objective. The best views are achieved not by virtue of height but by standing on the shoulders of Madisons.

—Steve Mirsky

In Brief, continued from page 28

Seeing the Bonds

In a first, researchers have imaged atomic bonds, visually confirming the textbook shapes of molecular orbitals—the regions where electrons are shared by bound atoms. John Spence and his colleagues at Arizona State University describe in the September 2 *Nature* their use of x-ray and electron diffraction on cuprite (Cu_2O) to reveal electron clouds in a dumbbell shape, consisting of a torus and three-petaled rings and corresponding to so-called s-$d_z{}^2$ orbital hybridization. The imaging technique may elucidate high-temperature superconductors and colossal magnetoresistance materials, compounds whose conductivity changes dramatically under a magnetic field.

ARIZONA STATE UNIVERSITY

Hybridized orbitals

Therapy-Resistant Gene

Some HIV-infected patients don't respond to treatment even though they do not harbor drug-resistant strains of the virus. John D. Schuetz and his colleagues at St. Jude Children's Research Hospital in Memphis may have found the reason: a gene identified as MRP4. It expresses a protein that helps T cells, part of the body's immune system, pump out anti-HIV nucleoside drugs, such as AZT, ddC and 3TC. The finding, which appeared in the September *Nature Medicine*, suggests that people with low MRP4 expression may benefit the most from therapy.

Ironing Out Super-Batteries

Stuart Licht and his colleagues at Technion-Israel Institute of Technology report in the August 13 *Science* on a battery that lasts 50 percent longer than ordinary alkalines and that discharges energy more quickly. The cathodes of today's batteries—the end point of a circuit that begins with the battery's electrolyte and anode—typically use manganese dioxide; during discharge, two molecules of this compound chemically react and absorb two electrons. The cathode of the new battery relies on a pure form of iron VI, which can absorb three electrons. With use, the cathode turns into rust, which is less toxic than manganese. The new battery is also rechargeable and can operate with existing anodes and electrolytes.

—Philip Yam

SA

NEUROBIOLOGY

MICKEY MOUSE, PH.D.

Inserting a single gene makes mice smarter

Princeton University molecular biologist Joe Z. Tsien and his colleagues reported in the September 2 *Nature* that they had boosted the intelligence of mice by adding a gene during the zygote stage of development. The mice, once adults, performed significantly better on behavioral tasks involving learning and showed a physiological change in the hippocampus, a region of the brain critical for memory, compared with nontransgenic mice.

The inserted gene created more of a protein subunit called NR2B. This subunit is part of a complex of proteins that form the NMDA receptor, a channel that sits on the surface of brain neurons. Research has indicated that the opening of the channel—triggered by a stimulus from two neurons—begins a biochemical cascade that results in memory retention and learning. The new experiment marks the first time that genetic manipulation has successfully led to NMDA enhancement in mammals.

The work is part of efforts by neurobiologists to better understand synaptic plasticity, or how modification in brain physiology converts stimuli into learning and memory. One experimental model focuses on long-lasting electrochemical changes at the synapse, often called long-term potentiation (LTP). The hypothesis is that repeated stimulation along neural pathways increases the efficacy of synaptic transmission and thus boosts LTP. Neuroscientists believe NMDA plays an important role in this process.

Tsien's work "strengthens the notion that LTP is the cellular substrate of learning," says Timothy P. Tully, a neurogeneticist at Cold Spring Harbor Laboratory in New York. "Humans always thought that learning and memory were something special, almost spiritual, but people are now realizing that it is just as biological as kidney function."

The transgenic mice, dubbed "Doogies" after a teenage physician character on television, exhibited about twice as much NR2B protein in the cerebral cortex and hippocampus as normal mice do. Additionally, Doogie NR2B channels stayed open significantly longer than those of the control mice, 250 milliseconds versus 150, and 50 milliseconds longer than those of normal juvenile mice. That finding is potentially significant, because the length of time a channel stays open normally decreases as animals age, Tsien notes.

As a result, Doogies were better at remembering an object previously encountered, more adept at linking an unpleasant stimulus with the context in which it was encountered and faster at figuring out that a fear-inducing stimulus had been removed. And they were twice as fast in getting through a water maze as compared with their normal counterparts. Although the transgenic mice made substantial performance gains (testing took place one hour, one day and 10 days after conditioning), Tsien advises against hiring a Doogie to tutor your child: "You can't make a quantum leap, you can't make a mouse sing a song. We're talking enhancement, making a system more efficient."

PRINCETON UNIVERSITY

DOOGIE MOUSE had better recall and was more curious about unfamiliar objects.

As Tully points out, genes rarely act alone, and it is difficult to know the effect that adding a gene may have on other genes and biochemical processes. Tully himself created smarter fruit flies by manipulating a gene called *CREB*, fiddling with which by other researchers produced similar memory boosts in marine snails. According to Tully, *CREB* appears to play an important role in long-term memory, while NR2B may be more directly linked to short-term memory or learning. Enzymes such as Src may also affect learning in conjunction with NMDA receptors.

Tsien explains that the goal of his work is to "understand biological processes, not create supersmart mice." Its most immediate application to humans, he says, may be the use of the NR2B receptor as a target for development of new drugs to help combat age-related memory loss such as that seen in Alzheimer's disease. Tsien has already been approached by pharmaceutical and biotech companies. Although any human therapeutic would probably be at least eight years away, Tsien says, he does believe NR2B "could be used as a very good drug target for a memory pill. We've demonstrated the principle."

Could such drugs enhance the cognitive abilities of healthy individuals? Several groups are pursuing "smart drugs," but many researchers question the efficacy—and ethics—of a brain-boosting compound. Tully, in fact, wonders whether it would even be a net benefit to boost plasticity in the adult brain: "If having enhanced learning is a good thing, why hasn't evolution given it to us? Maybe the research has created a very plastic brain where information cannot be burned in."

—Ken Howard

KEN HOWARD is a freelance journalist based in New York City.

PHYSICS

QUANTUM CLAUSTROPHOBIA

Physicists create Fermi degenerate matter, the stuff of neutron stars, in an ultracold gas

Deep down, the world is made of fermions. The familiar proton and neutron are fermions, and so are their constituent quarks. The fermionic nature of electrons underlies the structure of the periodic table of elements (and hence all of chemistry). Their cousins the bosons have received much attention in recent years, with the landmark 1995 achievement of Bose-Einstein condensation in a dilute gas. Now it is the fermions' turn in the spotlight, with the creation of atomic "Fermi degenerate" matter at a chilly 0.3 microkelvin above absolute zero by two young physicists, Deborah S. Jin of the National Institute of Standards and Technology and the University of Colorado at Boulder and her graduate student Brian DeMarco.

Bosons represent the gregarious side of the quantum particle family, and they exhibit this most strikingly in a condensate, in which millions gather in the same exact quantum state. Fermions, in contrast, are quantum individualists, and it is impossible to put two of them into an identical state in the same place. Thus, fermions, named in honor of Italian physicist Enrico Fermi, obey the Pauli exclusion principle: the presence of one forbids the presence of another.

Technically, bosons have whole-integer values of spin, or intrinsic angular momentum, whereas fermions have half-integer spin, such as $^1/_2$, $^3/_2$ and so on. But what really defines their quantum personalities is their behavior in groups, especially at extremely low temperatures where particles collect in the lowest available energy states. Cooled bosons abruptly slip en masse into *the* lowest level. Fermions behave more like people standing on a narrow staircase, at most one to a step, reluctantly filling the lower steps more completely as absolute zero is approached. Known as Fermi degeneracy, this crowded state plays a vital role in the electrical properties of metals and semiconductors and in stabilizing white dwarf and neutron stars against collapse.

To create their Fermi degenerate system, Jin and DeMarco used evaporative cooling of a gas of atoms in a magnetic trap, extending the technique that produced the first dilute Bose condensates. Jin's atom of choice was the rare potassium 40 isotope, and she and DeMarco exploited its unusual properties ingeniously. Most important, potassium 40 is fermionic, which follows simply because it is made of an odd number of more elementary fermions: 40 protons and neutrons and 19 orbiting electrons.

Producing Fermi degeneracy is more difficult than just throwing some fermions into a Bose condenser; fermions are harder to cool than bosons. Evaporative cooling depends on collisions between the particles to redistribute their energy continuously while the hottest particles are removed. But collisions between identical fermions become almost impossible near the quantum degenerate regime. Associated with every quantum

BY THE NUMBERS

Campaign Finance

In earlier days, parties were at the center of politics. They had a dominant role in choosing candidates, providing them with expert advice, circulating petitions and getting supporters to the polls. The effort required little cash—candidates often paid expenses out of personal funds—but when large amounts were needed, as in President William McKinley's reelection campaign of 1900, the money was supplied by corporations and people of wealth, the "fat cats" of legend. After World War II, power shifted radically from parties to candidates. Party organizations deteriorated: by 1970 Mayor Richard J. Daley's Democratic organization in Chicago was the last big-city machine left. Television compelled candidates to raise ever increasing sums for commercials, and candidates soon found that they could fill their war chests on their own.

The first comprehensive legislation was enacted in 1974, when strict limits on contributions and spending were set. That law also provided public financing for presidential (but not congressional) campaigns, established the Federal Election Commission (FEC)—which was charged with enforcement—and incorporated elements of earlier statutes (including bans on corporation and union donations).

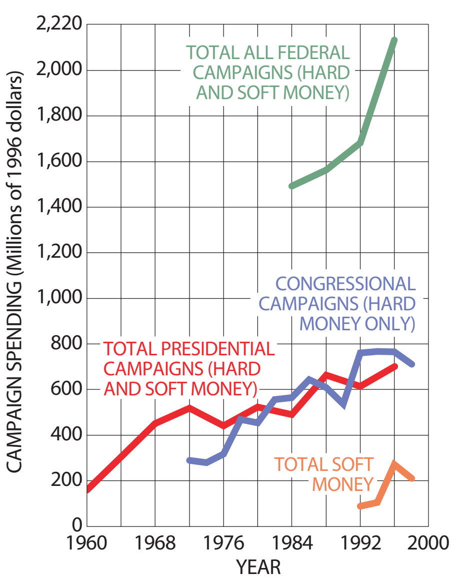
Beginning in the late 1970s, however, this legislation was gradually eviscerated by court decisions, rulings of the FEC and additional regulations. By 1996 the post-Watergate system of finance restrictions was effectively at an end. Through the "soft money" loophole, corporations, unions and individuals can donate large amounts to the parties. These contributions, some of them six and seven figures, can then be used to support individual candidates. (Soft money, unlike "hard money," is raised outside the framework of the 1974 limit: $25,000 per individual per calendar year.) The FEC reported that soft-money spending in the 1996 campaign was $271 million, and Common Cause, a citizens' lobby in Washington, D.C., predicts that it will reach $500 million in the 2000 campaign.

Another major loophole—"issue advocacy"—allows unlimited spending on advertisements attacking or supporting candidates, the only proviso being that the ads cannot use phrases such as "vote for," "vote against" or "Smith for Congress." Much of the funding for these ads comes from soft money. Spending on issue advocacy ads, which the U.S. Supreme Court supported on First Amendment grounds in 1976, does not have to be reported to the FEC. The Annenberg Public Policy Center at the University of Pennsylvania estimates that the Democratic and Republican parties together spent $64 million on such ads in 1998. Total direct spending by presidential and congressional candidates and political parties in the 2000 campaign is expected to be substantially higher than the $2.2 billion recorded in 1996.

The pressing need for campaign funds has had troubling consequences, not least of which is that lawmakers must spend long hours in solicitation. Compared with other democracies, the U.S. is not the most corrupt: Italy and Japan, for example, have been plagued with campaign finance scandals far more serious than the soft-money violations of the 1996 American campaign. Still, the U.S. has a ways to go before achieving the enviable status of Britain, which has not had a major campaign finance scandal since the 1920s. According to David M. Farrell of the University of Manchester and Paul Webb of Brunel University, campaign expenditures in the 1990s appear to have risen not only in the U.S. but also in Britain, Canada, Germany and Sweden. They seem to have stabilized in Australia, France and Ireland and fallen in Belgium, Finland and Italy.

The public favors reform yet is not passionate about it, which may help explain why Congress has not acted on the problem in recent years. In September the House passed the Shays-Meehan bill, which would end soft-money contributions and curb issue advocacy ads. As of press time, the Senate was scheduled to vote on the similar McCain-Feingold bill in October (it would get rid of soft money but would not curtail advocacy ads). Elimination of soft money would be an improvement but would still leave many undesirable features intact, including the burden on legislators to collect staggering sums of cash.

—Rodger Doyle (rdoyle2@aol.com)



SOURCE: Total for presidential campaigns is from Herbert E. Alexander, "Spending in the 1996 Elections," in Financing the 1996 Election, *edited by John Green (M. E. Sharpe, Armonk, N.Y., 1999). Presidential data are estimates of total expenditures. Congressional campaigns, total for all federal campaigns and total soft money are from the Federal Election Commission. (Soft money is used to support congressional and presidential candidates and for party-building activities, such as registration drives.) Both presidential and congressional data are all-party totals and include prenomination expenditures. The total for all federal campaigns includes party expenditures as well as those of presidential and congressional candidates.*

RODGER DOYLE

particle is a wave, with a characteristic wavelength that becomes longer at lower energies. The exclusion principle prevents a pair of identical fermions from getting much closer together than this wavelength. Contrary to everyday intuition, as the atoms' waves get bigger it becomes next to impossible for them to collide!

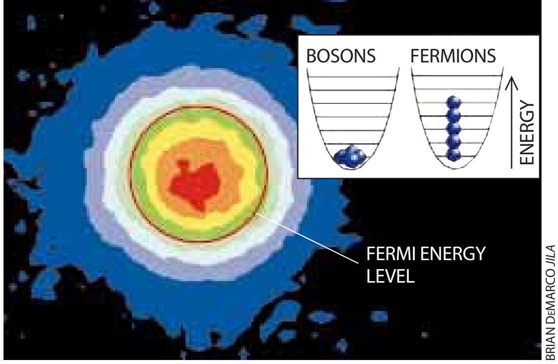
To get around this loss of collisions, Jin and DeMarco ensured that their atoms were in a nearly equal blend of two slightly different magnetic states, called Zeeman states. The existence of two such states that can be simultaneously caught in a magnetic trap is another key attribute of potassium 40. Two atoms in different Zeeman states can collide even in the degenerate regime, because they are not identical. The mixed collisions permit evaporative cooling of the two varieties of atoms. "It's a brilliant experiment," says Daniel Kleppner of the Massachusetts Institute of Technology, a pioneer in the quest to achieve Bose condensation.

The Colorado team detected several signals of their atoms' degeneracy. Below 0.3 microkelvin, the atoms had more energy and a different pattern of velocities than classical physics predicts. These features occur because when the lowest levels are filled, the remaining atoms must stack up in higher energy levels. Another signal was a marked degradation of the evaporative cooling a short way into the degenerate regime.

The new gaseous system provides a unique experimental testbed for studying the Fermi degenerate state. "When Bose condensates were discovered people were very excited, but I don't think anyone had an idea of the Pandora's box that was being opened," Kleppner points out. He expects that the Fermi gas will also lead to interesting new phenomena.

Other researchers are also pursuing Fermi degeneracy. John E. Thomas's team at Duke University recently demonstrated the first entirely laser-based trap that can hold ultracold atoms for long enough to implement evaporative cooling. His group plans to cool a mixture of two states of lithium 6 that cannot be held together in a magnetic trap. Randall G. Hulet's group at Rice University will be cooling a mixture of lithium 6 (fermionic) and lithium 7 (bosonic) using a magnetic trap. Hulet expects to be able to push deeper into the degenerate regime with a boson-fermion mixture.

Lithium 6 is of great interest because its atoms attract one another at ultracold temperatures, as is needed to form yet another degenerate state: the Cooper pairing state, which, when it occurs with electrons, produces superconductivity. Lithium 6 atoms would pair up, becoming composite bosons that would then deny their components' fermionic claustrophobia by undergoing Bose condensation. *—Graham P. Collins*



***FERMIONIC POTASSIUM ATOMS** crowd together. At absolute zero, all would lie inside the red circle, exactly filling the magnetic trap's lowest states* (inset).

PROFILE

The Ascent of Scent

By exploring the connection between memory and odor, psychologist Rachel S. Herz is giving smell its due

For some people, burning leaves and the woody, damp crisp smell of fall can do it. For others, it may take rosewater or lavender, the peculiar but particular musty dust of a certain attic or the stiff starch perfume of an ironed shirt. For Marcel Proust, it was the aroma of a madeleine soaked in lime-blossom tea. Whatever it may be that pulls your past into your present, that evokes a powerful and visceral remembrance, a rare experience of simultaneity, Rachel S. Herz plans to get to the bottom of it.

The psychologist at the Monell Chemical Senses Center in Philadelphia has been teasing apart Proustian phenomena for a decade, examining how smell, memory and emotion are related. Although the link between odor and recollection is something most people are familiar with as well as fascinated by, Herz is one of a surprisingly small number of researchers examining its underpinnings and implications. Her work has shown that odor is indeed a potent memory cue—but that it is better for recalling emotion than for recalling fact. She has explored, among other things, sexual differences in smell and mate selection, the role odor can play in performance on tests, hemispheric variations in the perception of scents and the influence of words on how we sense smell.

"She is sort of a pioneer," says Howard Eichenbaum, a neuroscientist and memory expert at Boston University. "She is taking all these old tales and hunches and incidental observations that have been made for hundreds of years and is putting them to test. Hers is really the only work in this area."

MARK HAVEN

REMEMBRANCE OF THINGS PAST: Rachel S. Herz plumbs the scientific basis of the evocations etched in literature by Marcel Proust's tea and madeleines.

An intense, petite woman with long brown hair and a lively quickness, Herz came to the study of smell circuitously—and it is perhaps because of her peripatetic path through several topics that her work on odor and memory is so varied. The daughter of an English professor and a mathematician, Herz spent her childhood moving around as her parents took academic posts in the U.S., Europe and, finally, Canada. She recalls being drawn when she was young to genetics and, especially, to psychiatry. "The idea of talking to people and finding out their problems was very interesting to me," she remarks. The intricacies of cadavers, however, were not, and it became clear that medical school was out of the question.

So Herz turned to psychology as an undergraduate at Queen's University in Kingston, Ontario. There she received a firm grounding in cognitive behavior and studied the effect of stimulants on environmental conditioning in rats. But Herz soon decided that rat cadavers didn't appeal to her any more than human ones did. She resolved to apply to graduate school in psychology—with an emphasis on living animals. It was while studying for the Graduate Record Exam that Herz remembers first thinking about smell. She came across a text stating that odors are a fundamental trigger for memory and emotion. "I had this question: Well, why is that? It is kind of bizarre and interesting, and I kind of filed that away."

Her applications in, Herz decided to travel. Her time abroad included residing in a cave in Greece for several weeks for the sheer adventure, sharing it with some wild goats, and occasionally calling her parents to see whether she had been accepted anywhere. "I certainly didn't have a stellar undergraduate record," Herz recounts. "And I remember thinking, just what will I do if this is where my life stops: interior decorating with goats. Maybe I would have gotten into odors that way, too."

The University of Toronto accepted her, and in 1986 Herz returned from her cave on Crete "ready to embrace Western capitalism and go to graduate school." She initially studied memory cues in black-capped chickadees. But catching the tiny birds in the freezing winter woods and chasing the ones that escaped from the lab down the hall with a butterfly net didn't make her happy: "The black-capped chickadee stuff drove me to distraction."

Although she was getting excellent training in evolutionary theory, Herz says it was becoming clear that she was not interested in animals at all—except as their behavior related to humans. After toying with the idea of becoming a sleep researcher ("I wasn't sleeping very well, so I thought, *this* is an area I can look at") and an astrophysicist ("I bought a textbook and said to myself I was going to do problems over Christmas break, and if I could do any of them I would switch into astrophysics"), Herz decided to work with Gerald C. Cupchik, who was studying aesthetics and emotion.

Herz started looking into people's impressions of their own emotional states. "But I wasn't very keen on it," she says. Then, during a course in primatology—the field she had chosen as a minor—she came across a 1988 study led by psychologist Howard Ehrlichman of the City University of New York. The scientists had used smells to create moods in their subjects. "And," Herz recounts, still excited 10 years later, "their introduction to the paper was this whole thing about how odors are fundamental biological cues!"

The echo of the earlier reference set off what Herz describes as a domino effect in her thinking: all the pieces of her studies fell into place. She asked Cupchik if she could study odor; he said he knew nothing about it, but she was free to—a response for which Herz remains grateful. "He didn't say, 'No, you have to do what I am interested in,' which is sort of the typical graduate supervisor attitude." Herz read all the papers she could find and traveled around, talking to experts. Richard L. Doty, now director of the Smell and Taste Center at the University of Pennsylvania, suggested she contact International Flavors & Fragrances, which is headquartered in New York City. "I think they thought, 'Who is this chick, coming out of nowhere and showing up and saying show me how to do this research?' " Herz laughs. Nevertheless, she left the company with a set of odor-producing compounds and investigative techniques.

At that time, there had been relatively few studies on odor and memory. Researchers knew that the olfactory system was unique among the senses in that it has direct contact with the limbic system: it connects into the amygdala, our emotional center, and into the hippocampus, a memory center. But beyond observing those physiological attributes and conducting a few experiments, scientists had done little. Herz resolved to find out whether odors are indeed the best cues to memory.

In one of her first experiments, she showed subjects paintings and at the same time had them smell a certain odor or told them to imagine smelling an odor. A few days later the subjects were given the smell or a word describing the smell. Herz found there was no difference in accuracy: in the presence of the word "apple" or the smell of an apple, people could remember seeing a painting of a boy and a dog. But the emotional aspect of the recollection—what that painting made them feel—was much more powerful in the presence of the odor itself.


MARK HAVEN

ASSOCIATED WITH AN ODOR, paintings can be recalled just by the scent. The emotion evoked by the painting is then much more powerfully remembered.

Herz continues this cross-modal work, in some cases using touch (having subjects feel objects hidden in a box), music that is not readily identifiable and abstract images. "One of the things I think might be my Achilles' heel is that odors are actually very difficult to verbally label," Herz explains. "Even when you smell suntan lotion, you can say, 'I know what this is,' but the name 'suntan lotion' doesn't come to you."

She worried that her subjects were more emotional describing a smell because it seemed more touchy-feely than words did. But she found that even the touchy-feely objects in the box and the verbally indescribable music don't evoke the same emotional memory or provoke the same increased heart rate that smell does.

The powerful emotions brought about by smell can work in many ways. Herz and Gisela Epple of Monell had children try to complete an impossible maze in the presence of a certain odor. They then gave the children a feasible task—some in the presence of the earlier smell, some in the presence of a new odor and some in a room with no odor. The children who smelled "failure" did much worse on the second test than did those who were not smelling the initial odor or were smelling a new one.

This emotional potency makes complete sense, Herz argues, given that in the beginning there was smell: organisms used chemical sense to move toward the good (food) and away from the bad (predator). Because the limbic system grew out of the olfactory system, the emotional dichotomy between good (survival, love, reproduction) and bad (danger, death, failure) reflects the chemosensory one. "I really believe that olfaction and emotion are the same thing on an evolutionary basis," Herz says. "I think emotions are just a kind of abstracted version of what olfaction tells an organism on a primitive level. And that is why I think odor has such a potent emotional cascade."

Herz's findings about sexual choice support this argument. Several investigators suggest that women have a better sense of smell than men do and that they sniff out mates who produce different antibodies. This selection may ensure that their offspring are able to make a wider array of antibodies. Herz found additional evidence for this idea. In a widely cited article, Herz reported that women consider smell "the single most important variable in mate choice," whereas men rate looks and smell equally.

Herz plans to continue looking at sex differences as well as genetics, how stimulants affect memory and emotion, neural activity, language, odor—the list goes on. She seems to have as many experiments waiting in the wings as she has performed so far. The secret life of smell may soon be revealed.

—Marguerite Holloway in Philadelphia

XENOTRANSPLANTATION

PORK PROGRESS

Cross-species infection, the main worry with putting pig organs into humans, seems less likely

Attempts to graft animal parts to people date to the 17th century, when a dog bone was said to have been used to repair the skull of a Russian aristocrat. In modern times, xenotransplantation has involved livers, kidneys, hearts, and bone marrow taken from chimpanzees and baboons. None were successful, and most patients succumbed to organ rejection or severe infection. Of most concern to scientists is cross-species infection, when a pathogen jumps from animal to human. But a recent study has brought encouraging news: patients who had been given living pig tissue showed no evidence of infection by a feared porcine retrovirus.

For the past few years, discussion of xenotransplantation has centered on two possible donor animals—baboons and pigs. Although baboon organs would not be rejected as violently, they carry a much greater risk of viral transmission than those of pigs. Moreover, pig organs are the right size, and the animals breed quickly and have been raised for food, so killing them is, for most people, less morally problematic.

And the problem of hyperacute rejection—a violent immune response that can destroy a transplanted organ in minutes—seems to have been solved for pig organs. David J. G. White, research director of Imutran in Cambridge, England, pioneered a technique in 1992 in which a human gene is inserted into a pig embryo. The pig's organs become covered with human complement regulatory proteins, and the human immune system is, in effect, tricked into accepting the animal organ.

Still, pigs harbor viruses, and the major source of public and regulatory fear has been porcine endogenous retrovirus (PERV). Endogenous retroviruses are integrated into their host's DNA and cannot be bred out. Another retrovirus, simian immunodeficiency virus, is widely thought to have crossed the species barrier and become HIV, the virus that causes AIDS. Robin A. Weiss of the Institute of Cancer Research in London and his colleagues showed that PERV crosses the species barrier in vitro. The crucial question was whether PERV would infect humans given xenografts.

To find the answer, Imutran, working with the U.S. Centers for Disease Control and Prevention, tested 160 human patients who had been treated with pig skin grafts or pig pancreatic islet cells or had had their blood perfused outside their bodies by pig livers, kidneys or spleens. This study, reported in *Science*, revealed no evidence of PERV infection in any of the patients, including 36 who had been immunosuppressed and were therefore at greater risk of infection. Most surprising, 23 patients showed evidence of circulating pig cells, demonstrating that pig tissue can survive for long periods in humans. For White, that means "real hope that the immunological hurdles facing xenotransplantation are not insurmountable."

Virologists remain cautious. In an accompanying commentary, Weiss notes that even though pathogen-free pigs might prove safer than grafts from unknown human donors, "the ethical and technical problems of maintaining vigilance over xenotransplantation should not be underestimated." Virologist Jonathan S. Allan of the Southwest Foundation for Biomedical Research in San Antonio cautions that the cells create "a potential that pig virus could be expressed and infect the patient at some later time." That could happen under long-term exposure and immunosuppression.

In any case, other hurdles remain. "We need to refine our treatment modalities for acute vascular rejection," White says of the process that appears to be related to antibody generation against the xenograft. Transplant physiology is another problem. Proteins and their receptors are species-specific. For example, human kidneys produce erythropoietin, which stimulates the production of red blood cells, whereas pig growth factor is specific for pig receptors. The longest survival times in monkeys for life-supporting pig kidneys and hearts are 39 days and 78 days, respectively (median kidney survival is 40 days). But although the pig-to-primate transplant model is illuminating, "measure of clinical survival based on such a model may be inappropriate," White states. Small clinical trials are now on the horizon, but he says predicting when they will begin is difficult: "It seems unlikely to be less than two years."

Yet that is far sooner than the possibility of creating spare organs from stem cells—progenitor cells that can become any other cell in the body. Researchers have isolated and cultivated such cells, but they are far from being able to grow human organs from them. Given the ethical issues as well—stem cells are harvested from human embryos—xenotransplantation may offer the best near-term hope. *—Arlene Judith Klotzko*

ARLENE JUDITH KLOTZKO, a lawyer and bioethicist based in New York City, has edited an anthology on cloning for Oxford University Press.

RICHARD HAMILTON SMITH *Corbis*

***ORGAN DONOR OF TOMORROW?** Cross-species infection may not be a threat.*

NEUROROBOTICS

MIND OVER MATTER

Getting rat thoughts to move robotic parts

The disabling effects of spinal injury or degenerative disease on voluntary movement can be permanent, because damaged nerve cells and their "wiring" fail to regenerate. In many cases, however, motor areas of the brain that normally control body movements are left intact. Could activity of these motor areas actually be used to operate robotic limbs? As far-off as it seems, research suggests that this idea might not be merely science fiction.

In the July issue of *Nature Neuroscience,* John K. Chapin and his colleagues at MCP Hahnemann Medical College in Philadelphia report how they got rat motor neurons to control a simple device to obtain a food reward. They implanted a rat's brain with a 16-electrode array that could record activity of about 30 neurons at once. Such simultaneous recording is critical, because a neuron's activity is not specific to a particular muscle contraction and so cannot give complete directions for appropriate movements by itself. The team then trained the rat to press a lever for a reward that was delivered by a robotic device.

They also developed a neural-network computer program, capable of changing its output based on previous input, and used the recordings to "train" the neural network to recognize brain-activity patterns during a lever press. In other words, by supplying the neural-network program with typical activity patterns, along with specific information about the movements that followed, they instructed it to predict movement from the rat's brain activity alone. This prediction could then be used to trigger the delivery device.

They then switched the control of the device from the lever to the computer. Because the robotic arm responded faster than the rat's muscles, the "wired" rat was actually rewarded before it pressed the lever. Eventually the rat learned that the lever press was unnecessary and abbreviated or stopped its paw movements. Thus, brain activity directly drove the robotic arm, bypassing nerves and muscles.

Chapin's work builds on research reported in 1996 by Apostolos Georgopoulos, Bagrat R. Amirikian and their colleagues at the University of Minnesota Medical School. They recorded in a monkey's brain single neurons that were activated when the animal reached for an object. They then trained a neural network with these recordings to recognize certain movement-related patterns and to translate them into directions for a computer-simulated arm incorporating two joints and six muscles.

They found that as few as 15 movement-related neurons could work the arm model. "The trick for making such an assemblage practical," Amirikian notes, "is to make it work in real time. This requires simultaneous recording of a number of neurons, rather than one at a time." Multielectrode arrays made this possible in Chapin's experiment. Amirikian points out, however, that Chapin's use of activity patterns during a lever press to trigger a simple device is still a long way from interpreting the complex motor activity patterns involved in reaching and grasping into directions for an elaborate, jointed robotic limb. Amirikian and his colleagues are now working to combine multielectrode recording with neural-network control of an actual robotic arm rather than a virtual one.

In collaboration with Miguel A. L. Nicolelis of Duke University, Chapin plans to use monkeys rather than rats and to set up larger arrays to record up to about 130 movement-related neurons simultaneously, which could encode directions for a more complex robotic device. Chapin envisions further miniaturization of microwire electrode arrays to pack in fourfold more contacts and to make the neural-network processor, currently a desktop PC, portable.

Direct brain control of robotic actions could be a boon to those disabled by spinal damage, but transferring the technology from animal experiments to regular human use poses several challenges. Although electrodes can be anchored to the skull, they are not "hardwired" to the neurons—in the soft brain tissue, the electrode tips and neurons could move slightly relative to one another. And any device would require paralyzed patients to learn, through trial and error, how to shape brain activity appropriate for driving it. "The real bottleneck for creating neural signal–based actuators is likely to be in the design of multielectrode arrays that are both stable and safe for humans over the long term," Georgopoulos suggests. *—Mimi Zucker*

MIMI ZUCKER, who earned a Ph.D. in neurobiology from the University of Texas at Austin, is a freelance writer based in New York City.

POLICY

LITTLE BIG SCIENCE

High-energy polemics erupt over plans to replace an aging French synchrotron

MICHEL LIPCHITZ *AP Photo*

CLAUDE ALLÈGRE, France's controversial education minister, has rebuffed critics of the government's decision to collaborate on a new synchrotron in England.

The physicists, engineers and technicians who went to work on September 6 at the x-ray synchrotron on the Orsay campus of the University of Paris had planned to begin dozens of experiments. But the 1.9-giga-electron-volt machine of the Laboratoire pour l'Utilisation du Rayonnement Électromagnétique (LURE), dormant for more than a month for its summer respite, was never fired up to begin probing the properties of high-temperature superconductors or the formation of zinc oxide colloidal particles. Virtually the entire complement of 400 LURE researchers and support staff voted against turning on the machine. Their protest was directed against Claude Allègre, the French minister of national education, research and technology, who decided to replace the aging instrument at LURE with a synchrotron based in England that would be owned jointly by the British and French governments and the Wellcome Trust. It would spell doom for a proposed machine based in France that has been contemplated since the early 1990s.

The vote to keep LURE's x-ray light source in the dark may mark the first time that a synchrotron has been commandeered as a tool of political protest. But it goes right in line with the student strikes and demonstrations that are as much a seasonal event in France as the wine grape harvest. The larger issue of finding ways of sharing the ever increasing burden of sophisticated experimental equipment, however, is by no means unique to France.

Allègre has become an outspoken and controversial minister in the Socialist government of Prime Minister Lionel Jospin. For instance, the renowned geochemist did little to endear himself to his countrymen, with their ardent defense of things French, when he remarked that English should not be a foreign language in France. The dispute over the synchrotron began after Allègre took his current post two years ago and declared that all big science hardware—known in French by the apt label of *très grands équipments,* or simply "TGE"—should be considered a candidate for joint ventures with other European partners for both scientific and financial reasons.

This mandate included a review of the

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Soleil project, a planned replacement for the LURE synchrotron that had received the support of the previous government. So-called third-generation synchrotrons like the proposed Soleil boast narrower but brighter beams than earlier machines do. Better than bigger synchrotrons for certain experiments, they are ideal for resolving the structures of proteins discovered through human genome research and for evaluating smaller samples for materials science experiments. Soleil and the joint French-British synchrotron, called Diamond, each could cost more than $200 million to build.

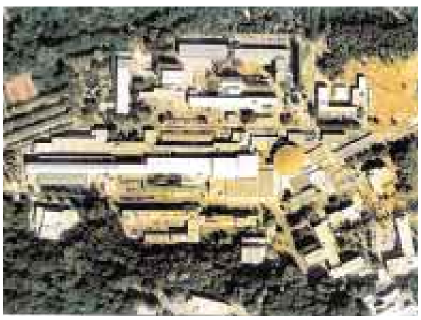
Allègre's announcement in the dead of August, when most of France is at the beach, revealed to what extent science infrastructure is still coveted as a national asset by scientists. At LURE, scientists make their case for a modern, medium-strength synchrotron as an essential component of any nation with an advanced scientific base. Even newly industrial countries such as Thailand, they note, have active synchrotron projects. "We're not a banana republic," LURE director Robert Comes asserts, adding that "you're throwing away a French community [of researchers] and a whole technology that is going to disappear."

Emphasizing that LURE already welcomes researchers from all over the world, Comes asserts that many of the facility's permanent staff will refuse to move to England. The French government, he charges, made its decision based on a confidential report by a physicist who knows nothing about synchrotron radiation. Diamond will provide French researchers with only about a third of LURE's capacity, as the facility must be shared with British colleagues. Moreover, it will cost about the same as building Soleil, he says, because the expenses for the British undertaking are underestimated and related costs (to keep LURE running while Diamond is being built, for instance) have not been taken into account. "It's an incredible and stupid story," he jibes.

The Education Ministry retorted that the LURE team refuses to adapt to the realities of the new Europe. "These people in LURE are indeed fossilized and a minority," says Vincent Courtillot, the ministry's director of research, who goes on to question the team's track record of publication in science journals. Courtillot declares that the "Soleil lobby," centered on LURE, has rejected overtures for collaborative ventures with other countries and may have overestimated the amount of capacity needed by French investigators.

Besides Soleil, the government wishes to enter into agreements to buy time on Italian and German synchrotrons to satisfy the nation's science agenda. The decision to move to Britain would save the French government nearly $160 million over eight years, he says, in part because of a contribution to Diamond by the Wellcome Trust. Savings from scrapping the Soleil project and reductions in other TGE, he notes, could be used to buy basic laboratory equipment and to employ a new, more dynamic generation of professors and scientists. "The French mandarin system is not completely extinguished," he observes, again referring to ossified academics.

The dispute will most likely heat up this fall as each side tries to marshal its forces. Regional political leaders will also have their say—a number of regions of France have tried to attract Soleil as a high-tech boost to local economies. Even



LABORATOIRE POUR L'UTILISATION DU RAYONNEMENT ÉLECTROMAGNÉTIQUE

LURE may be the first synchrotron recruited for a political protest.

Corsica, where a government-funded x-ray machine might make a compelling target for bombs planted by the island's separatist movement, has put in a claim to become the project's home. As for the LURE researchers, they were unsure in mid-September about when their synchrotron would be restarted.

In England, meanwhile, the Diamond project has also run into regional tug-of-wars. Lord Sainsbury of Turville, the British science minister, put on hold a decision about where to locate Diamond after scientists at Britain's own senescent synchrotron at Daresbury Laboratory in northwest England reacted harshly when they learned that Diamond might be located in the southeast. For the moment, both Soleil and Diamond are generating more noise than light.

—*Marie-Hélène Bojin and Gary Stix*

No Way to Run a Network

We are now in the third year of the acute phase of trying to revamp the domain name system—handing it off would be the final piece in the U.S. government's plan to disengage its involvement in running the network. But it seems as though the hypesters who a few years ago claimed that the Internet was essentially ungovernable may be right.

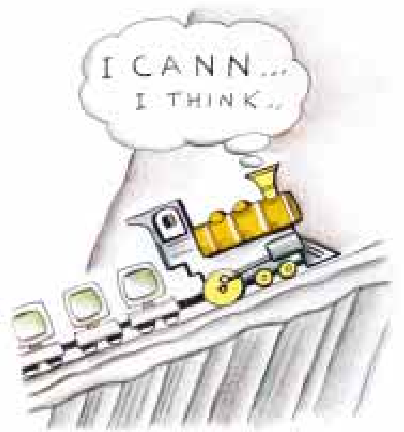
To recap: the domain name system is the interface that allows us to type in memorable names to send e-mail or to access Web pages. Each name gets translated into dotted clumps of numbers understandable to routing computers. The rightmost chunk in these addresses is the top-level domain, of which there are more than 200, most of them country codes managed by national registries. A few are global top-level domains. The best-known ones—.com, .net and .org—have been allocated since 1991 by the Virginia-based company Network Solutions, under government contract.

The original domain name system was put in place in 1983. By the mid-1990s complaints were rife that all the good names were taken, and in 1997 an alphabet stew of old-time Net engineers proposed creating global top-level domains. They then would open up those names—as well as all the original ones—to competition. Many attacked the plan, prompting the U.S. government to call for public comment. Ultimately, in September 1998, the nonprofit Internet Corporation for Assigned Names and Numbers (ICANN) was set up to manage global top-level domains. ICANN is also being handed the business of allocating Internet numbers (those dotted clumps), previously managed by the late Jonathan B. Postel, one of the domain name system's original designers. Before his unexpected death last October, Postel was deeply involved in the efforts to revamp and update the domain name system, and he may have believed at the time of his death that he had achieved a consensus.

Since then, the whole business has become an increasingly ugly squabble as ICANN discovers what Network Solutions has already learned: any proposed change to the Internet's vital organs will be met with rage and paranoiac claims.

The technical parts seem to have gone reasonably well. In April, ICANN appointed five organizations to test the shared registration system in progress and has since appointed 64 member organizations to serve as official registrars once the testbed phase is complete.

But more recently ICANN was hauled into Congress to answer criticisms about some of its practices, such as its intention to charge a $1 fee per domain name registration. ICANN has backed down on those practices, but opponents are still worried about its plans for handling trademark disputes, fearing ICANN will favor large businesses. Others fear that ICANN will overstep its bounds to enforce censorship and assist in invading privacy. In June 1999 three law professors, all highly respected in the Internet world, set up an ICANN Watch site.



DAVID SUTER

Meanwhile Network Solutions has lost friends and annoyed people by claiming that the entire registration database is its intellectual property; it withdrew bulk access to the database in mid-1999. Both the European Commission and the U.S. Department of Justice are talking about an antitrust investigation of its licensing agreements.

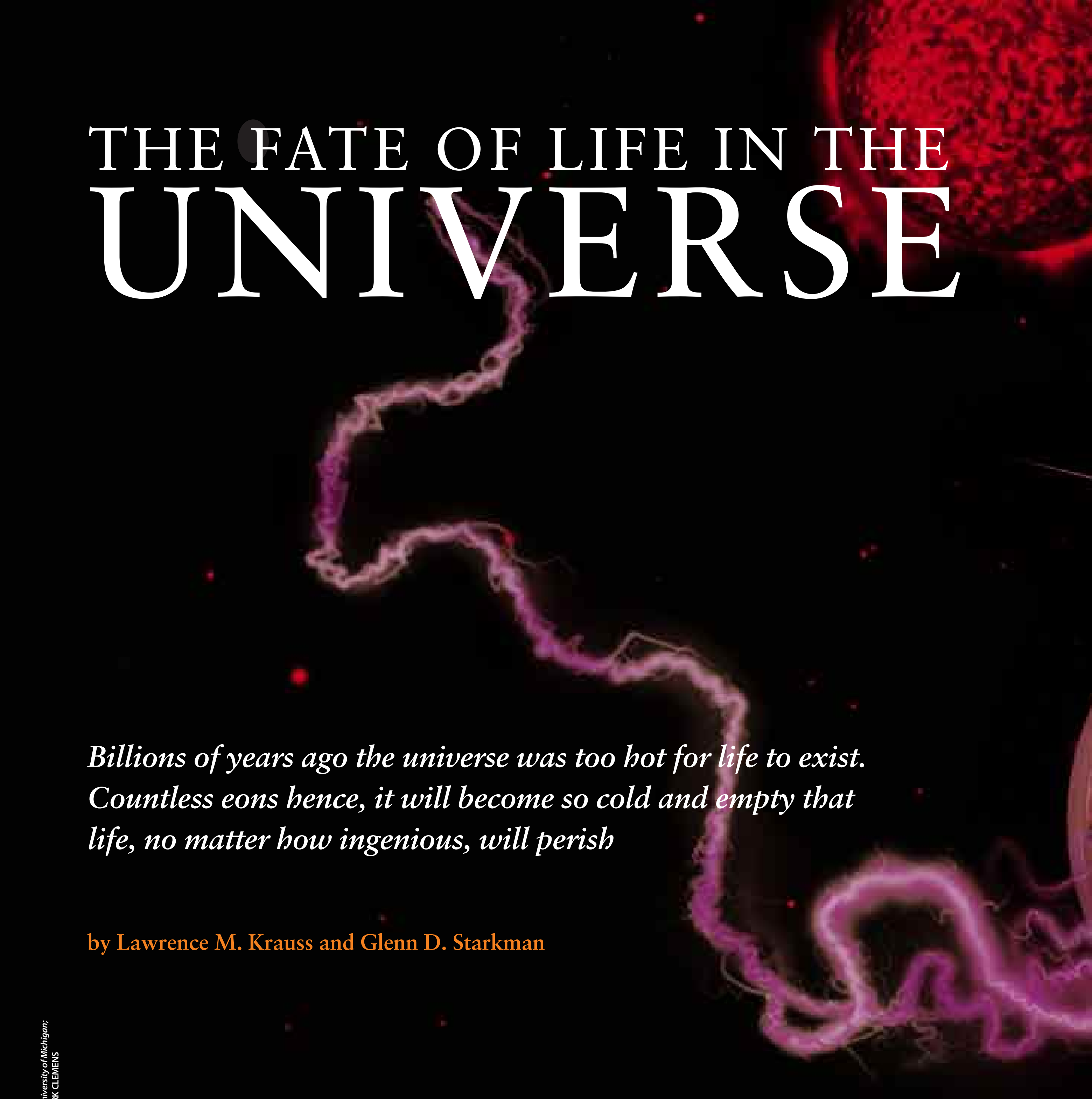
So what happens now? First, any reasonable person has to conclude that the database of .com, .net and .org registrations that was built under government contract (some of which predates Network Solutions's involvement) should be public property. Network Solutions, whose contract now extends to October 2000, will gain far more by behaving like a good Net citizen than it will by being seen as uncooperative. Money is certainly the big issue: Network Solutions has it and wants to keep it, ICANN has hardly any of it, and the government wants to stop funding the Internet's infrastructure.

Second, much of the concern over ICANN boils down to a fierce distrust of government (some distrust is, of course, healthy). Two years ago corporate and individual domain name registrants were united in their hatred of Network Solutions, complaining of billing snafus, unwarranted suspensions and technical ineptitude. Now some of the same people are complaining about handing over too much power to ICANN and predicting darkly that ICANN's position at the heart of the Net will encourage it to exceed its authority.

This problem crops up whenever something is centralized; it's the reason why the Net was designed as a distributed system. But someone somewhere has to be in charge if Internet numbers and domain names are to be handed out in an organized way to the benefit of all, although one could argue that it might be wiser to emulate the U.S. government in its separation of powers and not assign both to the same organization.

If the whole exercise has a lesson, it's how extraordinarily difficult it is to reach a global consensus, particularly on something experiencing such rampant growing pains as the Net. By all means, important questions of governance are bound up with the technical issues of managing names and numbers—which is why two years ago I thought more research was needed to modify the then current proposals [see Cyber View, Scientific American, October 1997]. But it's critical not to lose perspective: ICANN does not have as much scope to govern the Internet as opponents think, because it will not be in charge of the more than 200 country-coded registries. And although .com is currently the most desirable virtual-estate location, there is no reason to assume it has to stay that way, which in itself provides some check on ICANN's activities. The more we can build the principles of decentralization and separation of powers into the system we devise, the better protection the cooperative spirit of the Net will have. —*Wendy M. Grossman*

WENDY M. GROSSMAN, who is based in London, wrote about Internet-available data on chemical hazards in the September issue.



THE FATE OF LIFE IN THE UNIVERSE

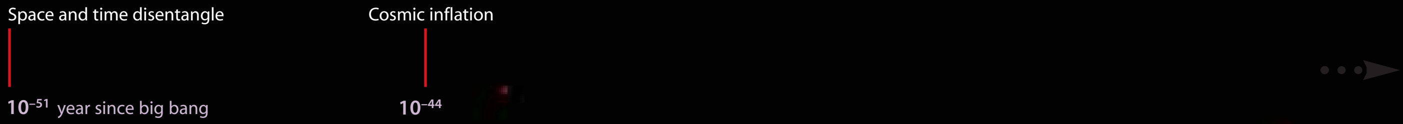
Billions of years ago the universe was too hot for life to exist. Countless eons hence, it will become so cold and empty that life, no matter how ingenious, will perish

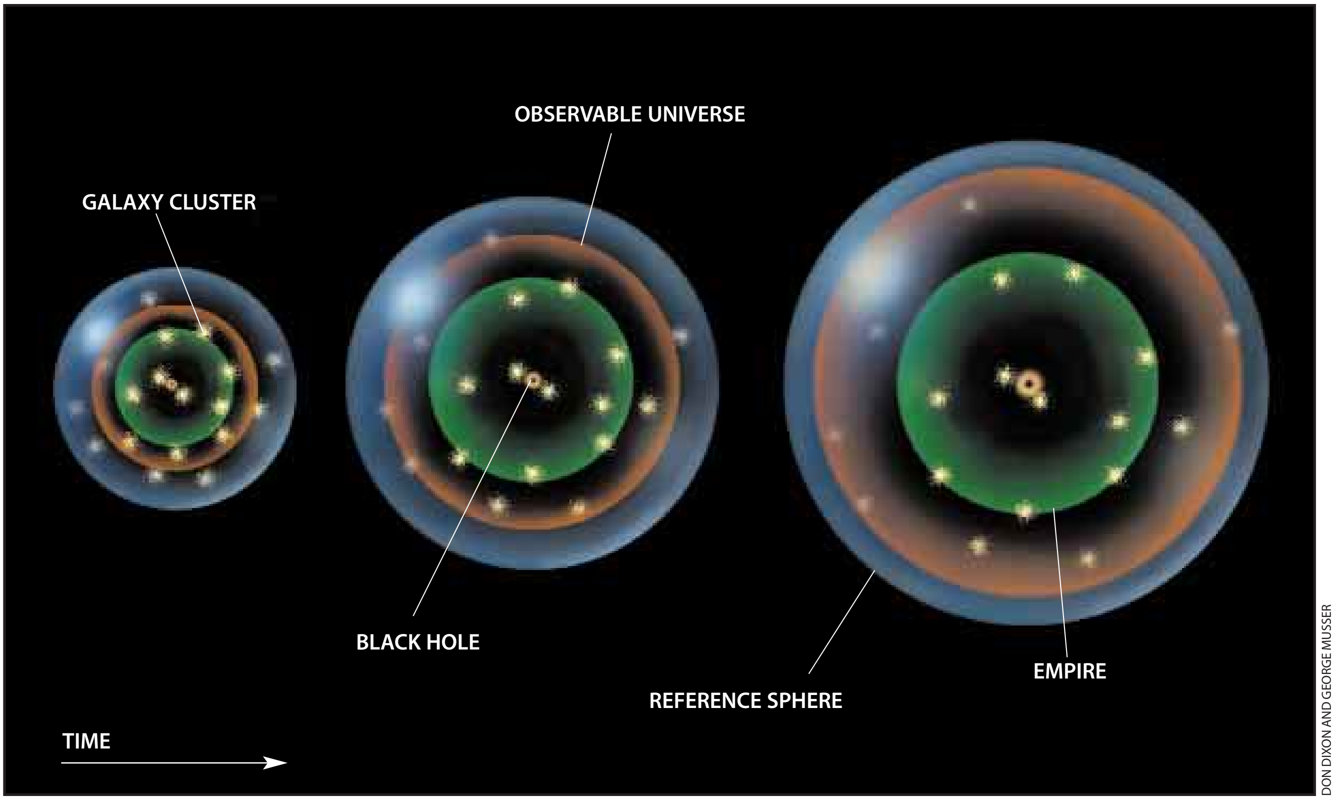
by Lawrence M. Krauss and Glenn D. Starkman

SLIM FILMS; SOURCES: FRED C. ADAMS AND GREGORY LAUGHLIN *University of Michigan*; LAWRENCE M. KRAUSS AND GLENN D. STARKMAN; TIMELINE BY MARK CLEMENS

Eternal life is a core belief of many of the world's religions. Usually it is extolled as a spiritual Valhalla, an existence without pain, death, worry or evil, a world removed from our physical reality. But there is another sort of eternal life that we hope for, one in the temporal realm. In the conclusion to *Origin of Species,* Charles Darwin wrote: "As all the living forms of life are the lineal descendants of those which lived before the Cambrian epoch, we may feel certain that the ordinary succession by generation has never once been broken.... Hence we may look with some confidence to a secure future of great length." The

MILESTONES ON THE ROAD TO ETERNITY range from the big bang through the birth and death of stars (*timeline below*). As the last stars wane, intelligent beings will need to find new sources of energy, such as cosmic strings (*illustration above*). Unfortunately, natural processes—such as outbreaks of black holes—will erode these linear concentrations of energy, eventually forcing life-forms to seek sustenance elsewhere, if they can find it. Because the governing processes of the universe act on widely varying timescales, the timeline is best given a logarithmic scale. If the universe is now expanding at an accelerating rate, additional effects (*shown on timeline in blue*) will make life even more miserable.





ENERGY COLLECTION STRATEGY devised by physicist Steven Frautschi illustrates how difficult it will be to survive in the far future, 10^{100} or so years from now. In many cosmological scenarios, resources multiply as the universe—and any arbitrary reference sphere within it (*blue sphere*)—expands and an increasing fraction of it becomes observable (*red sphere*). A civilization could use a black hole to convert matter—plundered from its empire (*green sphere*)—into energy. But as the empire grows, the cost of capturing new territory increases; the conquest can barely keep pace with the dilution of matter. In fact, matter will become so diluted that the civilization will not be able to safely build a black hole large enough to collect it.

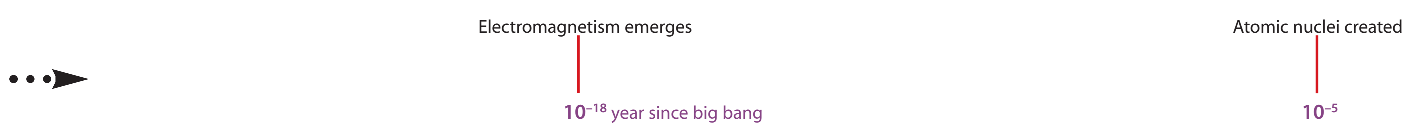
sun will eventually exhaust its hydrogen fuel, and life as we know it on our home planet will eventually end, but the human race is resilient. Our progeny will seek new homes, spreading into every corner of the universe just as organisms have colonized every possible niche of the earth. Death and evil will take their toll, pain and worry may never go away, but somewhere we expect that some of our children will carry on.

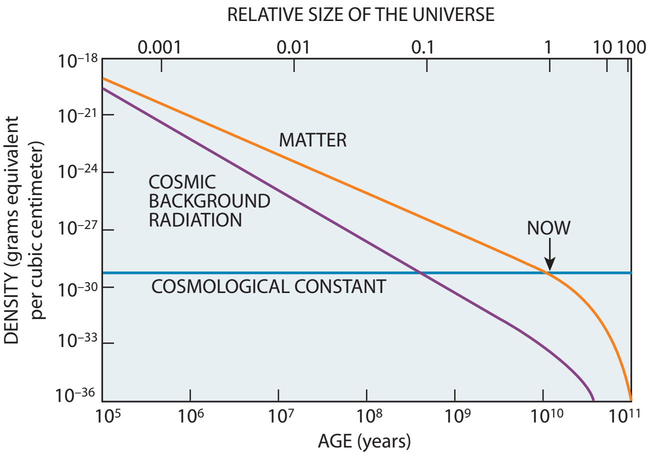
Or maybe not. Remarkably, even though scientists fully understand neither the physical basis of life nor the unfolding of the universe, they can make educated guesses about the destiny of living things. Cosmological observations now suggest the universe will continue to expand forever—rather than, as scientists once thought, expand to a maximum size and then shrink. Therefore, we are not doomed to perish in a fiery "big crunch" in which any vestige of our current or future civilization would be erased. At first glance, eternal expansion is cause for optimism. What could stop a sufficiently intelligent civilization from exploiting the endless resources to survive indefinitely?

Yet life thrives on energy and information, and very general scientific arguments hint that only a finite amount of energy and a finite amount of information can be amassed in even an infinite period. For life to persist, it would have to make do with dwindling resources and limited knowledge. We have concluded that no meaningful form of consciousness could exist forever under these conditions.

The Deserts of Vast Eternity

Over the past century, scientific eschatology has swung between optimism and pessimism. Not long after Darwin's confident prediction, Victorian-era scientists began to fret about the "heat death," in which the whole cosmos would come to a common temperature and thereafter be incapable of change. The discovery of the expansion of the universe in the 1920s allayed this concern, because expansion prevents the universe from reaching such an equilibrium. But few cosmologists thought through the other implications for life in an ever expanding universe, until a classic paper in 1979 by physicist





LAURIE GRACE AND GEORGE MUSSER

DILUTION of the cosmos by the expansion of space affects different forms of energy in different ways. Ordinary matter (*orange*) thins out in direct proportion to volume, whereas the cosmic background radiation (*purple*) weakens even faster as it is stretched from light into microwaves and beyond. The energy density represented by a cosmological constant (*blue*) does not change, at least according to present theories.

Freeman Dyson of the Institute for Advanced Study in Princeton, N.J., itself motivated by earlier work by Jamal Islam, now at the University of Chittagong in Bangladesh. Since Dyson's paper, physicists and astronomers have periodically reexamined the topic [see "The Future of the Universe," by Duane A. Dicus, John R. Letaw, Doris C. Teplitz and Vigdor L. Teplitz; Scientific American, March 1983]. A year ago, spurred on by new observations that suggest a drastically different long-term future for the universe than that previously envisaged, we decided to take another look.

Over the past 12 billion years or so, the universe has passed through many stages. At the earliest times for which scientists now have empirical information, it was incredibly hot and dense. Gradually, it expanded and cooled. For hundreds of thousands of years, radiation ruled; the famous cosmic microwave background radiation is thought to be a vestige of this era. Then matter started to dominate, and progressively larger astronomical structures condensed out. Now, if recent cosmological observations are correct, the expansion of the universe is beginning to accelerate—a sign that a strange new type of energy, perhaps springing from space itself, may be taking over.

Life as we know it depends on stars. But stars inevitably die, and their birth rate has declined dramatically since an initial burst about 10 billion years ago. About 100 trillion years from now, the last conventionally formed star will wink out, and a new era will commence. Processes currently too slow to be noticed will become important: the dispersal of planetary systems by stellar close encounters, the possible decay of ordinary and exotic matter, the slow evaporation of black holes.

Assuming that intelligent life can adapt to the changing circumstances, what fundamental limits does it face? In an eternal universe, potentially of infinite volume, one might hope that a sufficiently advanced civilization could collect an infinite amount of matter, energy and information. Surprisingly, this is not true. Even after an eternity of hard and well-planned labor, living beings could accumulate only a finite number of particles, a finite quantity of energy and a finite number of bits of information. What makes this failure all the more frustrating is that the number of available particles, ergs and bits may grow without bound. The problem is not necessarily the lack of resources but rather the difficulty in collecting them.

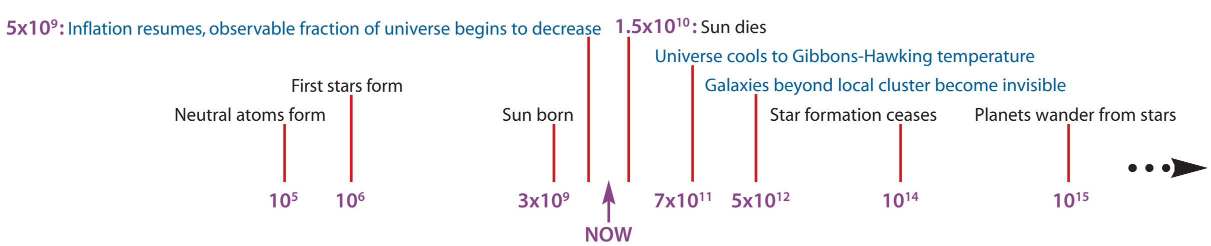
The culprit is the very thing that allows us to contemplate an eternal tenure: the expansion of the universe. As the cosmos grows in size, the average density of ordinary sources of energy declines. Doubling the radius of the universe decreases the density of atoms eightfold. For light waves, the decline is even more precipitous. Their energy density drops by a factor of 16 because the expansion stretches them and thereby saps their energy [*see illustration at left*].

As a result of this dilution, resources become ever more time-consuming to collect. Intelligent beings have two distinct strategies: let the material come to them or try to chase it down. For the former, the best approach in the long run is to let gravity do the work. Of all the forces of nature, only gravity and electromagnetism can draw things in from arbitrarily far away. But the latter gets screened out: oppositely charged particles balance one another, so that the typical object is neutral and hence immune to long-range electrical and magnetic forces. Gravity, on the other hand, cannot be screened out, because particles of matter and radiation only attract gravitationally; they do not repel.

Surrender to the Void

Even gravity, however, must contend with the expansion of the universe, which pulls objects apart and thereby weakens their mutual attraction. In all but one scenario, gravity eventually becomes unable to pull together larger quantities of material. Indeed, our universe may have already reached this point; clusters of galaxies may be the largest bodies that gravity will ever be able to bind together [see "The Evolution of Galaxy Clusters," by J. Patrick Henry, Ulrich G. Briel and Hans Böhringer; Scientific American, December 1998]. The lone exception occurs if the universe is poised between expansion and contraction, in which case gravity continues indefinitely to assemble ever greater amounts of matter. But that scenario is now thought to contradict observations, and in any event it poses its own difficulty: after 10^{33} years or so, the accessible matter will become so concentrated that most of it will collapse into black holes, sweeping up any life-forms. Being inside a black hole is not a happy condition. On the earth, all roads may lead to Rome, but inside a black hole, all roads lead in a finite amount of time to the center of the hole, where death and dismemberment are certain.

Sadly, the strategy of actively seeking resources fares no bet-



ter than the passive approach does. The expansion of the universe drains away kinetic energy, so prospectors would have to squander their booty to maintain their speed. Even in the most optimistic scenario—in which the energy is traveling toward the scavenger at the speed of light and is collected without loss—a civilization could garner limitless energy only in or near a black hole. The latter possibility was explored by Steven Frautschi of the California Institute of Technology in 1982. He concluded that the energy available from the holes would dwindle more quickly than the costs of scavenging [*see illustration on page 60*]. We recently reexamined this possibility and found that the predicament is even worse than Frautschi thought. The size of a black hole required to sweep up energy forever exceeds the extent of the visible universe.

The cosmic dilution of energy is truly dire if the universe is expanding at an accelerating rate. All distant objects that are currently in view will eventually move away from us faster than the speed of light and, in doing so, disappear from view. The total resources at our disposal are therefore limited by what we can see today, at most [*see box at right*].

Not all forms of energy are equally subject to the dilution. The universe might, for example, be filled with a network of cosmic strings—infinitely long, thin concentrations of energy that could have developed as the early universe cooled unevenly. The energy per unit length of a cosmic string remains unchanged despite cosmic expansion [see "Cosmic Strings," by Alexander Vilenkin; SCIENTIFIC AMERICAN, December 1987]. Intelligent beings might try to cut one, congregate around the loose ends and begin consuming it. If the string network is infinite, they might hope to satisfy their appetite forever. The problem with this strategy is that whatever lifeforms can do, natural processes can also do. If a civilization can figure out a way to cut cosmic strings, then the string network will fall apart of its own accord. For example, black holes may spontaneously appear on the strings and devour them. Therefore, the beings could swallow only a finite amount of string before running into another loose end. The entire string network would eventually disappear, leaving the civilization destitute.

What about mining the quantum vacuum? After all, the cosmic acceleration may be driven by the so-called cosmological constant, a form of energy that does not dilute as the universe expands [see "Cosmological Antigravity," by Lawrence M. Krauss; SCIENTIFIC AMERICAN, January]. If so, empty space is filled with a bizarre type of radiation, called Gibbons-Hawking or de Sitter radiation. Alas, it is impossible to extract energy from this radiation for useful work. If the vacuum yielded up energy, it would drop into a lower energy state, yet the vacuum is already the lowest energy state there is.

No matter how clever we try to be and how cooperative the universe is, we will someday have to confront the finiteness of the resources at our disposal. Even so, are there ways to cope forever?

The obvious strategy is to learn to make do with less, a scheme first discussed quantitatively by Dyson. In order to reduce energy consumption and keep it low despite exertion, we would eventually have to reduce our body temperature. One might speculate about genetically engineered humans who function at somewhat lower temperatures than 310 kelvins (98.6 degrees Fahrenheit). Yet the human body temperature cannot be reduced arbitrarily; the freezing point of blood is a firm lower limit. Ultimately, we will need to abandon our bodies entirely.

While futuristic, the idea of shedding our bodies presents no fundamental difficulties. It presumes only that consciousness is not tied to a particular set of organic molecules but

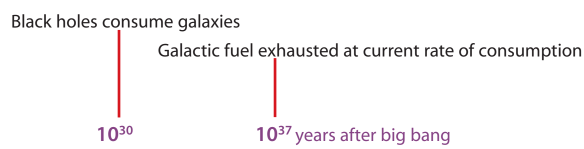
The Worst of All Possible Universes

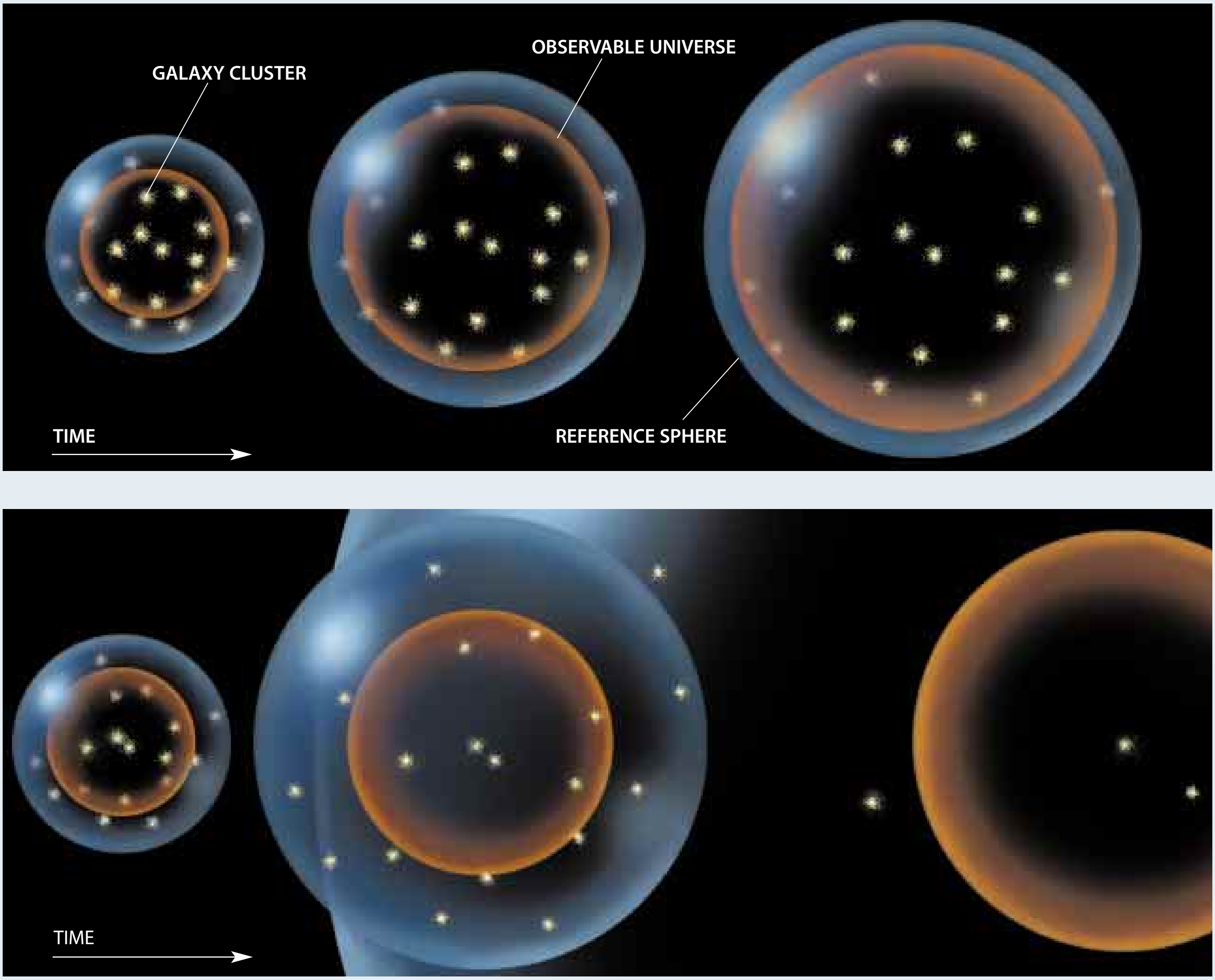
Among all the scenarios for an eternally expanding universe, the one dominated by the so-called cosmological constant is the bleakest. Not only is it unambiguous that life cannot survive eternally in such a universe, but the quality of life will quickly deteriorate as well. So if recent observations that the expansion is accelerating [see "Surveying Space-Time with Supernovae," by Craig J. Hogan, Robert P. Kirshner and Nicholas B. Suntzeff; SCIENTIFIC AMERICAN, January] are borne out, we could face a grim future.

Cosmic expansion carries objects away from one another unless they are bound together by gravity or another force. In our case, the Milky Way is part of a larger cluster of galaxies. About 10 million light-years across, this cluster remains a cohesive whole, whereas galaxies beyond it are whisked away as intergalactic space expands. The relative velocity of these distant galaxies is proportional to their distance. Beyond a certain distance called the horizon, the velocity exceeds the speed of light (which is allowed in the general theory of relativity because the velocity is imparted by the expansion of space itself). We can see no farther.

If the universe has a cosmological constant with a positive value, as the observations suggest, the expansion is accelerating: galaxies are beginning to move apart ever more rapidly. Their velocity is still proportional to their distance, but the constant of proportionality remains constant rather than decreasing with time, as it does if the universe decelerates. Consequently, galaxies that are now beyond our horizon will forever remain out of sight. Even the galaxies we can currently see—except for those in the local cluster—will eventually attain the speed of light and vanish from view. The acceleration, which resembles inflation in the very early universe, began when the cosmos was about half its present age.

The disappearance of distant galaxies will be gradual. Their light will stretch out until it becomes undetectable. Over time, the amount of matter we can see will decrease, and the number of worlds our starships can reach will diminish. Within two trillion years, well before the last stars in the universe die, all objects outside our own cluster of galaxies will no longer be observable or accessible. There will be no new worlds to conquer, literally. We will truly be alone in the universe. *—L.M.K. and G.D.S.*



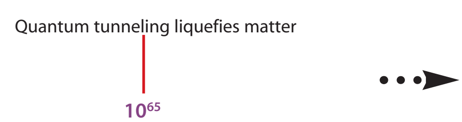


DON DIXON AND GEORGE MUSSER

EXPANDING UNIVERSE looks dramatically different depending on whether the growth is decelerating (*upper sequence*) or accelerating (*lower sequence*). In both cases, the universe is infinite, but any patch of space—demarcated by a reference sphere that represents the distance to particular galaxies—enlarges (*blue sphere*). We can see only a limited volume, which grows steadily as light signals have time to propagate (*red sphere*). If expansion is decelerating, we can see an increasing fraction of the cosmos. More and more galaxies fill the sky. But if expansion is accelerating, we can see a decreasing fraction of the cosmos. Space seems to empty out.

rather can be embodied in a multitude of different forms, from cyborgs to sentient interstellar clouds [see "Will Robots Inherit the Earth?" by Marvin Minsky; Scientific American, October 1994]. Most modern philosophers and cognitive scientists regard conscious thought as a process that a computer could perform. The details need not concern us here (which is convenient, as we are not competent to discuss them). We still have many billions of years to design new physical incarnations to which we will someday transfer our conscious selves. These new "bodies" will need to operate at cooler temperatures and at lower metabolic rates—that is, lower rates of energy consumption.

Dyson showed that if organisms could slow their metabolism as the universe cooled, they could arrange to consume a finite total amount of energy over all of eternity. Although the lower temperatures would also slow consciousness—the number of thoughts per second—the rate would remain large enough for the total number of thoughts, in principle, to be unlimited. In short, intelligent beings could survive forever, not just in absolute time but also in subjective time. As long



as organisms were guaranteed to have an infinite number of thoughts, they would not mind a languid pace of life. When billions of years stretch out before you, what's the rush?

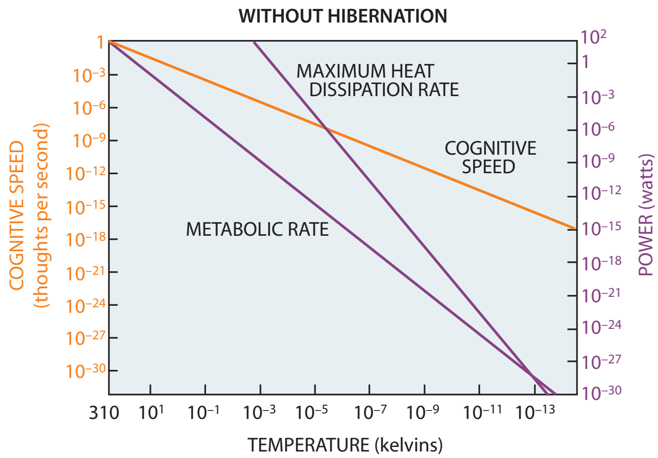
At first glance, this might look like a case of something for nothing. But the mathematics of infinity can defy intuition. For an organism to maintain the same degree of complexity, Dyson argued, its rate of information processing must be directly proportional to body temperature, whereas the rate of energy consumption is proportional to the square of the temperature (the additional factor of temperature comes from basic thermodynamics). Therefore, the power requirements slacken faster than cognitive alacrity does [*see illustration at right*]. At 310 kelvins, the human body expends approximately 100 watts. At 155 kelvins, an equivalently complex organism could think at half the speed but consume a quarter of the power. The trade-off is acceptable because physical processes in the environment slow down at a similar rate.

To Sleep, to Die

Unfortunately, there is a catch. Most of the power is dissipated as heat, which must escape—usually by radiating away—if the object is not to heat up. Human skin, for example, glows in infrared light. At very low temperatures, the most efficient radiator would be a dilute gas of electrons. Yet the efficiency even of this optimal radiator declines as the cube of the temperature, faster than the decrease in the metabolic rate. A point would come when organisms could not lower their temperature further. They would be forced instead to reduce their complexity—to dumb down. Before long, they could no longer be regarded as intelligent.

To the timid, this might seem like the end. But to compensate for the inefficiency of radiators, Dyson boldly devised a strategy of hibernation. Organisms would spend only a small fraction of their time awake. While sleeping, their metabolic rates would drop, but—crucially—they would continue to dissipate heat. In this way, they could achieve an ever lower average body temperature [*see illustration on opposite page*]. In fact, by spending an increasing fraction of their time asleep, they could consume a finite amount of energy yet exist forever and have an infinite number of thoughts. Dyson concluded that eternal life is indeed possible.

Since his original paper, several difficulties with his plan have emerged. For one, Dyson assumed that the average temperature of deep space—currently 2.7 kelvins, as set by the cosmic microwave background radiation—would always decrease as the cosmos expands, so that organisms could continue to decrease their temperature forever. But if the universe has a cosmological constant, the temperature has an absolute floor fixed by the Gibbons-Hawking radiation. For current estimates of the value of the cosmological constant, this radiation has an effective temperature of about 10^{-29} kelvin. As was pointed out independently by cosmologists J. Richard Gott II, John Barrow, Frank Tipler and us, once or-



ETERNAL LIFE ON FINITE ENERGY? If a new form of life could lower its body temperature below the human value of 310 kelvins (98.6 degrees Fahrenheit), it would consume less power, albeit at the cost of thinking more sluggishly (*left graph*). Because metabolism would decline faster than cognition, the lifeform could arrange to have an infinite number of thoughts on limited resources. One caveat is that its ability to dissipate waste heat would also decline, preventing it from cooling below about

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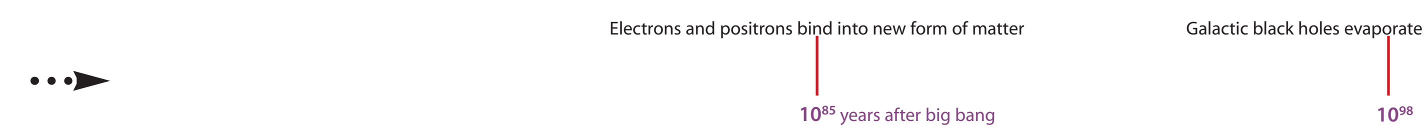
ganisms had cooled to this level, they could not continue to lower their temperature in order to conserve energy.

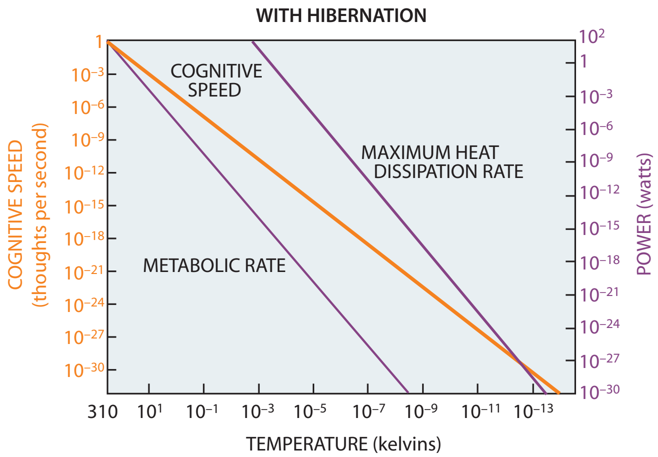
The second difficulty is the need for alarm clocks to wake the organisms periodically. These clocks would have to operate reliably for longer and longer times on less and less energy. Quantum mechanics suggests that this is impossible. Consider, for example, an alarm clock that consists of two small balls that are taken far apart and then aimed at each other and released. When they collide, they ring a bell. To lengthen the time between alarms, organisms would release the balls at a slower speed. But eventually the clock will run up against constraints from Heisenberg's uncertainty principle, which prevents the speed and position of the balls from both being specified to arbitrary precision. If one or the other is sufficiently inaccurate, the alarm clock will fail, and hibernation will turn into eternal rest.

One might imagine other alarm clocks that could forever remain above the quantum limit and might even be integrated into the organism itself. Nevertheless, no one has yet come up with a specific mechanism that could reliably wake an organism while consuming finite energy.

The Eternal Recurrence of the Same

The third and most general doubt about the long-term viability of intelligent life involves fundamental limitations on computation. Computer scientists once thought it was impossible to compute without expending a certain min-





10^{-13} kelvin. Hibernation (*right graph*) might eliminate the problem of heat disposal. As the life-form cools, it would spend an increasing fraction of its time dormant, further reducing its average metabolic rate and cognitive speed. In this way, the power consumption could always remain lower than the maximum rate of heat dissipation, while still allowing for an infinite number of thoughts. But such a scheme might run afoul of other problems, such as quantum limits.

imum amount of energy per operation, an amount that is directly proportional to the temperature of the computer. Then, in the early 1980s, researchers realized that certain physical processes, such as quantum effects or the random Brownian motion of a particle in a fluid, could serve as the basis for a lossless computer [see "The Fundamental Physical Limits of Computation," by Charles H. Bennett and Rolf Landauer; SCIENTIFIC AMERICAN, July 1985]. Such computers could operate with an arbitrarily small amount of energy. To use less, they simply slow down—a trade-off that eternal organisms may be able to make. There are only two conditions. First, they must remain in thermal equilibrium with their environment. Second, they must never discard information. If they did, the computation would become irreversible, and thermodynamically an irreversible process must dissipate energy.

Unhappily, those conditions become insurmountable in an expanding universe. As cosmic expansion dilutes and stretches the wavelength of light, organisms become unable to emit or absorb the radiation they would need to establish thermal equilibrium with their surroundings. And with a finite amount of material at their disposal, and hence a finite memory, they would eventually have to forget an old thought in order to have a new one. What kind of perpetual existence could such organisms have, even in principle? They could collect only a finite number of particles and a finite amount of information. Those particles and bits could be configured in only a finite number of ways. Because thoughts are the reorganization of information, finite information implies a finite number of thoughts. All organisms would ever do is relive the past, having the same thoughts over and over again. Eternity would become a prison, rather than an endlessly receding horizon of creativity and exploration. It might be nirvana, but would it be living?

It is only fair to point out that Dyson has not given up. In his correspondence with us, he has suggested that life can avoid the quantum constraints on energy and information by, for example, growing in size or using different types of memory. As he puts it, the question is whether life is "analog" or "digital"—that is, whether continuum physics or quantum physics sets its limits. We believe that over the long haul life is digital.

Is there any other hope for eternal life? Quantum mechanics, which we argue puts such unbending limits on life, might come to its rescue in another guise. For example, if the quantum mechanics of gravity allows the existence of stable wormholes, life-forms might circumvent the barriers erected by the speed of light, visit parts of the universe that are otherwise inaccessible, and collect infinite amounts of energy and information. Or perhaps they could construct "baby" universes [see "The Self-Reproducing Inflationary Universe," by Andrei Linde; SCIENTIFIC AMERICAN, November 1994] and send themselves, or at least a set of instructions to reconstitute themselves, through to the baby universe. In that way, life could carry on.

The ultimate limits on life will in any case become significant only on timescales that are truly cosmic. Still, for some it may seem disturbing that life, certainly in its physical incarnation, must come to an end. But to us, it is remarkable that even with our limited knowledge, we can draw conclusions about such grand issues. Perhaps being cognizant of our fascinating universe and our destiny within it is a greater gift than being able to inhabit it forever. SA

The Authors

LAWRENCE M. KRAUSS and GLENN D. STARKMAN consider their ruminations on the future of life as a natural extension of their interest in the fundamental workings of the universe. Krauss's books on the predictions of science fiction, *The Physics of Star Trek* and *Beyond Star Trek,* have a similar motivation. The chair of the physics department at Case Western Reserve University in Cleveland, Krauss was among the first cosmologists to argue forcefully that the universe is dominated by a cosmological constant—a view now widely shared. Starkman, also a professor at Case Western, is perhaps best known for his work on the topology of the universe. Both authors are frustrated optimists. They have sought ways that life could persist forever, to no avail. Nevertheless, they maintain the hope that the Cleveland Indians will win the World Series in the ample time that remains.

Further Reading

TIME WITHOUT END: PHYSICS AND BIOLOGY IN AN OPEN UNIVERSE. Freeman J. Dyson in *Reviews of Modern Physics,* Vol. 51, No. 3, pages 447–460; July 1979.

THE ANTHROPIC COSMOLOGICAL PRINCIPLE. John D. Barrow and Frank J. Tipler. Oxford University Press, 1988.

THE LAST THREE MINUTES: CONJECTURES ABOUT THE ULTIMATE FATE OF THE UNIVERSE. Paul C. W. Davies. HarperCollins, 1997.

THE FIVE AGES OF THE UNIVERSE: INSIDE THE PHYSICS OF ETERNITY. Fred Adams and Greg Laughlin. Free Press, 1999.

QUINTESSENCE: THE MYSTERY OF THE MISSING MASS. Lawrence M. Krauss. Basic Books, 1999.

LIFE, THE UNIVERSE, AND NOTHING: LIFE AND DEATH IN AN EVER-EXPANDING UNIVERSE. Lawrence M. Krauss and Glenn D. Starkman in *Astrophysical Journal* (in press). Available at xxx.lanl.gov/abs/astro-ph/9902189 on the World Wide Web.

SALVADOR DALÍ MUSEUM, ST. PETERSBURG, FLORIDA, USA/BRIDGEMAN ART LIBRARY

Vision: A Window on Consciousness

In their search for the mind, scientists are focusing on visual perception—how we interpret what we see

by Nikos K. Logothetis

When you first look at the center image in the painting by Salvador Dalí reproduced at the left, what do you see? Most people immediately perceive a man's face, eyes gazing skyward and lips pursed under a bushy mustache. But when you look again, the image rearranges itself into a more complex tableau. The man's nose and white mustache become the mobcap and cape of a seated woman. The glimmers in the man's eyes reveal themselves as lights in the windows—or glints on the roofs—of two cottages nestled in darkened hillsides. Shadows on the man's cheek emerge as a child in short pants standing beside the seated woman—both of whom, it is now clear, are looking across a lake at the cottages from a hole in a brick wall, a hole we once saw as the outline of the man's face.

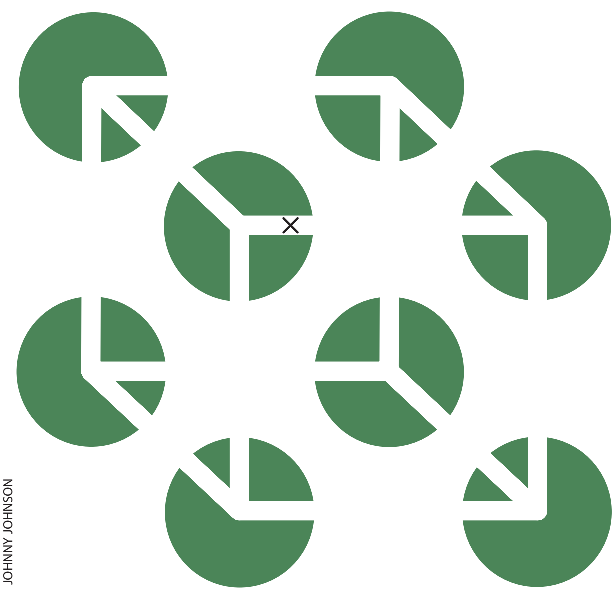
In 1940, when he rendered *Old Age, Adolescence, Infancy (The Three Ages)*—which contains three "faces"—Dalí was toying with the capacity of the viewer's mind to interpret two different images from the same set of brushstrokes. More than 50 years later researchers, including my colleagues and I, are using similarly ambiguous visual stimuli to try to identify the brain activity that underlies consciousness. Specifically, we want to know what happens in the brain at the instant when, for example, an observer comprehends that the three faces in Dalí's picture are not really faces at all.

Consciousness is a difficult concept to define, much less to study.

AMBIGUOUS STIMULI, such as this painting by Salvador Dalí, entitled *Old Age, Adolescence, Infancy (The Three Ages)*, aid scientists who use visual perception to study the phenomenon of consciousness.

Neuroscientists have in recent years made impressive progress toward understanding the complex patterns of activity that occur in nerve cells, or neurons, in the brain. Even so, most people, including many scientists, still find the notion that electrochemical discharges in neurons can explain the mind, and in particular consciousness, challenging.

Yet, as Nobel laureate Francis Crick of the Salk Institute for Biological Studies in San Diego and Christof Koch of the California Institute of Technology have recently argued, the problem of consciousness can be broken down into several separate questions, some of which can be subjected to scientific inquiry [see "The Problem of Consciousness," by Francis Crick and Christof Koch; Scientific American, September 1992]. For example, rather than worrying about what consciousness is, one can ask: What is the difference between the neural processes that correlate with a particular conscious experience and those that do not?



JOHNNY JOHNSON

NECKER CUBE can be viewed two different ways, depending on whether you see the "x" on the top front edge of the cube or on its rear face. Sometimes the cube appears superimposed on the circles; other times it seems the circles are holes and the cube floats behind the page.

Now You See It . . .

That is where ambiguous stimuli come in. Perceptual ambiguity is not a whimsical behavior specific to the organization of the visual system. Rather it tells us something about the organization of the entire brain and its way of making us aware of all sensory information. Take, for instance, the meaningless string of French words *pas de lieu Rhône que nous,* cited by the psychologist William James in 1890. You can read this over and over again without recognizing that it sounds just like the phrase "paddle your own canoe." What changes in neural activity occur when the meaningful sentence suddenly reaches consciousness?

In our work with ambiguous visual stimuli, we use images that not only give rise to two distinct perceptions but also instigate a continuous alternation between the two. A familiar example is the Necker cube [*see illustration at left*]. This figure is perceived as a three-dimensional cube, but the apparent perspective of the cube appears to shift every few seconds. Obviously, this alternation must correspond to something happening in the brain.

A skeptic might argue that we sometimes perceive a stimulus without being truly conscious of it, as when, for example, we "automatically" stop at a red light when driving. But the stimuli and the situations that I investigate are actually designed to reach consciousness.

We know that our stimuli reach awareness in human beings, because they can tell us about their experience. But it is not usually possible to study the activity of individual neurons in awake humans, so we perform our experiments with alert monkeys that have been trained to report what they are perceiving by pressing levers or by looking in a particular direction. Monkeys' brains are organized like those of humans, and they respond to such stimuli much as humans do. Consequently, we think the animals are conscious in somewhat the same way as humans are.

We investigate ambiguities that result when two different visual patterns are presented simultaneously to each eye, a phenomenon called binocular rivalry. When people are put in this situation, their brains become aware of first one perception and then the other, in a slowly alternating sequence [*see box on opposite page*].

In the laboratory, we use stereoscopes to create this effect. Trained monkeys exposed to such visual stimulation report that they, too, experience a perception that changes every few seconds. Our experiments have enabled us to trace neural activity that corresponds to these changing reports.

In the Mind's Eye

Studies of neural activity in animals conducted over several decades have established that visual information leaving the eyes ascends through successive stages of a neural data-processing system. Different modules analyze various attributes of the visual field. In general, the type of processing becomes more specialized the farther the information moves along the visual pathway [*see illustration on page 72*].

At the start of the pathway, images from the retina at the back of each eye are channeled first to a pair of small structures deep in the brain called the lateral geniculate nuclei (LGN). Individual neurons in the LGN can be activated by visual stimulation from either one eye or the other but not both. They respond to any change of brightness or color in a specific region within an area of view known as the receptive field, which varies among neurons.

From the LGN, visual information moves to the primary visual cortex, which is at the back of the head and conventionally abbreviated as V1. Neurons in V1 behave differently than those in the LGN do. They can usually be activated by either eye, but they are also sensitive to specific attributes, such as the direction of motion of a stimulus placed within their receptive field. Visual information is transmitted from V1 to more than two dozen other distinct cortical regions.

Some information from V1 can be traced as it moves through areas known as V2 and V4 before winding up in regions known as the inferior temporal cortex (ITC), which like all the other structures are bilateral. A large number of investigations, including neurological studies of people who have experienced brain damage, suggest that the ITC is important in perceiving form and recognizing objects. Neurons in V4 are known to respond selectively to aspects of visual stimuli critical to discerning shapes. In the ITC, some neurons behave like V4 cells, but others respond only when entire objects, such as faces, are placed within their very large receptive fields.

Other signals from V1 pass through regions V2, V3 and an area called MT/V5 before eventually reaching a part of the brain called the parietal lobe. Most neurons in MT/V5 respond strongly to items moving in a specific direction. Neurons in other areas of the parietal lobe respond when an animal pays attention to a stimulus or intends to move toward it.

One surprising observation made in early experiments is that many neurons in these visual pathways, both in V1 and in higher levels of the processing hierarchy, still respond with their characteristic selectivity to visual stimuli even in animals that have been completely anesthetized. Clearly, an animal (or a human) is not conscious of all neural activity.

The observation raises the question of whether awareness is the result of the activation of special brain regions or clusters of neurons. The study of binocular rivalry in alert, trained monkeys allows us to approach that question, at least to some extent. In such experiments, a researcher presents each animal with a variety of visual stimuli, usually patterns or figures projected onto a screen. Monkeys can easily be trained to report accurately what stimulus they perceive by means of rewards of fruit juice [*see box on pages 74 and 75*].

How to Experience Binocular Rivalry

To simulate binocular rivalry at home, use your right hand to hold the cardboard cylinder from a roll of paper towels (or a piece of paper rolled into a tube) against your right eye. Hold your left hand, palm facing you, roughly four inches in front of your left eye, with the edge of your hand touching the tube.

At first it will appear as though your hand has a hole in it, as your brain concentrates on the stimulus from your right eye. After a few seconds, though, the "hole" will fill in with a fuzzy perception of your whole palm from your left eye. If you keep viewing, the two images will alternate, as your brain selects first the visual stimulus viewed by one eye, then that viewed by the other. The alternation is, however, a bit biased; you will probably perceive the visual stimulus you see through the cylinder more frequently than you will see your palm.

The bias occurs for two reasons. First, your palm is out of focus because it is much closer to your face, and blurred visual stimuli tend to be weaker competitors in binocular rivalry than sharp patterns, such as the surroundings you are viewing through the tube. Second, your palm is a relatively smooth surface with less contrast and fewer contours than your comparatively rich environment has. In the laboratory, we select the patterns viewed by the subjects carefully to eliminate such bias. —*N.K.L.*

DAN WAGNER

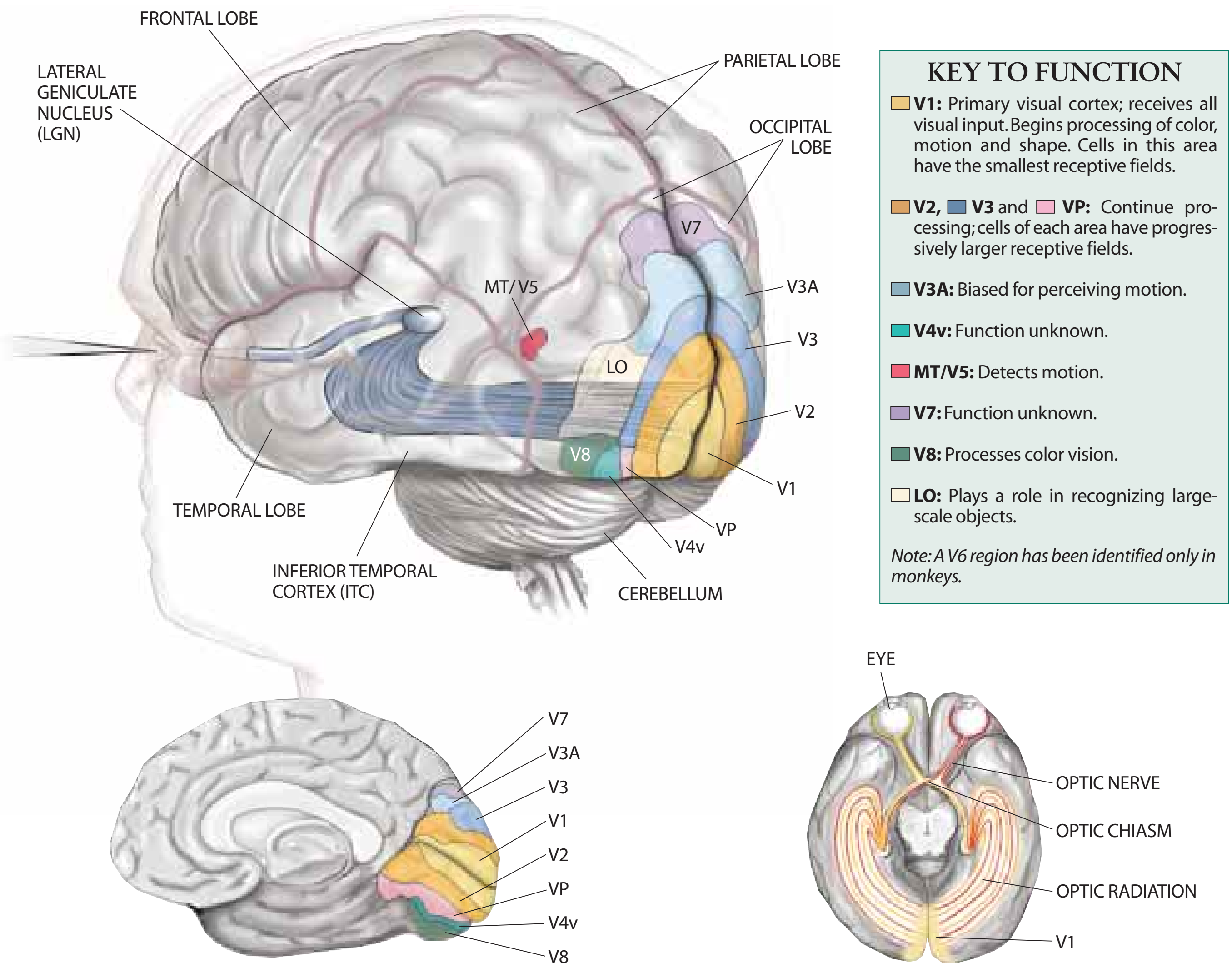
During the experiment, the scientist uses electrodes to record the activity of neurons in the visual-processing pathway. Neurons vary markedly in their responsiveness when identical stimuli are presented to both eyes simultaneously. Stimulus pattern A might provoke activity in one neuron, for instance, whereas stimulus pattern B does not.

Once an experimenter has identified an effective and an ineffective stimulus for a given neuron (by presenting the same stimulus to both eyes at once), the two stimuli can be presented so that a different one is seen by each eye. We expect that, like a human in this situation, the monkey will become aware of the two stimuli in an alternating sequence. And, indeed, that is what the monkeys tell us by their responses when we present them with such rivalrous pairs of stimuli. By recording from neurons during successive presentations of rivalrous pairs, an experimenter can evaluate which neurons change their activity only when the stimuli change and which neurons alter their rate of firing when the animal reports a changed perception that is not accompanied by a change in the stimuli.

Jeffrey D. Schall, now at Vanderbilt University, and I carried out a version of this experiment in which one eye saw a grating that drifted slowly upward while the other eye saw a downward-moving grating. We recorded from visual area MT/V5, where cells tend to be responsive to motion. We found that about 43 percent of the cells in this area changed their level of activity when the monkey indicated that its perception had changed from up to down, or vice versa. Most of these cells were in the deepest layers of MT/V5.

The percentage we measured was actually a lower proportion than most scientists would have guessed, because almost all neurons in MT/V5 are sensitive to direction of movement. The majority of neurons in MT/V5 did behave somewhat like those in V1, remaining active when their preferred stimulus was in view of either eye, whether it was being perceived or not.

There were further surprises. Some 11 percent of the neurons examined were excited when the monkey report-



TERESE WINSLOW, WITH ASSISTANCE FROM NOUCHINE HADJIKHANI AND ROGER TOOTELL *Harvard Medical School*

HUMAN VISUAL PATHWAY begins with the eyes and extends through several interior brain structures before ascending to the various regions of the visual cortex (V1, and so on). At the optic chiasm, the optic nerves cross over partially so that each hemisphere of the brain receives input from both eyes. The information is filtered by the lateral geniculate nucleus, which consists of layers of nerve cells that each respond only to stimuli from one eye. The inferior temporal cortex is important for seeing forms. Researchers have found that some cells from each area are active only when a person or monkey becomes conscious of a given stimulus.

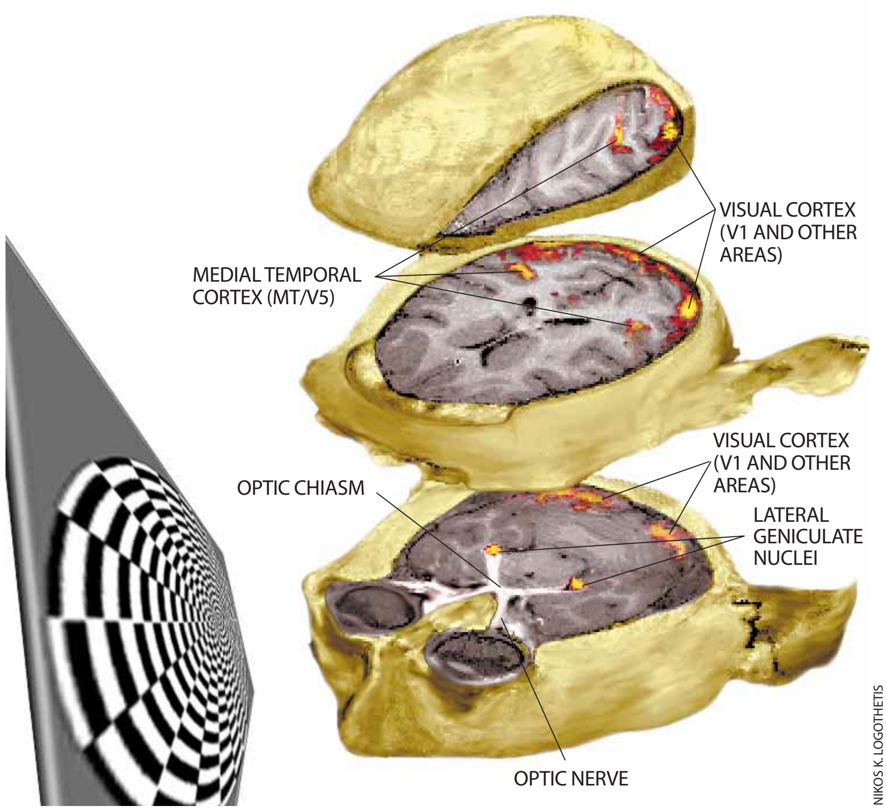
ed perceiving the more effective stimulus of an upward/downward pair for the neuron in question. But a similar proportion of neurons, paradoxically, was most excited when the most effective stimulus was not perceived—even though it was in clear view of one eye. Other neurons could not be categorized as preferring one stimulus over another.

While we were both at Baylor College of Medicine, David A. Leopold and I studied neurons in parts of the brain known to be important in recognizing objects. (Leopold is now with me at the Max Planck Institute for Biological Cybernetics in Tübingen, Germany.) We recorded activity in V4, as well as in V1 and V2, while animals viewed stimuli consisting of lines sloping either to the left or to the right. In V4 the proportion of cells whose activity reflected perception was similar to that which Schall and I had found in MT/V5, around 40 percent. But again, a substantial proportion fired best when their preferred stimulus was not perceived. In V1 and V2, in contrast, fewer than one in 10 of the cells fired exclusively when their more effective stimulus was perceived, and none did so when it was not perceived.

The pattern of activity was entirely different in the ITC. David L. Sheinberg—who also moved with me from Baylor to the Max Planck institute—and I recorded from this area after training monkeys to report their perceptions during rivalry between complex visual patterns, such as images of humans, animals and various manmade objects. We found that almost all neurons, about 90 percent, responded vigorously when their preferred pattern was perceived, but their activity was profoundly inhibited when this pattern was not being experienced.

So it seems that by the time visual signals reach the ITC, the great majority of neurons are responding in a way that is linked to perception. Frank Tong, Ken Nakayama and Nancy Kanwisher of Harvard University have used a technique called functional magnetic resonance imaging (fMRI)—which yields pictures of brain activity by measuring increases in blood flow in specific areas of the brain—to study people experiencing binocular rivalry. They found that the ITC was particularly active when the subjects reported they were seeing images of faces.

In short, most of the neurons in the earlier stages of the visual pathway responded mainly to whether their preferred visual stimulus was in view or not, although a few showed behavior that could be related to changes in the animal's perception. In the later stages of processing, on the other hand, the proportion whose activity reflected the animal's perception increased until it reached 90 percent.



IMAGES OF BRAIN ACTIVITY are from an anesthetized monkey that was presented with a rotating, high-contrast visual stimulus (*lower left*). These views, taken using functional magnetic resonance imaging, show that even though the monkey is unconscious, its vision-processing areas—including the lateral geniculate nuclei (LGN), primary visual cortex (V1) and medial temporal cortex (MT/V5)—are busy.

A critic might object that the changing perceptions that monkeys report during binocular rivalry could be caused by the brain suppressing visual information at the start of the visual pathway, first from one eye, then from the other, so that the brain perceives a single image at any given time. If that were happening, changing neural activity and perceptions would simply represent the result of input switched from one eye to the other and would not be relevant to visual consciousness in other situations. But experimental evidence shows decisively that input from both eyes is continuously processed in the visual system during rivalry.

We know this because it turns out that in humans, binocular rivalry produces its normal slow alternation of perceptions even if the competing stimuli are switched rapidly—several times per second—between the two eyes. If rivalry were merely a question of which eye the brain is paying attention to, the rivalry phenomenon would vanish when stimuli are switched quickly in this way. (The viewer would see, rather, a rapid alternation of the stimuli.) The observed persistence of slowly changing rivalrous perceptions when stimuli are switched strongly suggests that rivalry occurs because alternate stimulus representations compete in the visual pathway. Binocular rivalry thus affords an opportunity to study how the visual system decides what we see even when both eyes see (almost) the same thing.

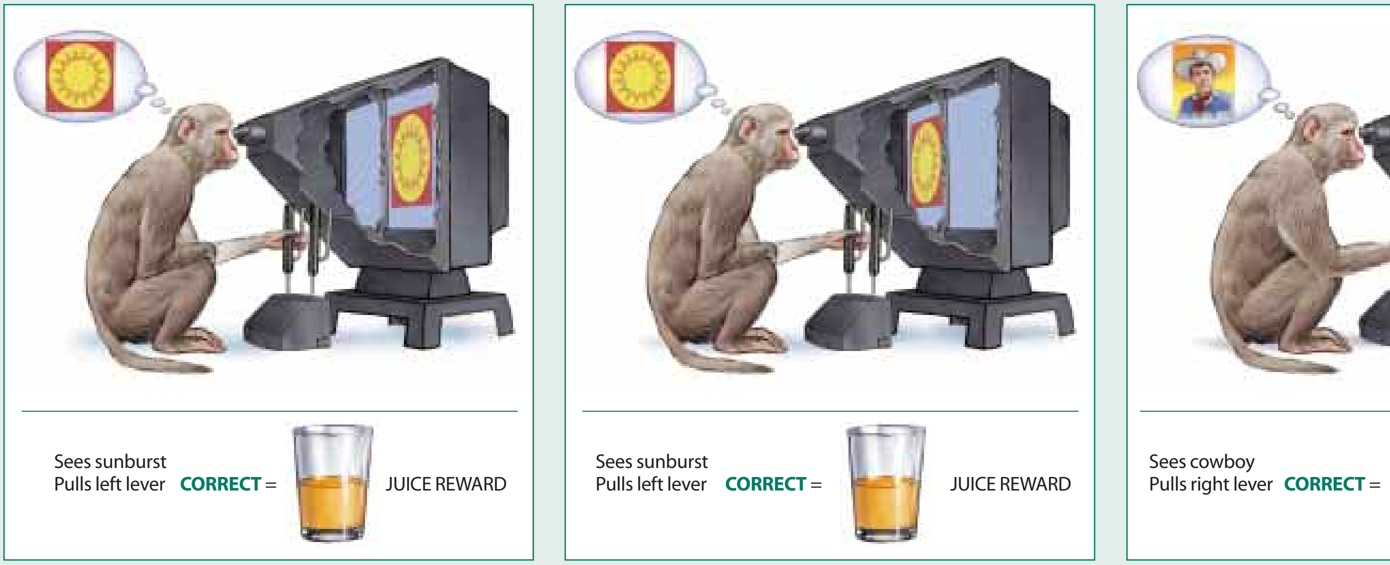
A Perceptual Puzzle

What do these findings reveal about visual awareness? First, they show that we are unaware of a great deal of activity in our brains. We have long known that we are mostly unaware of the activity in the brain that maintains the body in a stable state—one of its evolutionarily most ancient tasks. Our experiments show that we

Keeping Monkeys (and

One possible objection to the experiments described in the main article is that the monkeys might have been inclined to cheat to earn their juice rewards. We are, after all, unable to know directly what a monkey (or a human) thinks or perceives at a given time. Because our monkeys were interested mainly in drinking juice rather than in understanding how consciousness arises from neuronal activity, it is possible that they could have developed a response strategy that appeared to reflect their true perceptions but really did not.

In the training session depicted below, for example, the monkey was being taught to pull the left lever only when it saw a sunburst and the right lever only when it saw a cowboy. We were able to ensure that the monkey continued to report truthfully by interject-



are also unaware of much of the neural activity that generates—at least in part—our conscious experiences.

We can say this because many neurons in our brains respond to stimuli that we are not conscious of. Only a tiny fraction of neurons seem to be plausible candidates for what physiologists call the "neural correlate" of conscious perception—that is, they respond in a manner that reliably reflects perception.

We can say more. The small number of neurons whose behavior reflects perception are distributed over the entire visual pathway, rather than being part of a single area in the brain. Even though the ITC clearly has many more neurons that behave this way than those in other regions do, such neurons may be found elsewhere in future experiments. Moreover, other brain regions may be responsible for any decision resulting from whatever stimulus reaches consciousness. Erik D. Lumer and his colleagues at University College London have studied that possibility using fMRI. They showed that in humans the temporal lobe is activated during the conscious experience of a stimulus, as we found in monkeys. But other regions, such as the parietal and the prefrontal cortical areas, are activated precisely at the time at which a subject reports that the stimulus changes.

Learning more about the locations of, and connections between, neurons that correlate with conscious experience will tell us more about how the brain generates awareness. But the findings to date already strongly suggest that visual awareness cannot be thought of as the end product of such a hierarchical series of processing stages. Instead it involves the entire visual pathway as well as the frontal parietal areas, which are involved in higher cognitive processing. The activity of a significant minority of neurons reflects what is consciously seen even in the lowest levels we looked at, V1 and V2; it is only the proportion of active neurons that increases at higher levels in the pathway.

Currently it is not clear whether the activity of neurons in the very early areas is determined by their connections with other neurons in those areas or is the result of top-down, "feedback" connections emanating from the temporal or parietal lobes. Visual information flows from higher levels down to the lower ones as well as in the opposite direction. Theoretical studies indicate that systems with this kind of feedback can exhibit complicated patterns of behavior, including multiple stable states. Different stable states maintained by top-down feedback may correspond to different states of visual consciousness.

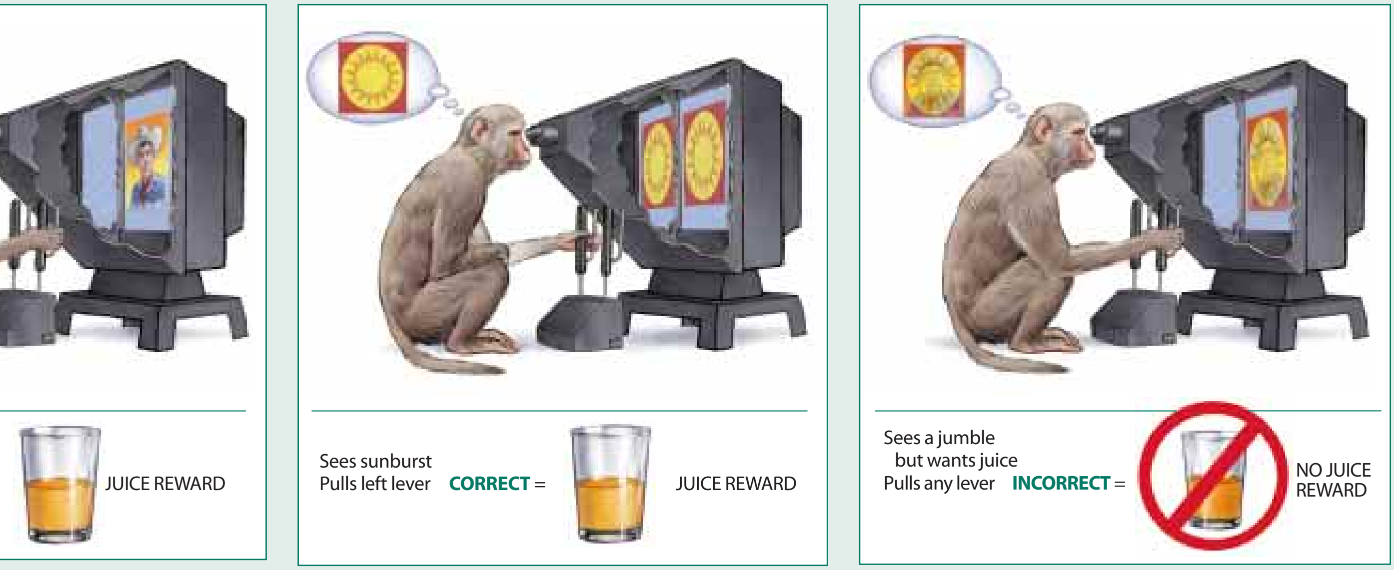
One important question is whether the activity of any of the neurons we have identified truly determine an animal's conscious perception. It is, after all, conceivable that these neurons are merely under the control of some other unknown part of the brain that actually determines conscious experience.

Elegant experiments conducted by William T. Newsome and his colleagues at Stanford University suggest that in area MT/V5, at least, neuronal activity can indeed determine directly what a monkey perceives. Newsome first identified neurons that selectively respond to a stimulus moving in a particular direction, then artificially activated them

Experimenters) Honest

ing instances in which no rivalrous stimuli were shown (*below*). During these occasions, there was a "right" answer to what was perceived, and if the monkey did not respond correctly, the trial—and thus the opportunity to earn more juice rewards—was immediately ended. Similarly, if the monkey pulled any lever when presented with a jumbled image, in which the sunburst and the cowboy were superimposed (*last panel*), we knew the monkey was lying in an attempt to get more juice.

Our results indicate that monkeys report their experiences accurately. Even more convincing is our observation that monkeys and humans tested with the same apparatus perform at similar levels in different tasks. *—N.K.L.*



MATT COLLINS

with small electric currents. The monkeys reported perceiving motion corresponding to the artificial activation even when stimuli were not moving in the direction indicated.

It will be interesting to see whether neurons of different types, in the ITC and possibly in lower levels, are also directly implicated in mediating consciousness. If they are, we would expect that stimulating or temporarily inactivating them would change an animal's reported perception during binocular rivalry.

A fuller account of visual awareness will also have to consider results from experiments on other cognitive processes, such as attention or what is termed working memory. Experiments by Robert Desimone and his colleagues at the National Institute of Mental Health reveal a remarkable resemblance between the competitive interactions observed during binocular rivalry and processes implicated in attention. Desimone and his colleagues train monkeys to report when they see stimuli for which they have been given cues in advance. Here, too, many neurons respond in a way that depends on what stimulus the animal expects to see or where it expects to see it. It is of obvious interest to know whether those neurons are the same ones as those firing only when a pattern reaches awareness during binocular rivalry.

The picture of the brain that starts to emerge from these studies is of a system whose processes create states of consciousness in response not only to sensory inputs but also to internal signals representing expectations based on past experiences. In principle, scientists should be able to trace the networks that support these interactions. The task is huge, but our success identifying neurons that reflect consciousness is a good start. SA

The Author

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Further Reading

A Vision of the Brain. Semir Zeki. Blackwell Scientific Publications, 1993.

The Astonishing Hypothesis: The Scientific Search for the Soul. Francis Crick. Scribner's, 1994.

Eye, Brain and Vision. David H. Hubel. Scientific American Library, 1995.

The Visual Brain in Action. A. David Milner and Melvyn A. Goodale. Oxford University Press, 1996.

Flammable Ice

Methane-laced ice crystals in the seafloor store more energy than all the world's fossil fuel reserves combined. But these methane hydrate deposits are fragile, and the gas that escapes from them may exacerbate global warming

by Erwin Suess, Gerhard Bohrmann, Jens Greinert and Erwin Lausch

ROGER SASSEN *Texas A&M University*

It was a thrilling moment when the enormous seafloor sampler opened its metallic jaws and dumped its catch onto the deck of our ship, *Sonne*. A white substance resembling effervescent snow gleamed amid the dark mud hauled up from the bottom of the North Pacific Ocean. Watching it melt before our eyes, we sensed that we had struck our own kind of gold.

As members of the Research Center for Marine Geosciences (GEOMAR) at Christian Albrechts University in Kiel, Germany, we and our colleagues were searching for methane hydrate—a white, icelike compound made up of molecules of methane gas trapped inside cages of frozen water. To that end, we had undertaken several expeditions to inspect, with the help of a video camera tethered to the ship, a submarine ridge about 100 kilometers (62 miles) off the coast of Oregon. Earlier seismic investigations and drilling had suggested that this area might hold a substantial stash of our treasure. On July 12, 1996, we noticed peculiar white spots in the mud 785 meters (2,575 feet) below our ship.

To make sure this telltale sign of hydrate was the real thing, we directed our sampler, a contraption like a backhoe with two scoops, to take a giant bite out of the seafloor. Even while retrieving the payload, we saw our expectations confirmed. As the sampler ascended, the video camera mounted inside its jaws revealed that bubbles—attesting to the rapid escape of methane gas—were beginning to emerge from the muddy heap. Stable only at near-freezing temperatures and under the high-pressure conditions generated by the weight of at least 500 meters of overlying water, methane hydrates decompose rapidly above that depth. As the sample approached the ocean's surface, the flow of bubbles gradually increased and burst through the water's sparkling surface long before the jaws of the sampler did.

We wondered how much intact hydrate would reach the deck. Moving quickly, we managed to safeguard roughly 100 pounds (45 kilograms) of the hissing chunks in containers cooled with liquid nitrogen. In the end, we even had a few pieces left over, which inspired an impromptu fireworks display. Just holding a burning match to one of the white lumps ignited the hydrate's flammable methane, which also is one of the primary hydrocarbon components of natural gas. The lump burned with a reddish flame and left only a puddle of water as evidence of its former glory.

Before 1970 no one even knew that methane hydrates existed under the sea, and our haul was by far the largest quantity ever recovered from the ocean depths. Yet hydrates are by no means a rarity. On the contrary, in recent years they have been found to occur worldwide—from Japan to New Jersey and from

BUBBLES OF METHANE escape from a decomposing gas hydrate mound surrounded by tube worms. Such icelike hydrate deposits become unstable when the surrounding temperature rises more than a few degrees above freezing or when the pressure becomes lower than that found about 500 meters (1,064 feet) below the ocean surface.

PHOTOGRAPHS COURTESY OF RESEARCH CENTER FOR MARINE GEOSCIENCES (GEOMAR)

GERMAN RESEARCH VESSEL *SONNE* (*top*) has spearheaded many methane hydrate explorations off the coast of Oregon. Researchers hauled up fresh sediment from a methane hydrate field there with the aid of a video-guided sampler in the summer of 1996 (*middle*). The muddy chunks (*bottom*) consist of alternating layers of pure-white methane hydrate, sediments and limestone.

Oregon to Costa Rica—in enormous quantities. Estimates vary widely, but most experts agree that marine gas hydrates collectively harbor twice as much carbon as do all known natural gas, crude oil and coal deposits on the earth [*see illustration on page 81*].

The energy stored in methane hydrates could potentially fuel our energy-hungry world in the future (if practical mining techniques are devised). But the hydrates also have a worrisome aspect: methane escaping from disturbed undersea hydrates may be an ecological threat. If even a small portion of these deposits decompose through natural processes, astonishing quantities of methane will be set free to exacerbate the greenhouse effect and global warming.

Although methane remains in the atmosphere relatively briefly—10 years on average—it does not vanish without a trace. In the presence of free oxygen, a methane molecule's single atom of carbon disengages from its four hydrogen atoms to become carbon dioxide, the most infamous of all greenhouse gases because it is one of those spewed into the atmosphere during the combustion of fossil fuels.

But are decomposing methane hydrates contributing to global warming now? And are they likely to do so in the future? Our 1996 journey—along with dozens of voyages and experiments since—have revealed something about the structure and origins of a variety of these massive yet remarkably unstable deposits and have provided some answers to the climate questions, but our understanding is far from complete. We and our colleagues at GEOMAR continue our quest to understand just what role methane hydrates play in ocean-floor stability and both past and future climatic change.

Turning Heads

It was the immense cache of energy trapped in marine methane hydrates that first turned the heads of politicians. But the challenges of tapping that resource are now making some officials look the other way. Hydrates tend to form along the lower margins of continental slopes, where the seabed drops from the relatively shallow shelf, usually about 150 meters below the surface, toward the ocean's abyss several kilometers deep. The hydrate deposits may reach beneath the ocean floor another few hundred meters—deeper than most drilling rigs can safely operate. Moreover, the roughly sloping seafloor makes it difficult to run a pipeline from such deposits to shore.

Countries that wish to rely less on foreign fossil fuels have started to overcome these technical difficulties, however. Japan was scheduled to launch an experimental hydrate drilling project off the coast of Hokkaido in October. U.S. engineers also are playing with ideas for tapping hydrate energy sources [*see box on page 80*]. But as long as relatively cheap gas and oil remain available, most industrial countries are unlikely to invest heavily in the technologies needed to harvest hydrates efficiently.

Methane hydrates captured the attention of petroleum geologists a bit earlier than that of politicians. When engineers first realized in the 1930s that gas-laden ice crystals were plugging their gas and oil pipelines, laboratory researchers spent time studying hydrate structure and composition. For example, they learned that one type of hydrate structure consists of icy cages that can absorb small gas molecules such as methane, carbon dioxide and hydrogen sulfide. A different type forms larger cavities that can enclose several small molecules or larger hydrocarbon molecules, such as pentane. What is more, the individual cages can differ in the kinds of gas molecules they capture.

In the 1960s scientists discovered that hydrates could also form in natural environments. They found the first natural deposits in the permafrost regions of Siberia and North America, where the substances were known as marsh gas. In the 1970s geophysicists George Bryan and John Ewing of Lamont-Doherty Earth Observatory of Columbia University found the earliest indication that methane hydrates also lurk beneath the seafloor. The hint came from seismological studies at Blake Ridge, a 100-kilometer-long feature off the North Carolina coast.

Seismologists can distinguish layers beneath the seafloor because sound waves bounce off certain kinds of dirt and rock differently than off other kinds. Some 600 meters below the ocean floor Bryan and Ewing saw an unusual reflection that mimicked the contour of the ridge. Their conclusion: this bottom-simulating reflector was the boundary between a methane hydrate layer and a layer of free methane gas that had accumulated below. Other experts found similar features elsewhere, and soon this type of reflector was being mapped as a methane hydrate deposit in ocean basins around the globe.

We used a bottom-simulating reflector, along with underwater video cameras, to guide our 1996 search for methane hydrates along the North Pacific seafloor promontory that has since been named Hydrate Ridge. Our successful recovery of intact hydrate on that expedition made it possible to study this unusual material in detail for the first time. Being able to analyze the texture and chemistry of its microscopic structure allowed us to confirm the plausible but previously unproved notion that the methane derives from the microbial decomposition of organic matter in the sediment.

Most telling were chemical tests that showed the hydrates to be enriched in carbon 12. Inorganic methane that seeps out of volcanic ridges and vents has higher levels of carbon 13, an isotope of carbon with an additional neutron. But the bacteria that digest organic matter in oxygen-deficient conditions such as those in sediments at the bottom of the sea tend to sequester more carbon 12 in the methane they generate.

The seafloor off the coast of Oregon also proved an especially fruitful theater of operations for assessing the stability of methane hydrate deposits and their potential role in releasing carbon into the atmosphere. Combined with research from other sites, these analyses indicate that methane hydrate deposits can be disturbingly labile.

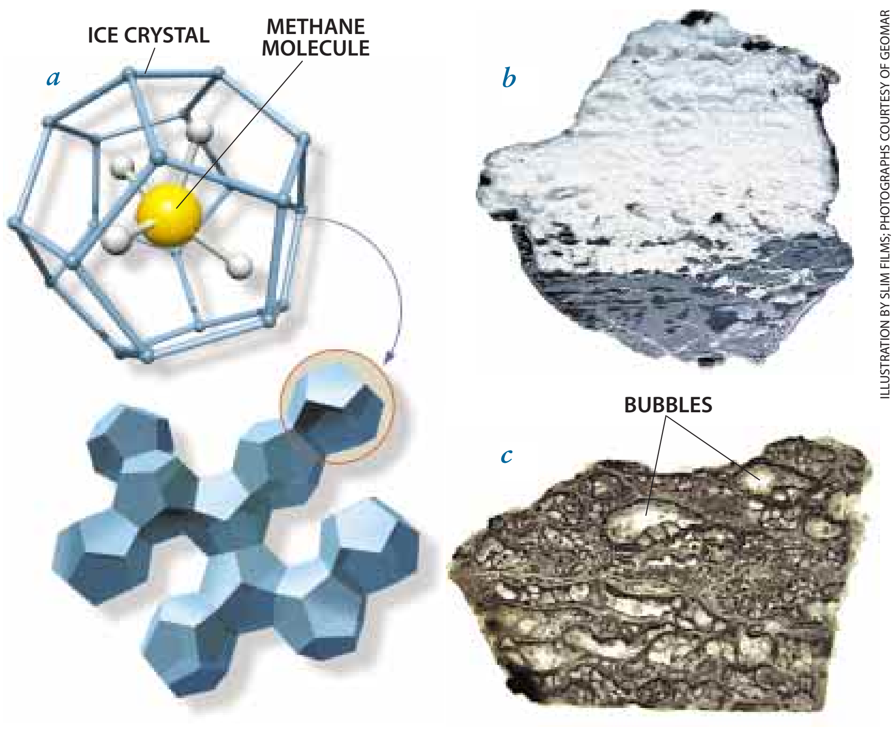
We now know that in places along Hydrate Ridge, the seabed is virtually paved with hundreds of square meters of hydrate. These deposits form part of the packet of sediments riding piggyback on the Juan de Fuca tectonic plate, which is sliding underneath North America at a rate of 4.5 centimeters (1.7 inches) a year. As the Juan de Fuca plate is subducted, the sediments and hydrates it carries are partially sheared off by the upper plate and pressed into folds or piled several layers high like a giant stack of pancakes. This distorted material forms a wedge of mud that accumulates against the North American plate in the shape of ridges running nearly parallel to the coast.

Methane Plumes

In 1984 one of us (Suess) was the first to observe these ridges and their world of cold, eternal night from *Alvin,* the research submersible operated by the Woods Hole Oceanographic Institution. Outside *Alvin*'s porthole, Suess saw a landscape of stone chimneys built by minerals precipitated from hazes of water and gas spewing out of the earth's crust. Only later did we realize that these chimneys are partially the product of a methane hydrate deposit being squeezed as one tectonic plate scrapes past the other.

Plumes of gas and fluids also escape along faults that cut through the sediment and gas hydrates alike. Although these plumes, also called cold vents, are unlike the hot springs that form along mid-oceanic ridges (where hot lava billows out of a crack in the seafloor), they are nonetheless warm enough to further destabilize the hydrates. These melt when the surrounding temperature creeps even a few degrees above freezing. As new hydrates form near the seafloor, the lower portions melt away, with the result that the overall layer migrates upward over time.

Melting at the bottom of a hydrate layer liberates not only freshwater but also methane and small amounts of hydrogen sulfide and ammonia. Oxidation of these chemicals into carbon dioxide, sulfate and nitrate provides nourishment to rich communities of



CRYSTALLINE CAGES OF FROZEN WATER (*a*) sometimes snare molecules of methane gas that have been given off as microbes digest organic matter in the seafloor mud. The fresh hydrate sample shown above (*b*) formed a few meters beneath the seafloor off the coast of Oregon, where rising bubbles of methane gas were trapped underneath denser layers of mud. The methane reacted with the near-freezing water to form hydrates. Lens-shaped bubbles are clearly visible in another slice of the same methane hydrate sample (*c*), which was polished with a cold saw.

Fuel of the Future?

Given the vastness of the world's marine methane hydrate deposits—more than twice the carbon reserves of all other fossil fuels combined—it's not surprising that government agencies and the petroleum and natural gas industries have long been interested in harvesting this new energy supply. Research and development programs already exist in a number of countries, particularly Japan. But tapping into this giant energy storehouse at a reasonable cost presents enormous difficulties.

Not the least of the challenges is that marine hydrate deposits are located in ocean mud up to a kilometer (0.62 mile) below the seafloor. In addition, hydrates decompose rapidly if removed from the high pressures and low temperatures of the deep sea. Even if engineers could construct a system to bring a load of hydrate to the surface before it disappeared, extracting the methane from the matrix of mud and rock would still present a problem.

Free methane gas trapped under the hydrate layer is no easier to tap. Unlike the conditions in conventional natural gas deposits, the pressure of the overlying water and rock is too low to expel methane at a rate sufficient to make extraction worthwhile.

Methane hydrate is not completely out of reach, however. By harnessing methods similar to those used to recover dense, viscous petroleum, engineers could pump steam or hot water down a drill hole to melt the hydrate and release more methane to escape. They could then pump the escaping methane to the surface of the seafloor through another drill hole. Ultimately, the methane would have to be brought ashore, but submarine pipelines are expensive, and on a continental slope avalanches would threaten their rigging. Mining the very hydrate that had helped stabilize the slope would exacerbate this risk.

The extent of such difficulties is reflected in the boldness of some of the mining approaches that experts in the field are discussing. For example, Timothy Collett of the U.S. Geological Survey in Denver proposes to save the cost of pipelines by liquefying the gas on ships or drilling platforms. In Collett's setup the methane would be partly burned to form hydrogen and carbon monoxide. A catalyst would then convert the mixture into a liquid hydrocarbon, which could be readily transported by ship. The downside: a 35 percent loss of energy.

GEOMAR

REDDISH FLAME consuming a hydrate sample is fed by methane trapped in the ice.

In contrast, Roger Sassen of Texas A&M University envisions a production facility on the ocean floor, where the emerging methane would be combined with water to form hydrate uncontaminated by mud and rock. Submarines would then tow the hydrate in zeppelin-shaped storage tanks to shallower destinations where engineers could safely decompose it into water and fuel.

"We should see gas hydrate becoming a meaningful and environmentally friendly resource in the next century," Sassen says. Indeed, as the world's other energy reserves diminish, mining companies may find themselves compelled to invest in technologies for exploiting the world's last great reserve of carbon-based fuel. *—E.S., G.B., J.G. and E.L.*

chemical-eating bacteria. These microbes in turn serve as food for such creatures as clams and colonies of tube worms. Such oases of life stand out on the otherwise sparsely inhabited seabed.

Our investigations also revealed that the gases liberated at these densely populated vents give rise to an immensely active turnover of carbon. Oxidation of the liberated methane generates bicarbonate, which combines with calcium ions in the seawater to form calcium carbonate, better known as limestone. Such limestone is what Suess saw in 1984 in the form of chimneys and vent linings along the crest of Hydrate Ridge—and what we now realize is a hint of a deeper hydrate layer.

Along the western flank of Hydrate Ridge, massive limestone blocks cover the crack created by a large fault. But despite the limestone casing and the activities of the vent organisms, surprising quantities of methane escape into the surrounding ocean water. In fact, we measured concentrations that are roughly 1,300 times the methane content of water at equilibrium with the methane content of the air. We still do not know how much of the methane is oxidized in the water and how much actually enters the air, but it is easy to imagine that an earthquake or other dramatic tectonic event could release large amounts of this highly potent greenhouse gas into the atmosphere.

Researchers at GEOMAR have a much better idea of how much methane escapes in plumes rising up from hydrate fields in the Sea of Okhotsk off the east coast of Asia. About as big as the North Sea and the Baltic Sea combined, this body of water is delineated by the Kamchatka Peninsula and the Kuril island arc. In the summer of 1998 a joint German-Russian team using fish-finder sonar documented methane plumes as tall as 500 meters billowing out of methane hydrate deposits on the seafloor. With our video camera tethered to the boat, we also saw giant chimneys reminiscent of the cold vents along Hydrate Ridge in the Pacific.

Even before we had visual evidence of the hydrate deposits, we knew that enormous quantities of methane accumulate under the blanket of ice that typically covers much of the Sea of Okhotsk for seven months a year. We measured a concentration of 6.5 milliliters of methane per liter of water just beneath the ice during a 1991 expedition. When the sea was free of ice the next summer, this figure was only 0.13—the difference had vented into the atmosphere. No similar methane flux has yet been observed anywhere else in the world, so this event may be unique. Still, this one-time measurement of methane escape from the Sea of Okhotsk clearly demonstrates that methane hydrates below the oceans can be a significant source of atmospheric methane. To help evaluate the possible current and future climatic impact of the methane, scientists are now sampling methane concentrations in the Okhotsk seawater every two months.

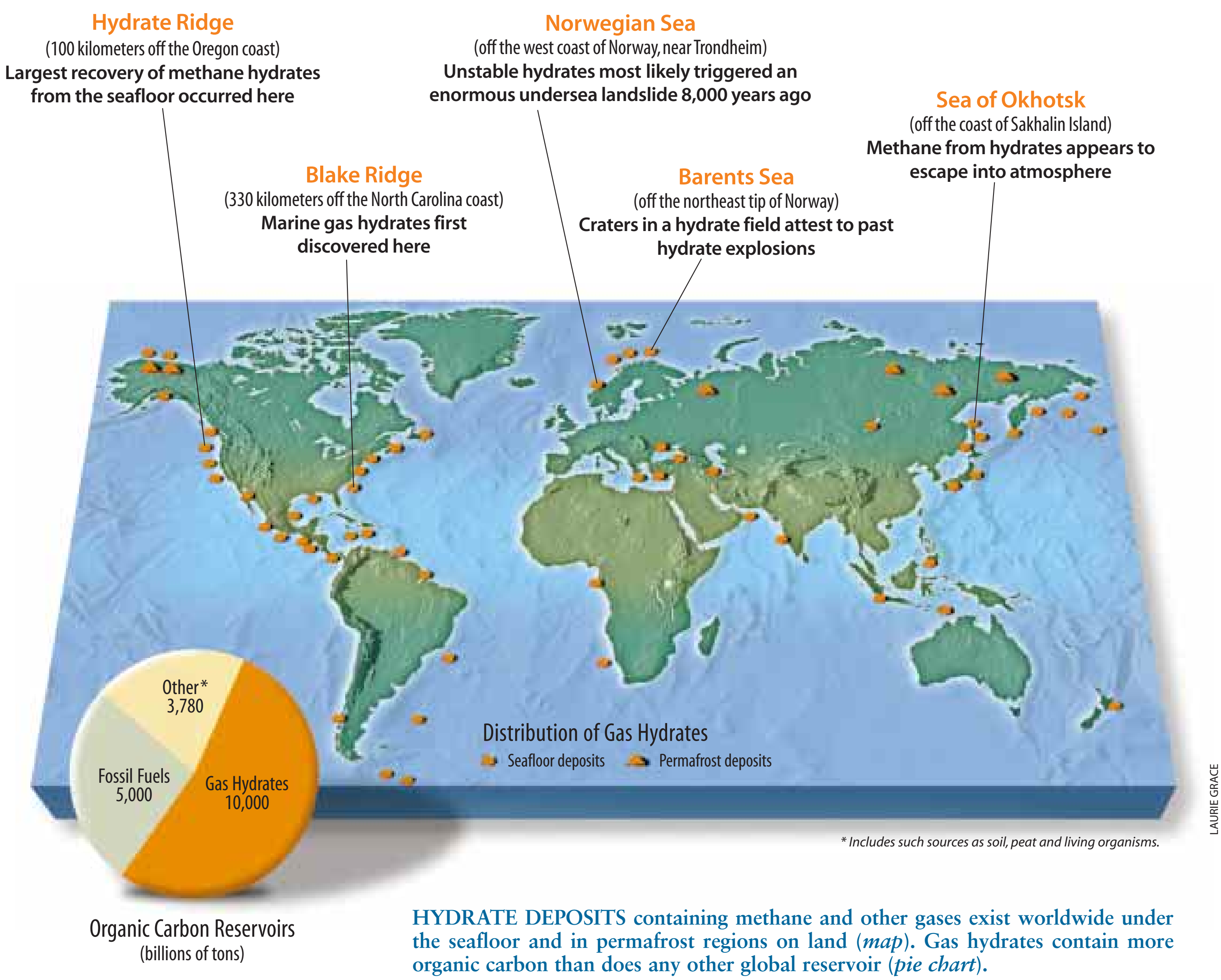
Shaky Ground

Plumes caused by seafloor faulting and the natural decomposition of hydrates can release methane slowly to the atmosphere, but it turns out that this process is sometimes much more explosive. In the summer of 1998 Russian researchers from the Shirshov Institute of Oceanology in Moscow found unstable hydrate fields off the west coast of Norway that they suspect are the cause of one of history's most impressive releases of trapped methane, an event known as the Storrega submarine landslide.

From previous explorations of the seafloor, scientists know that 8,000 years ago some 5,600 cubic kilometers (1,343 cubic miles) of sediments slid a distance of 800 kilometers from the upper edge of the continental slope into the basin of the Norwegian Sea, roughly at the latitude of Trondheim. The consequence of so much mud pushing water out of its path would have been devastating tsunamis—horrific swells that suddenly engulf the coastline.

The presence of methane hydrate fields in the same seafloor vicinity implies that unstable hydrates triggered the slide as they rapidly decomposed because of a change in the pressure or temperature after the last ice age. As the glaciers receded, the seafloor no longer had to support the enormous weight of the ice. As the land rebounded, the overlying sea and ice both warmed and became more shallow, suddenly moving the hydrates out of their zone of stability.

Could a geologic event like this strike again? Off the coast of southern Norway the risk of new slides appears to be relatively small, because the hydrate fields have for the most part decomposed. But the issue of the stability of the continental slope is assuming a heightened importance in view of current global warming and the strong possibility of further changes in the earth's climate in the near future. Be-



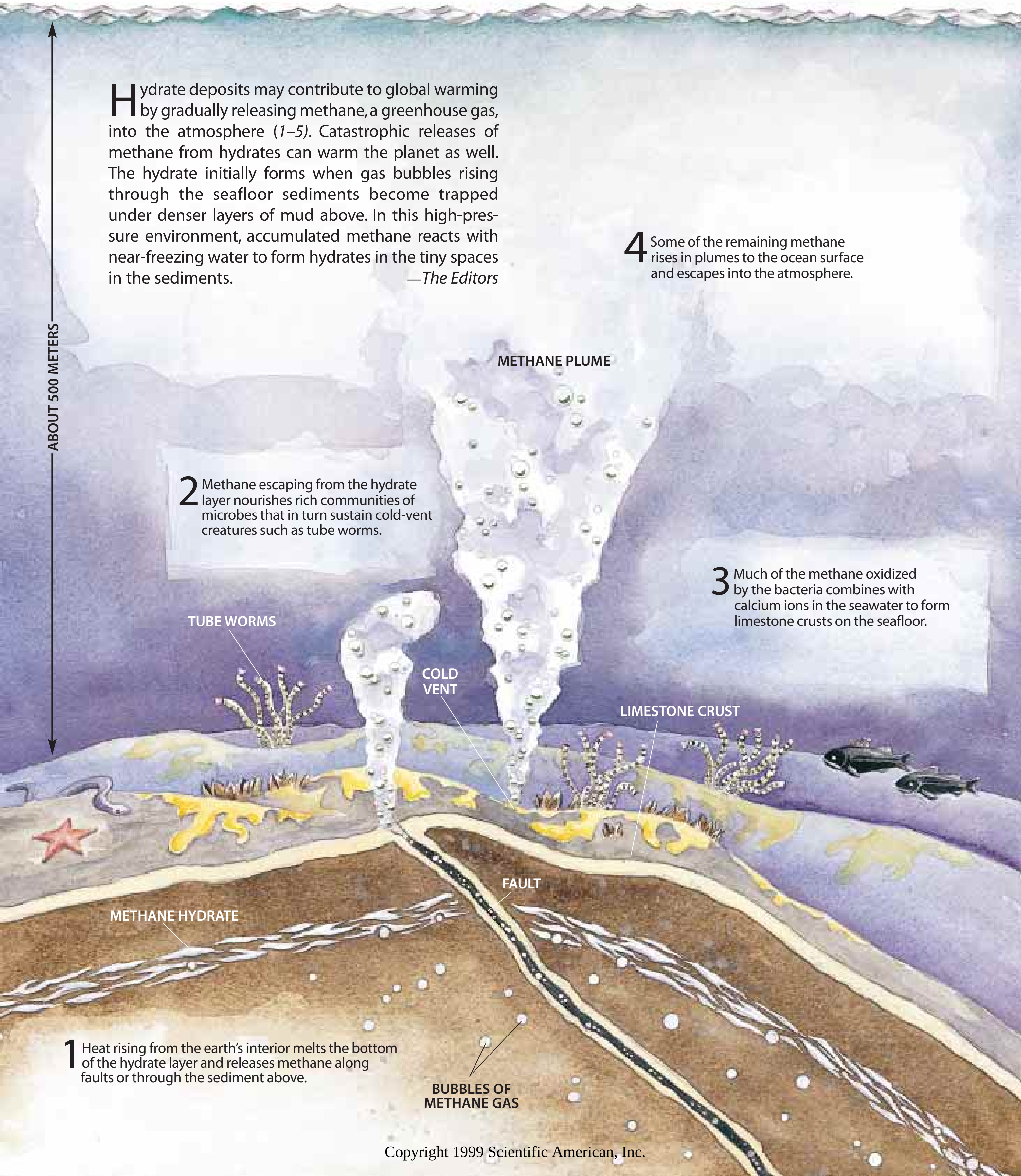
HYDRATE DEPOSITS containing methane and other gases exist worldwide under the seafloor and in permafrost regions on land (*map*). Gas hydrates contain more organic carbon than does any other global reservoir (*pie chart*).

From the Seafloor to the Sky

HOW METHANE HYDRATES MAY ALTER THE CLIMATE

5 In the atmosphere the methane converts to another greenhouse gas, carbon dioxide. Both gases can gather into an insulating layer that heats the lower atmosphere and thereby changes climate patterns.

Hydrate deposits may contribute to global warming by gradually releasing methane, a greenhouse gas, into the atmosphere (*1–5*). Catastrophic releases of methane from hydrates can warm the planet as well. The hydrate initially forms when gas bubbles rising through the seafloor sediments become trapped under denser layers of mud above. In this high-pressure environment, accumulated methane reacts with near-freezing water to form hydrates in the tiny spaces in the sediments. —*The Editors*



yond contributing to tsunamis, hydrate formations that become unstable and decompose will release methane into the oceans. In fact, melting a mere cubic meter of hydrate releases up to 164 cubic meters of methane, some of which would surely reach the atmosphere. In turn, a warming of the lower atmosphere would heat the oceans, launching a vicious circle of more dissolution of hydrates and more atmospheric warming.

Many researchers think that an explosive methane release from a single large site can create dramatic climate changes on short timescales. James P. Kennett, an oceanographer at the University of California at Santa Barbara, has hypothesized that catastrophic releases of methane could have triggered the notable increase in temperature that occurred over just a few decades during the earth's last ice age some 15,000 years ago. An international team led by former GEOMAR member Jürgen Mienert, now at Tromsø University in Norway, recently found possible evidence of this methane release on the floor of the Barents Sea, just off Norway's northeastern tip.

There, fields of giant depressions reminiscent of bomb craters pockmark the immediate vicinity of methane hydrate deposits. Mienert's team measured the biggest of these craters at 700 meters wide and 30 meters deep—a size clearly suggestive of catastrophic explosions of methane. Whether these eruptions occurred more or less simultaneously has not yet been determined, but faults and other structural evidence indicate they probably took place toward the end of the last ice age, as Kennett proposed. The explosions very likely followed a scenario like the one suggested for the cause of the Storrega landslide: warming seas rendered the hydrates unstable, and at a critical point they erupted like a volcano.

Older Hints

Researchers have also uncovered evidence that methane liberated from gas hydrates affected the global climate in the more distant past—at the end of the Paleocene, about 55 million years ago. Fossil evidence suggests that land and sea temperatures rose sharply during this period. Many species of single-celled organisms dwelling in the seafloor sediment became extinct. A flux of some greenhouse gas into the atmosphere presumably warmed the planet, but what was the source? Carbon isotopes turned out to be the key to interpreting the cause of the rapid rise in temperature.

Scientists found a striking increase in the lighter carbon 12 isotope in the preserved shells of microscopic creatures that survived the heat spell. Methane hydrates are the likeliest source for the light carbon—and for the greenhouse gas flux—because these deposits are the only places where organic methane accumulates to levels that could influence the isotopic signature of the seawater when they melt. The carbon 12 enrichment characteristic of the hydrates disperses into the seawater with the liberated methane and persists in its oxidation product, carbon dioxide. Some of the carbon dioxide in turn becomes incorporated into the calcium carbonate shells of the sea creatures, while some of the methane makes its way to the atmosphere to help warm things up.

Gerald Dickens, now at James Cook University in Australia, used a computer simulation to test whether melting methane hydrates could have belched out enough greenhouse gases to subject the earth to a heat shock 55 million years ago. He and his former collaborators at the University of Michigan based their simulation on the assumption that hydrates corresponding to about 8 percent of today's global reserves decomposed at that time. Because liberated methane is converted immediately (on a geologic timescale) into carbon dioxide, they tracked this compound only.

In 10,000 simulated years, 160 cubic kilometers of carbon dioxide containing carbon 12 showed up in their model atmosphere every year. Adding this carbon dioxide caused the lower atmosphere to warm by two degrees Celsius (3.6 degrees Fahrenheit). At the same time, the isotope ratio of carbon in the water and atmosphere shifted to correspond to the values observed in the fossils. Moreover, this carbon isotope ratio gradually returned to normal within 200,000 years, just as it does in actual fossil records.

Dickens's model is compelling but rare. So far the significance of methane from natural gas hydrate sources as a greenhouse gas has received only limited consideration in global climate modeling. The contribution of methane hydrates to global carbon budgets has likewise not been adequately taken into account. Trying to come up with data to correct these shortfalls is one of the greatest motivations for our work on methane hydrates at GEOMAR. We continue to focus on Hydrate Ridge off the Oregon coast—eight marine expeditions targeted the site earlier this year. We will also be looking at the seafloor off the coasts of Costa Rica, Nicaragua, Alaska's Aleutian Islands and New Zealand. Whatever happens in methane hydrate research, the future will be anything but dull. SA

The Authors

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Further Reading

Authigenic Carbonates from the Cascadia Subduction Zone and Their Relation to Gas Hydrate Stability. Gerhard Bohrmann et al. in *Geology,* Vol. 26, No. 7, pages 647–650; 1998.

Fluid Venting in the Eastern Aleutian Subduction Zone. Erwin Suess et al. in *Journal of Geophysical Research B: Solid Earth and Planets,* Vol. 103, No. B2, pages 2597–2614; February 10, 1998.

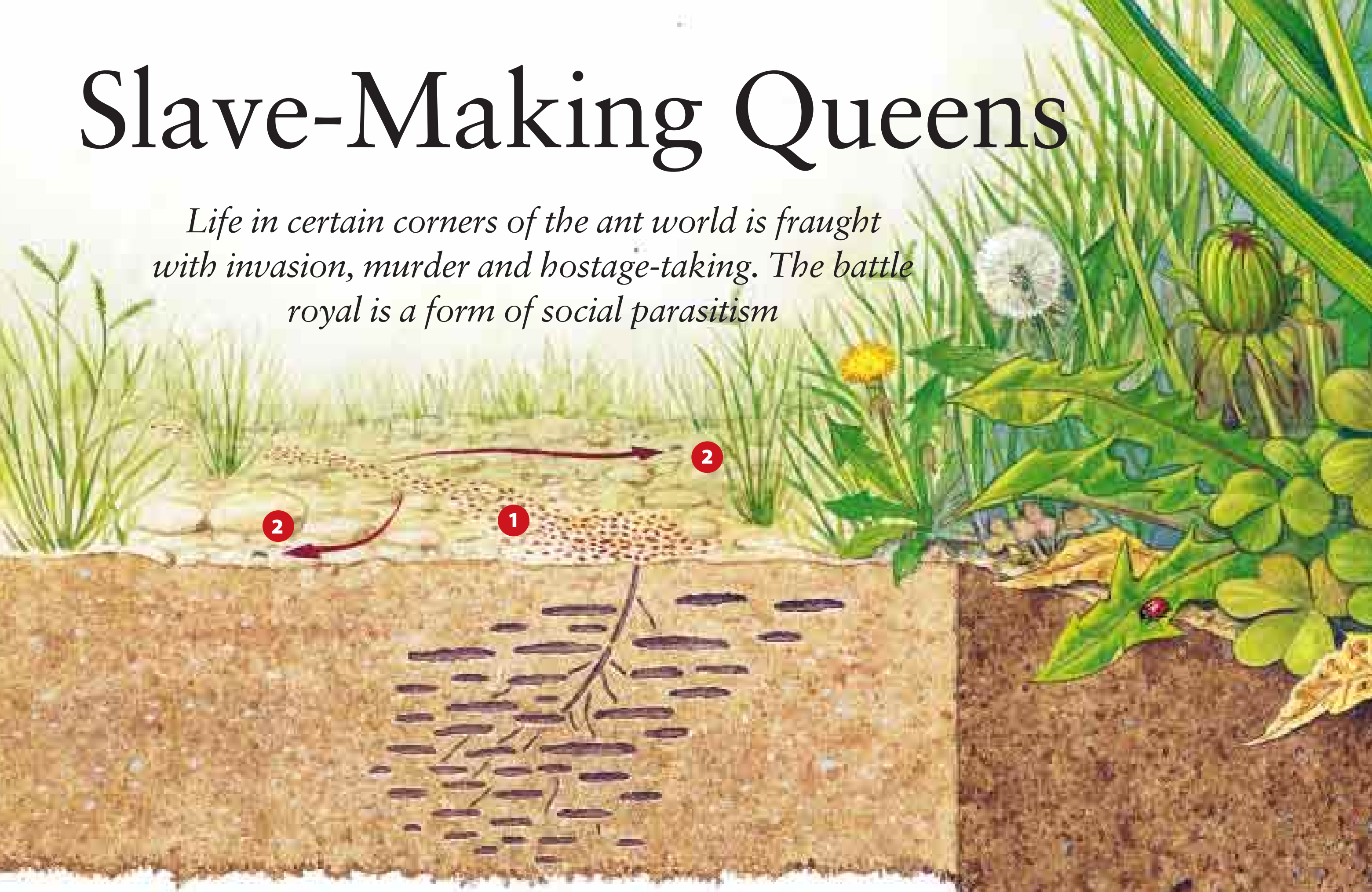
Gas Hydrates: Relevance to World Margin Stability and Climate Change. Edited by J.-P. Henriet and J. Mienert. Geological Society Special Publications, Vol. 137; 1998.

Potential Effects of Gas Hydrate on Human Welfare. Keith A. Kvenvolden in *Proceedings of the National Academy of Sciences USA,* Vol. 96, No. 7, pages 3420–3426; March 30, 1999.

RICK JONES

Slave-Making Queens

Life in certain corners of the ant world is fraught with invasion, murder and hostage-taking. The battle royal is a form of social parasitism



by Howard Topoff

In the animal world, both predators and parasites survive at the expense of other species. Nevertheless, they don't get the same press. I am besieged with mail containing pleas for money on behalf of wolves and killer whales, but I have yet to see a T-shirt with the slogan "Long Live the Hookworm." The problem is, of course, that humans associate a parasitic lifestyle with disease. Our perception is of a furtive organism that insinuates itself inside us and, unlike a decent predator, intends to destroy us ever so slowly.

But there exists a form of parasitism considerably less macabre. Social parasitism, as it is called, has evolved independently in such diverse creatures as ants and birds. A female cuckoo, for instance, lays her egg in the nest of another species, such as a warbler, and leaves it for the host to rear. The brown-headed cowbird does the same. Each bird has evolved so that it produces eggs that match those of its chosen baby-sitter.

Even more varied than these avian parasites are the slave-making ants. The unusual behavior of the parasitic ant *Polyergus breviceps*—which I have been studying for 15 years in Arizona at the American Museum of Natural History's Southwestern Research Station—offers a perfect ex-

ILLUSTRATION BY ROBERTO OSTI

SLAVE RAID by *Polyergus* ants on a *Formica* ant colony can be a complex undertaking. The *Polyergus* workers charge into a *Formica* nest (*1*), stealing pupae that they will take back home and enslave. Meanwhile young *Polyergus* queens mate amid this warring frenzy, and then each one sets off alone to establish her own colony (*2*). The newly mated queen battles *Formica* workers at the entrance of their burrow some distance from her natal nest (*3*), fights her way to the *Formica* queen in the chamber below and kills her (*4*). By licking the dying queen, the *Polyergus* queen acquires chemicals that win over the *Formica* workers, and so they tend to her eggs as well as those of their deceased queen (*5*).


3
4
5

These ants have completely lost the ability to care for themselves. The workers do

COURTESY OF HOWARD TOPOFF

***FORMICA* PUPA is carried by a *Polyergus* worker to the *Polyergus* nest (*above*), where it will become part of a brood that the previously captured *Formica* slaves attend to. Some 1,500 *Polyergus* workers go out on each pupae-pilfering raid (*right*); over the course of a single season, a *Formica* nest may lose as many as 14,000 pupae to the *Polyergus* hordes.**

ample. Like the other four species of *Polyergus* found throughout the world, these ants have completely lost the ability to care for themselves. The workers do not forage for food, feed the young or the queen, or even clean up their own nest. To survive, *Polyergus* ants must get workers from the related ant genus *Formica* to do their chores for them. Thus, *Polyergus* workers periodically undertake a slave raid in which about 1,500 of them travel up to 150 meters (492 feet), enter a *Formica* nest, expel the *Formica* queen and workers, and capture the pupae.

Back at the *Polyergus* nest, slaves rear the raided brood until the young emerge. The newly hatched *Formica* workers then assume all responsibility for maintaining the mixed-species nest. They forage for nectar and dead arthropods, regurgitate food to colony members, remove wastes and excavate new chambers. When the population becomes too large for the existing nest, it is the 3,000 or so *Formica* slaves that locate another site and physically transport the approximately 2,000 *Polyergus* workers, together with eggs, larvae, pupae and even the queen, to the new nest.

This master-slave arrangement is not unique. Of the approximately 8,800 species of ants, at least 200 have evolved some form of symbiotic relationship with one another. At one end of the behavioral continuum are facultative parasites, such as the ant *Formica wheeleri*. These ants are capable of caring for themselves but undertake periodic slave raids on different ant species to supplement their labor force. In contrast, *Polyergus* and other dulotic (from the Greek word for "servant") ants are obligatory social parasites. The workers and queen cannot survive without the assistance of slaves.

My field research on *Polyergus* has been guided by one stubborn objective: to determine the most important adaptations in the evolution of obligatory social parasitism. Accordingly, I have homed in on the one behavior that is truly specific to *Polyergus* ants: the capacity of a queen to take over a *Formica* nest single-handedly. Because, in addition to the large slave-capturing raids that can be seen in some other ant species, *Polyergus* has developed an unusual way for a new queen to establish her own colony.

In most ant species, the process of setting up a new nest is straightforward. After flying away from her natal colony and mating, a queen tears away her wings, excavates a chamber, lays a few eggs and nourishes her larvae with stored nutrients. When the brood matures, the adult workers immediately assume the job of colony maintenance. But a parasitic queen like *Polyergus* is incapable of rearing her first brood without slaves. So she is confronted with a seemingly impossible mission: to invade a colony of *Formica,* kill the resident queen and become accepted by the workers. Moreover, she must accomplish all this without the assistance of a single soldier ant.

For several weeks every year, a few hundred eggs laid by an established *Polyergus* queen develop into males and into queens that leave the parent colony and attempt to form a new one. In Arizona the young queens of *P. breviceps* have waived even the most traditional sexual ritual among ants: the mating flight. Instead of soaring off, winged *Polyergus* queens embark with workers in a well-timed slave raid. Amid the tumult of the advancing swarm, a primed queen will stop running, attract a male with a pheromone from her mandibular gland, mate with him and then pull off her wings. (Clandestine it's not.)

Two strategies of colony founding are now available to this just-inseminated queen. First, she may continue in the slave not forage for food, feed the young or the queen, or even clean up their own nest.

RAYMOND A. MENDEZ (*left*); COURTESY OF HOWARD TOPOFF (*right*)

FORMICA **WORKER emerges from its pupal state and views itself as a *Polyergus,* because that is the only life it knows. It cares for the *Polyergus* workers and queen, feeding them, cleaning the nest and even moving the nest if it becomes too crowded. A colony of 2,000 *Polyergus* may have as many as 3,000 *Formica* slaves. Without them, the colony would perish.**

raid and arrive in an invaded colony of *Formica* whose workers and queen are scattered across the terrain. Such disorganization could facilitate the queen's mission, but success is usually short-lived. The problem is that colonies of *Polyergus* are extremely territorial and will not tolerate other colonies of the same species within their raiding turf. The next time this (now usurped) nest is raided by the parent *Polyergus* colony, the new *Polyergus* queen, along with any workers she has produced, will be destroyed.

The alternative tactic for an up-and-coming *Polyergus* queen is to bolt from the raiding column and on her own locate a more distant colony of *Formica*. Although there are no guarantees, this behavior at least increases the likelihood of finding an appropriate host nest outside the raiding territory of a resident *Polyergus* population.

Killing Machines

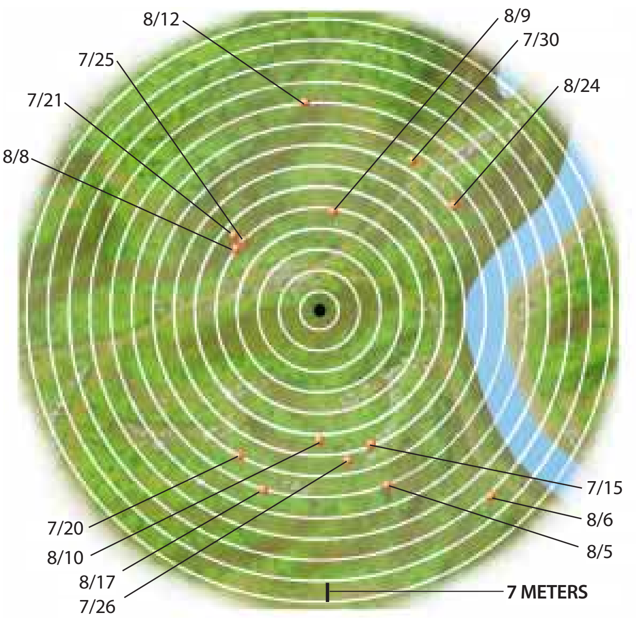
After locating a suitable *Formica* nest, the serious business of colony usurpation begins. Because this takes place underground, where direct observations are not possible, my graduate students and I conducted our studies using transparent laboratory nests. Before each test we placed 15 *Formica gnava* workers in a nest with 15 pupae and one queen. (In contrast, a wild colony of *F. gnava* contains about 5,000 workers.) We then placed a newly mated *Polyergus* queen just outside the nest.

In most cases the *Polyergus* queen quickly detects the entrance and erupts into a frenzy of ruthless activity. She bolts straight for the *Formica* queen, literally pushing aside any *Formica* workers that attempt to grab and bite her. Our earlier studies had shown that the *Polyergus* queen's two main defensive adaptations are powerful mandibles for biting her attackers and a repellent pheromone secreted from the Dufour's gland in her abdomen. With worker opposition liquidated, the *Polyergus* queen grabs the *Formica* queen and bites her head, thorax and abdomen for an unrelenting 25 minutes. Between bouts of biting she uses her extruded tongue to lick the wounded parts of her dying victim. Within seconds of the host queen's death, the nest undergoes a most remarkable transformation. The *Formica* workers behave as if sedated. They calmly approach the *Polyergus* queen and start grooming her—just as they did their own queen. The *Polyergus* queen, in turn, assembles the scattered *Formica* pupae into a neat pile and stands triumphantly on top of it. At this point, colony takeover is a done deal.

The Royal Feast

Our next goal was to find the key to this remarkable brainwashing of the *Formica* workers. One hypothesis was "chemical acquisition," whereby the *Polyergus* queen acquires *Formica* queen chemicals during the act of killing and licking her. To test this idea, my student Ellen Zimmerli and I added a twist to our original study: we killed the *Formica* queen—by freezing and defrosting her—immediately prior to introducing the *Polyergus* female. Our hypothesis predicted that the *Polyergus* queen would still have to attack the dead host queen, pierce her exoskeleton and ingest her body fluids.

The results were exactly as we had anticipated. On entering the nest, the *Polyergus* queen pounced on the motionless *Formica* queen and started to bite and lick her for about 25 minutes, just as if she were alive. As soon as she finished



TOM MOORE

***FORMICA* NESTS (*red*) that are attacked often lie within 150 meters (492 feet) of a *Polyergus* nest (*center*). This particular *Polyergus* colony conducted 14 raids on 12 *Formica* colonies in the course of about six weeks between July 15 and August 24.**

"killing" the lifeless *Formica* queen, the *Polyergus* queen was groomed by the *Formica* workers and permanently accepted as their new ruler.

A second prediction of the "chemical acquisition" hypothesis is that it would be difficult for a *Polyergus* queen to be welcomed by *Formica* workers if no *Formica* queen were present in the nest. So in our next series of laboratory studies we simply removed the *Formica* queen before introducing the *Polyergus* female. Sure enough, this act provoked the proverbial battle royal. Fighting between the *Formica* workers and the *Polyergus* queen was relentless. Although neither species has a stinger, the mandibles of the workers are sufficiently formidable to pin the queen down by the legs and bite her until she dies.

Wanted: Single Queen with Workers

Because mature *Formica* nests often have many queens—unlike *Polyergus* colonies—we were also curious to see what would happen when a newly mated *Polyergus* queen invaded a polygynous nest. We established a series of *Formica* colonies that contained between two and 25 queens. Surprisingly, the number of *Formica* queens was of no consequence to the *Polyergus* queen. Because she is accepted as the royal party once she dispatches the first *Formica* queen, she is in no rush. Hour by hour, day by day, she methodically locates and kills every *Formica* queen, sometimes taking several weeks to clear out all remnants of the opposition.

Although our tests had uncovered this suite of behavioral adaptations on the part of *Polyergus* queens, we also discovered that success was not routine. Sometimes the phalanx of *Formica* workers in the queen's path was simply too powerful, and she was ripped to pieces. Perhaps, I thought, queens have another strategy. Because the mating seasons of *Polyergus* and *Formica* queens overlap, it seemed reasonable to postulate that they must, at least occasionally, encounter one another on the ground shortly after mating. Suppose a *Polyergus* queen killed a *Formica* queen in the field? Having thus acquired the relevant chemicals, the victorious *Polyergus* queen should immediately be able to enter any *Formica* colony with impunity. Without worker attacks to contend with, this queen could leisurely embark on her killing spree, eliminating any resident *Formica* queens.

Not so. When we introduced a newly mated *Polyergus* queen to a newly mated queen of *F. gnava,* the result was a nonevent. The two spent a few seconds checking each other out with their antennae, but we never witnessed a single aggressive interaction between any of the opposing queens we tested.

These results suggested that young *Formica* queens do not possess the same chemical signature found in more mature queens. To figure out when a *Formica* queen takes on the aura, or "aroma," of an established queen, we set up another experiment. Christine A. Johnson and I kept newly mated *Formica* queens in laboratory nests until they laid their eggs. Then we repeated the earlier test. Still no interest on the part of *Polyergus*. After several weeks the eggs hatched into larvae, and we conducted yet another round of tests. The *Polyergus* queens continued to ignore their *Formica* counterparts.

To unravel the mystery, it became clear that we had to start thinking like an ant. Suppose, we reasoned, a newly mated *Polyergus* queen entered a new nest and killed a *Formica* queen that was raising her first brood of eggs or larvae. The invading queen would be unable to feed herself or the brood and would soon starve. The earliest time that killing the *Formica* queen would be effective is when her brood had developed into workers eager to assist in foraging and nest maintenance.

Johnson discovered that it took almost two months from the time a *Formica* queen was inseminated to the stage when her first brood completed development. As soon as these first eight workers were functional, Johnson introduced a *Polyergus* queen that had been ruling her own nest of *Formica* workers.

Surprisingly, the *Polyergus* queen remained passive. Indeed, it took an additional five months, by which time 19 young *Formica* workers were present, before the *Polyergus* queen assaulted the *Formica* queen. Despite her previous disinterest, it was clear that the *Polyergus* queen had retained her regicidal inclination and aptitude. The *Formica* queen was killed, and the handful of newly emerged workers accepted the *Polyergus* as their new queen. We concluded that the chemistry of the *Formica* queen must change dramatically between the moment of fertilization and the time she has an established nest. But it appears that the change is a maturational one brought about by internal processes, not by merely having a brood. Elucidating the nature of this chemical transformation should prove a fruitful path for future studies.

A Dangerous Living

Having determined that invading an established *Formica* nest is the key to successful colony takeover, we were faced with one final thorny issue. Linda Goodloe, a graduate student working with the eastern species *Polyergus lucidus,* had discovered that new queens go after only the *Formica* species that they grew up with—in other words, the ones that had been enslaved by their parent queen's colony. But social parasitism requires intricate behavioral interactions between

COURTESY OF HOWARD TOPOFF (*top left and top right*); RAYMOND A. MENDEZ (*bottom*)

BATTLE ROYAL between the *Formica* queen (*top left*) and the *Polyergus* queen (*top right*) can take 30 minutes or more. Roughly the same size and often evenly matched, the queens repeatedly bite each other with their strong jaws. If the *Polyergus* queen wins, she licks the wounds of the *Formica* queen, thereby gathering the chemicals that make the *Formica* workers view her as their leader.

two species: parasite and host. Clearly, the evolution from a free-living to a parasitic way of life required that a newly mated queen occasionally invade the nest of an unfamiliar species. Although a risky business at best, a successful adoption by the foreign workers would enable the invading queen to lay many more eggs than she could possibly raise on her own. Rapid colony development, in turn, would set the stage for the debut of slave raids and the chemical imprinting necessary for the slave ants to care for their captors.

So we decided to set up a situation in which this chance happening could occur. To do so, we traveled to a habitat higher in elevation, one where *Polyergus* conducts slave raids on *Formica occulta* instead of *F. gnava*. We captured colonies of *F. occulta,* installed them in our laboratory nests and introduced a newly mated *Polyergus* queen from a colony found at the lower elevation—a colony that therefore contained *F. gnava* slaves.

As expected, attempts by *Polyergus* queens to take over colonies of *Formica* containing unfamiliar workers and queens were only partially successful. Five *Polyergus* queens showed no interest in attacking the *F. occulta* queens; three of these nonaggressive *Polyergus* queens were killed by *F. occulta* workers, and two others evaded attack by abandoning the nest. But the most significant outcome was that two of the seven *Polyergus* queens did seize and kill the foreign *Formica* queen. And when they had finished licking the dead ruler, both *Polyergus* queens were promptly adopted by the *F. occulta* workers.

What's in a Name?

In *Origin of Species,* Charles Darwin's description of *Polyergus* shows that he was keenly aware of the numerous conundrums raised by the evolution of social parasitism—one of those being the issue of what is in it for the slaves. After all, a colony of *Formica* can forfeit more than 14,000 pupae during a single raiding season. Their only evolutionary "defense" seems to be brood replacement, thanks to the *Formica* queen's enormous reproductive ability. Although defenseless *Formica* pupae are unable to thwart their capture, it is unclear why adult

Seconds after the host queen's death, the Polyergus *queen assembles the* Formica *pupae into a neat pile and stands triumphantly on top of it.*

RAYMOND A. MENDEZ

***POLYERGUS* QUEEN stands atop her booty. The future well-being of her colony lies in the *Formica* slaves that will emerge. Although there are about 200 species of ants that take slaves, the *Polyergus* situation is unusual in that the queen can act as a solitary agent.**

slaves don't abandon the *Polyergus* colony and rejoin their free-living nestmates.

The answer lies in imprinting. Newly hatched slaves view the *Polyergus* workers, brood and queen as their family. Even though they do not participate in raids on other *Formica* nests, the slaves respond aggressively to any *Formica* they meet while foraging. The imprinting process is similar to that occurring between a duckling and its mother—except that in ants the stimuli are chemical rather than visual and auditory. The fact that parasitism develops from olfactory bonds between *Formica* and *Polyergus* suggests that "slavery" is an inappropriate term for these insects. A more accurate human analogy would be adoption, because the *Polyergus* nest is the only "home" ever known by *Formica* workers.

Early experience can promote social bonds between different species of ants, but the process is not open-ended. The ability to form such interspecific attachments declines as the evolutionary relatedness of the creatures decreases. This fact explains why parasite-host relations invariably conform to the rule identified by Italian entomologist Carlo Emery: social parasites are taxonomically close to their hosts. Not surprisingly, this genetic relatedness is connected to ecological similarity—the quintessence of a successful parasite-host relationship. The *Polyergus-Formica* association works well precisely because *Formica* workers in a *Polyergus* nest need only conduct the same foraging and nest maintenance activities that they do in their own colonies. Having been reared in a *Polyergus* nest does not change *Formica*'s species-specific behaviors of foraging, feeding or fighting. (Fortunately, workers don't mate.)

Since the publication of *Origin of Species,* scientists have recognized social parasitism in insects and birds as a classic example of convergent evolution. My field and laboratory research on the most salient adaptations for parasitism by *Polyergus* reveal the depth of this convergence. In England, cuckoos parasitize four species of host, but any given individual female cuckoo specializes in one particular host species. And how does this female cuckoo select the appropriate host species? Simple: she uses the "*Polyergus* principle" of imprinting. Just as a *Polyergus* queen selects the same species of *Formica* present in her nest when she emerged, a female cuckoo opts for the host species in whose nest she hatched.

When I first heard the term "social parasitism" as a college student, it sounded like an oxymoron. After all, the term "social" denotes communication, cooperation and even altruism—all diametrically opposed to the patently selfish habits of parasites. As I learned, however, the term is appropriate because a social parasite's infiltration into the host's life is based on the same developmental and communicative processes that both parasite and host use for interacting with members of their own species. Nevertheless, 15 years of research have reinforced my empathy with Darwin as he struggled to incorporate social parasitism into his theory of natural selection. As usual, Darwin put it best: "I tried to approach the subject in a skeptical frame of mind, as any one may well be excused for doubting the existence of so extraordinary an instinct as that of making slaves." SA

The Author

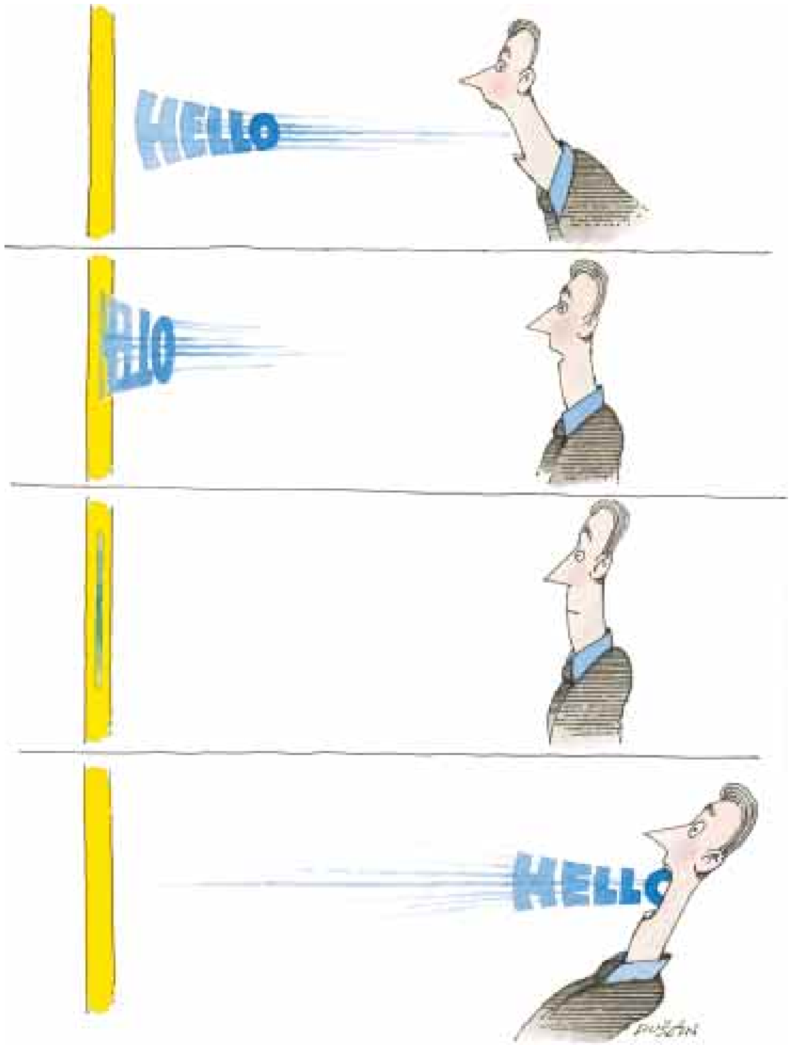
HOWARD TOPOFF became interested in social insects as an undergraduate, when he studied army ants in the department of animal behavior at the American Museum of Natural History in New York City. After receiving his Ph.D. in 1968 from a joint program of the museum and the City University of New York, he joined the museum as a curator and continued his field research on the social behavior of army ants. Though a professor in the department of psychology at Hunter College of C.U.N.Y., his research is field-oriented and based primarily at the museum's Southwestern Research Station, located in the Chiricahua Mountains of Arizona. His interest in the evolution of behavior in social insects led to his more recent studies of slave-making ants. When not teaching or "slaving" away in the field, he develops multimedia science presentations for schoolchildren, college students and the adult public. He invites questions and can most easily be reached by e-mail: HTopoff@aol.com.

Further Reading

COLONY TAKEOVER BY A SOCIALLY PARASITIC ANT, *POLYERGUS BREVICEPS:* THE ROLE OF CHEMICALS OBTAINED DURING HOST-QUEEN KILLING. Howard Topoff and Ellen Zimmerli in *Animal Behaviour,* Vol. 46, Part 3, pages 479–486; September 1993.

QUEENS OF THE SOCIALLY PARASITIC ANT *POLYERGUS* DO NOT KILL QUEENS OF *FORMICA* THAT HAVE NOT FORMED COLONIES. Howard Topoff and Ellen Zimmerli in *Journal of Insect Behavior,* Vol. 7, No. 1, pages 119–121; January 1994.

ADAPTATIONS FOR SOCIAL PARASITISM IN THE SLAVE-MAKING ANT GENUS *POLYERGUS*. Howard Topoff in *Comparative Psychology of Invertebrates*. Edited by Gary Greenberg and Ethel Tobach. Garland Publishing, 1997.



DUSAN PETRICIC

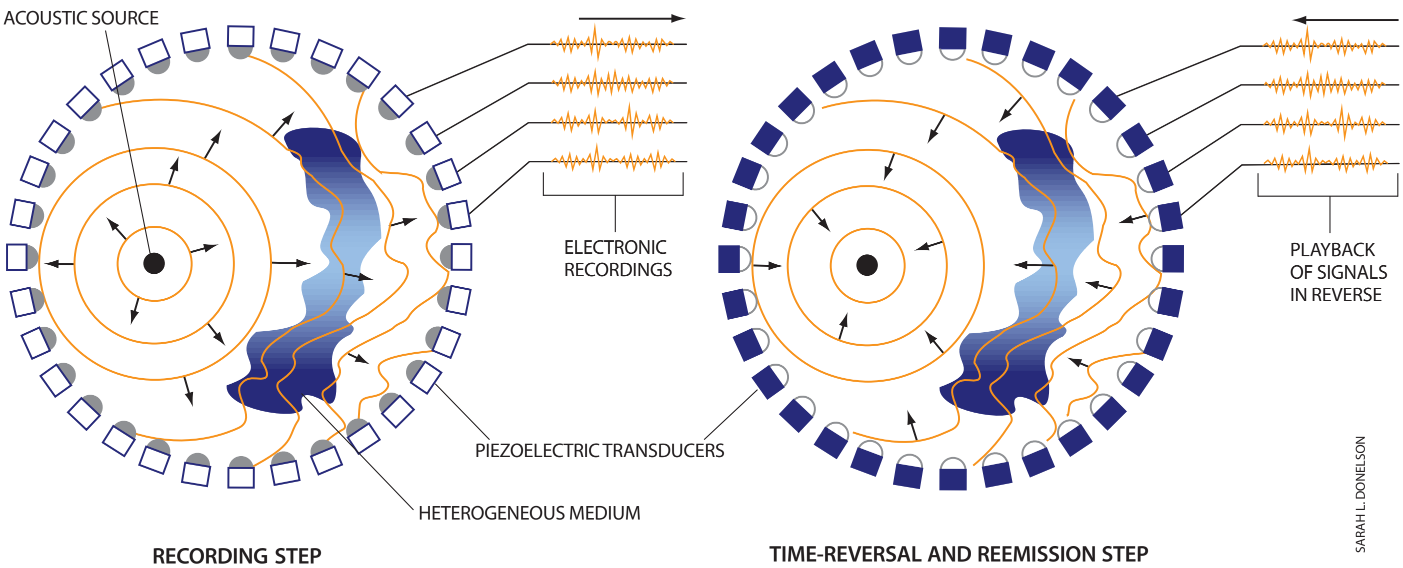
TIME-REVERSED ACOUSTICS

Arrays of transducers can re-create a sound and send it back to its source as if time had been reversed. The process can be used to destroy kidney stones, detect defects in materials and communicate with submarines

by Mathias Fink

In a room inside the Waves and Acoustics Laboratory in Paris is an array of microphones and loudspeakers. If you stand in front of this array and speak into it, anything you say comes back at you, but played in reverse. Your "hello" echoes—almost instantaneously—as "olleh." At first this may seem as ordinary as playing a tape backward, but there is a twist: the sound is projected back exactly toward its source. Instead of spreading throughout the room from the loudspeakers, the sound of the "olleh" converges onto your mouth, almost as if time itself had been reversed. Indeed, the process is known as time-reversed acoustics, and the array in front of you is acting as a "time-reversal mirror."

Such mirrors are more than just a novelty item. They have a range of applications, including destruction of tumors and kidney stones, detection of defects in metals, and long-distance communication and mine detection in the ocean.



ACOUSTIC TIME-REVERSAL MIRROR operates in two steps. In the first step (*left*) a source emits sound waves (*orange*) that propagate out, perhaps being distorted by inhomogeneities in the medium. Each transducer in the mirror array detects the sound arriving at its location and feeds the signal to a computer. In the second step (*right*), each transducer plays back its sound signal in reverse in synchrony with the other transducers. The original wave is re-created, but traveling backward, retracing its passage back through the medium, untangling its distortions and refocusing on the original source point.

They can also be used for elegant experiments in pure physics.

The magic of time-reversed acoustics is possible because sound is composed of waves. When you speak you produce vibrations in the air that travel like ripples on a pond spreading out from the point where a stone splashed in. A fundamental property of waves is that when two of them pass through the same location, they reinforce each other if their peaks and troughs correspond, and they tend to cancel each other out if the peaks of one combine with the troughs of the other. This process takes place constantly wherever sound propagates. Echoes reflect back from walls and other obstacles, mixing together different portions of the same wave. Architects of concert halls must pay careful attention to such factors so that their designs result in high-quality sound arriving in the part of the auditorium where the audience sits.

The other essential property that makes time-reversed acoustics possible is that the underlying physical processes of waves would be unchanged if time were reversed. If you play a movie of waves backward, the waves still obey the correct equations. This is also true of ordinary particle mechanics, which governs objects such as billiard balls, but except in simple cases one cannot "time-reverse" particle mechanics in practice. The problem is the phenomenon of chaos. A small change in a particle's initial position can result in a large change in its final position.

For example, consider a kind of pinball machine where a ball is fired through a fixed array of 100 randomly arranged obstacles. Even in a computer simulation the ball cannot be sent back to retrace its path in reverse: after a dozen or so collisions the ball misses an obstacle that it should have hit (or vice versa), and the subsequent path is utterly different. In a simulation, tiny truncation and round-off errors (which occur when a computer stores numbers and performs arithmetic) are enough to set the time reversal awry. And in a real-life experiment, it would be impossible to start the ball back on *exactly* the reversed trajectory, which again would totally alter the final outcome.

In contrast, wave propagation is linear. That is, a small change in the initial wave results in only a small change in the final wave. Likewise, reproducing the "final" wave, moving in reverse but with the inevitable small inaccuracies, will result in the wave propagating and re-creating the "initial" wave, also moving in reverse and having only relatively minor imperfections.

Time-Reversal Mirrors

This is how the time-reversal acoustic mirror succeeds in playing back "olleh" onto the mouth of the visitor at the lab in Paris. The final wave is the sound of the "hello" arriving at the array of microphones after traveling outward from the visitor's mouth. Each microphone detects the acoustic wave (that is, the sound) that arrives at its location and passes the ongoing signal to a computer that stores the data. When the last of the "hello" dies down, the computer reverses each microphone's signal and plays it back through the corresponding loudspeaker in exact synchrony with the other reversed signals. What emerges from the array of speakers is a close approximation to the final wave, now traveling in reverse, which propagates across the room, retracing the path of the original "hello" back to the speaker's mouth.

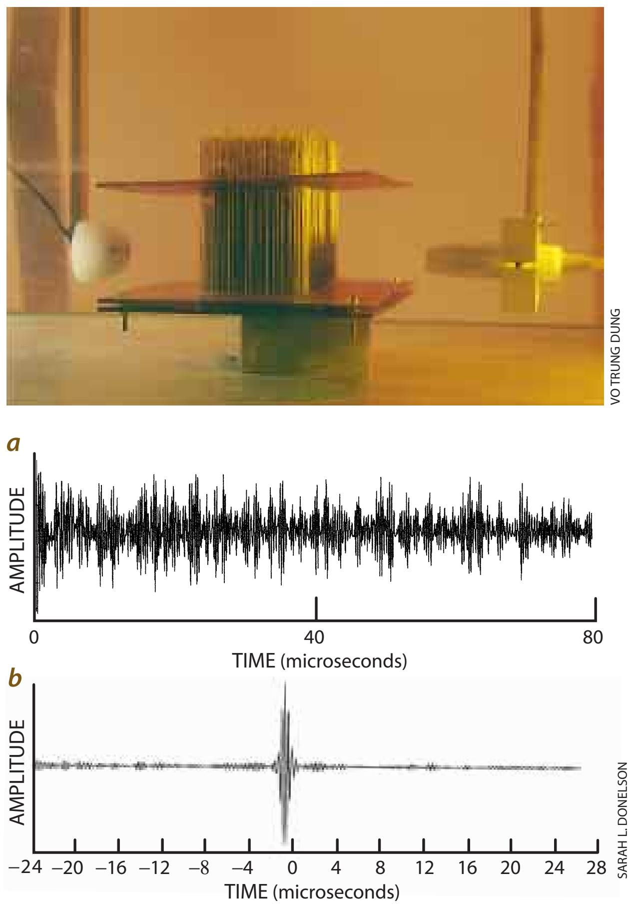
Each microphone/loudspeaker pair can be combined into a single device, such as a piezoelectric transducer, which converts sound into a voltage when the wave passes, and vibrates like a loudspeaker to produce sound when a voltage signal is applied across it [*see illustration above*].

For time-reversed acoustics to work, the sound wave must propagate without losing too much energy to heat, which consists of the random motion of individual air molecules instead of their collective movement in the sound wave. This requirement is analogous to having very little friction in a particle-mechanics experiment. For instance, reversing the trajectories of balls on a pool table is impractical because there is no way to make the balls speed up correctly in the time reverse of being slowed by friction and air resistance.

When such energy losses are small enough, the equations governing the waves guarantee that for every burst of sound that diverges from a source, there exists in theory a set of waves that would precisely retrace the path of the sound back to the source. This remains true even if the propagation medium is complicated by objects and variations in density, which reflect, scatter and refract the sound. The reversed waves would follow all these intricate pathways and converge in synchrony at the original source, as if time were going backward. In 1988 my research group built and tested such an acoustic time-reversal mirror with ultrasonic waves in weakly heterogeneous media similar to biological tissues.

You might think that the array of transducers has to have no gaps in it, so that the reversed wave will be re-created without gaps. But because of how waves diffract, gaps as large as half the wavelength will get filled in as the wave propagates. Thus, the transducers can be spaced as far apart as half the smallest wavelength without impairing the quality of the reproduction. For the same reason, however, the waves will refocus to a spot no smaller than half the smallest wavelength. Any details of the source smaller than that are lost.

In the ideal situation, the array of transducers would cover all the walls and even the floor and ceiling of the room, so that the whole final wave could be generated [*see illustration on opposite page*]. In practice it is often impossible to entirely surround the source with transducers, and the time reversal is usually performed with a limited area of transducers, which we call a time-reversal mirror (TRM). Of course, some information is lost, and as the aperture of the mirror gets smaller, the size of the focal spot gets larger. This is exactly analogous to the case in optics, where a telescope with a large mirror can achieve finer resolution than one with a small mirror. In fact, an analogue of the TRM has been studied for about 20 years in optics: phase-conjugated mirrors. Such mirrors exhibit retroreflectance—the light reflects back toward the source, wherever it is in relation to the mirror. These phase-conjugated mirrors, however, do not produce the time reverse of a varying light signal.



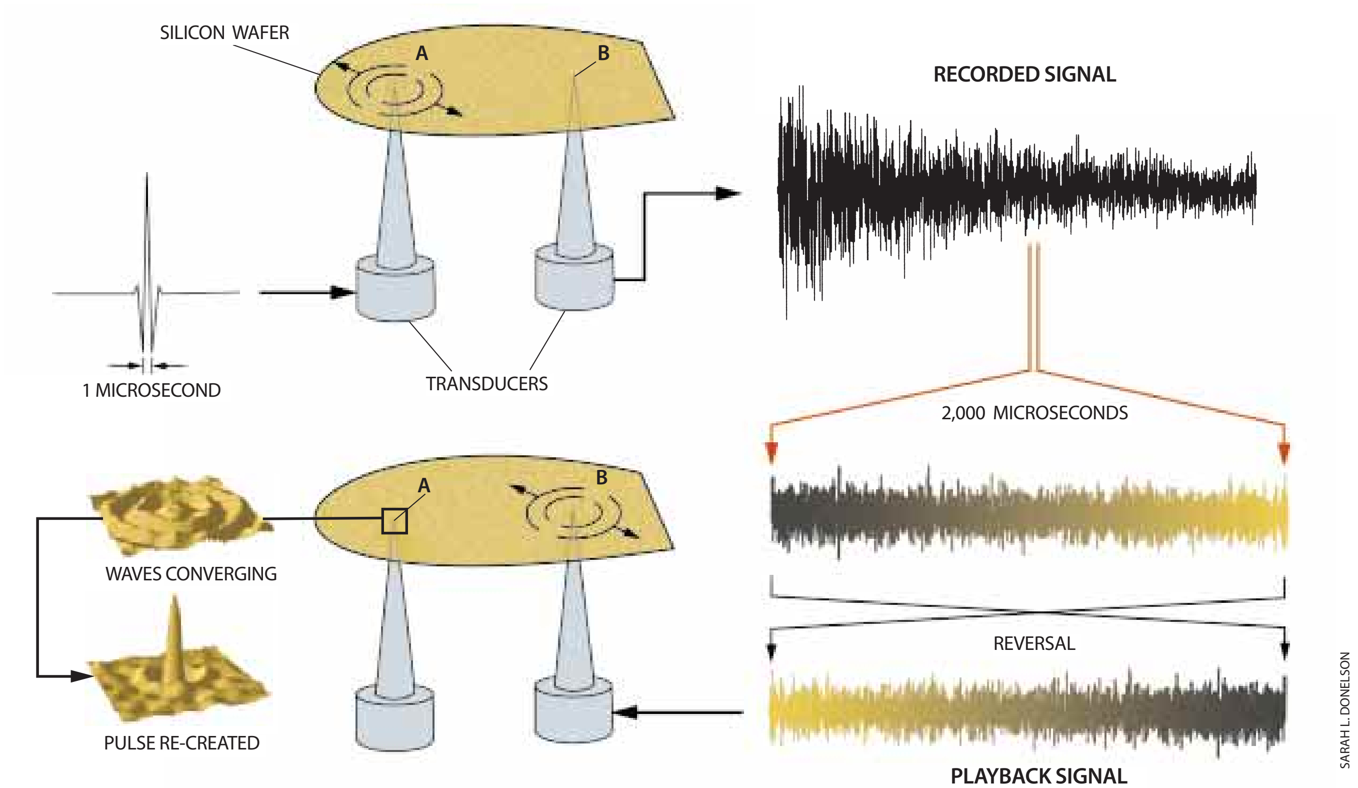
ACOUSTIC CHAOTIC PINBALL occurs when an underwater ultrasonic pulse emitted by the transducer (*at left in photograph*) ricochets among 2,000 randomly placed steel rods before reaching the 96-element time-reversing mirror at right. Each element of the array receives a chaotic-seeming sound signal (a portion of one is shown in *a*) lasting much longer than the original one-microsecond pulse. When the mirror plays back the chaotic signals, reversed and in synchrony, they ricochet back through the maze of rods and combine to re-create a well-defined pulse (*b*) at the transducer.

Chaotic Pinball

In 1994 my students Arnaud Derode and Philippe Roux and I demonstrated ultrasonic time reversal through a medium analogous to the chaotic pinball machine mentioned earlier. The results were surprising. The obstacles were made of a random set of 2,000 parallel steel rods immersed in a water tank [*see illustration at left*]. The wave started from a small transducer as a pulse lasting one microsecond (1 µs) and propagated through this "forest" of rods to a line of 96 piezoelectric transducers. This array detected an initial wavefront that was the part of the sound that threaded its way directly through the forest, followed by a long chaotic wave lasting up to 200 µs. The chaotic wave corresponded to the portions of the initial pulse scattered along all possible paths between the rods.

In the second step of the experiment, we time-reversed these signals, and a hydrophone measured the wave arriving at the source location. Even though the array played back a 200-µs signal through the chaotically scattering forest, at the source location a pulse of about 1 µs was regenerated. We also carried out both steps of the experiment in the absence of the rods. Remarkably, the time-reversed beam was focused to a spot six times smaller *with* the scattering rods than without them. This paradoxical result is explained by considering that the multiple reflections in the forest redirect toward the mirror parts of the initial wave that would otherwise miss the transducer array. After the time-reversal operation, the whole multiple-scattering medium acts somewhat like a focusing lens, making the mirror appear to have an aperture six times larger and thus improving its resolution sixfold.

The experiment also showed that the time-reversal process is surprisingly stable. The recorded signals were sampled with analog-to-digital converters that introduced quantization errors. Moreover, if the array and the rods are moved a small fraction of the wavelength (0.5 millimeter, or 0.02 inch) after doing the forward step, the time reversal



SINGLE TRANSDUCER can time-reverse a wave in an enclosed "cavity." A source transducer emits a pulse at location A on a small silicon wafer (*top*). A transducer at location B records chaotic reverberations of the pulse reflected off the wafer edges hundreds of times. The transducer at B plays back a short segment of that signal in reverse (*bottom*). After many reflections, these recombine to re-create the short pulse focused again at location A, as was revealed by imaging the waves on the wafer near A (*bottom left*).

still works—in absolute contrast to what would happen in a particle experiment. Each particle follows a well-defined trajectory, whereas waves travel along all possible trajectories, visiting all the scattering objects in all possible combinations. A small error in the initial velocity or position makes the particle miss an obstacle and utterly change its trajectory thereafter. The wave amplitude, however, is much more stable, because it results from the interference of all possible trajectories. In chaotic environments, wave physics is much more robust than particle physics, and the focusing properties of TRMs are improved.

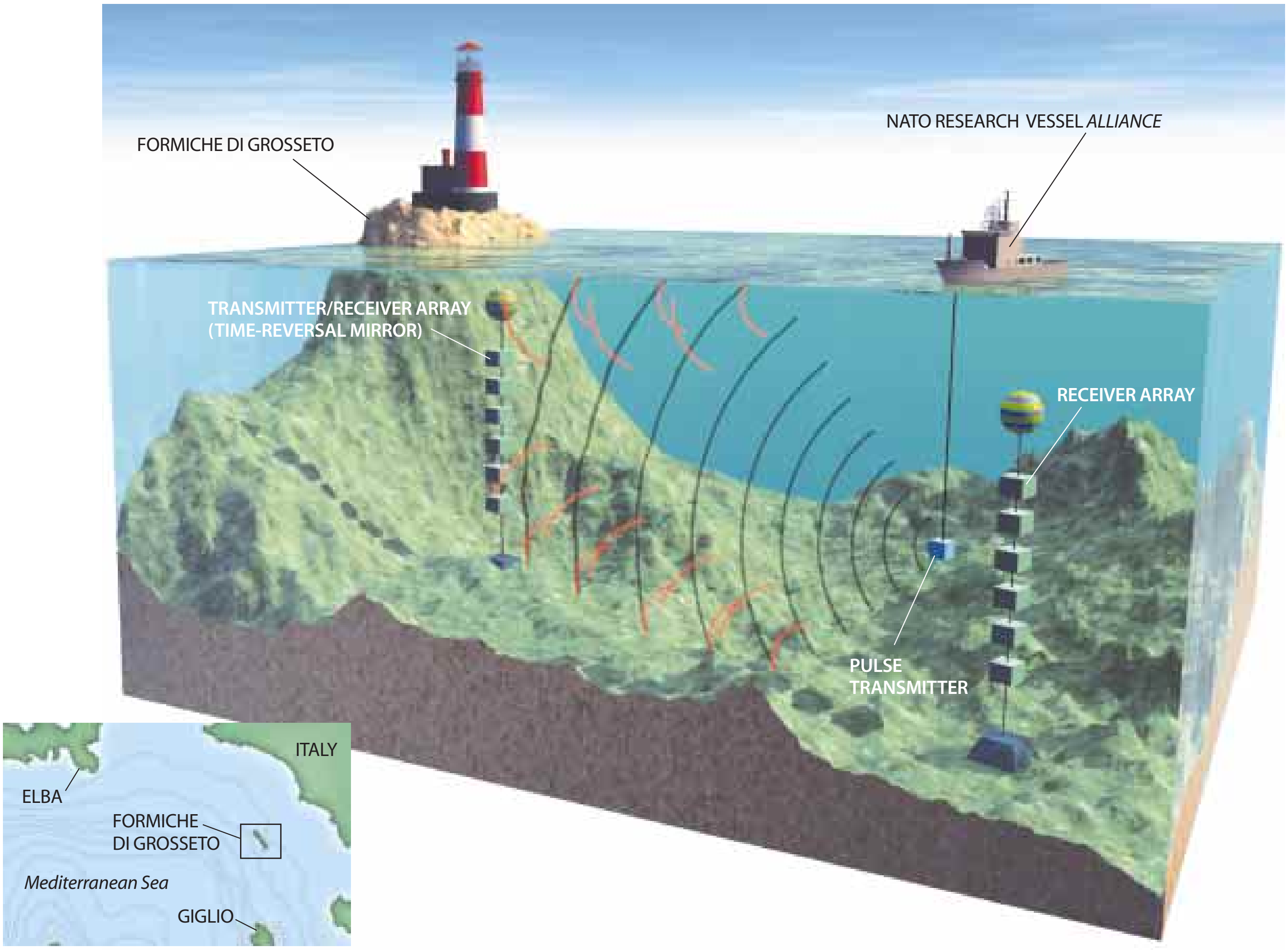
Time Reversal on a Silicon Wafer

With these ideas of focusing and robustness in mind, we wondered if the number of time-reversal transducers could be decreased to one. How can the information about a source be redirected toward a single time-reversal transducer? We decided to try enclosing the source and the transducer inside perfectly reflective walls, creating a cavity with a peculiar property called ergodicity. A frictionless billiard table shaped with curved ends like a stadium would be ergodic: a ball hit in almost any direction would eventually pass every location on the tabletop. Similarly, in an ergodic cavity all the sound rays emitted by a source will pass by the transducer if we wait long enough.

Three years ago my student Carsten Draeger and I demonstrated one-transducer time reversal using elastic waves propagating on the surface of a silicon wafer [*see illustration above*]. The source transducer at point A transmitted a circular surface wave lasting 1 µs. The time-reversal transducer at point B recorded a chaotic signal that continued for more than 50 milliseconds (50,000 times the initial pulse duration), corresponding to some 100 reflections of the initial pulse from the wafer's edge. Then a two-millisecond portion of the signal was time-reversed and reemitted by the transducer at point B. The elastic waves induced small vertical displacements of the silicon surface, which we observed by scanning the surface around point A with an optical interferometer.

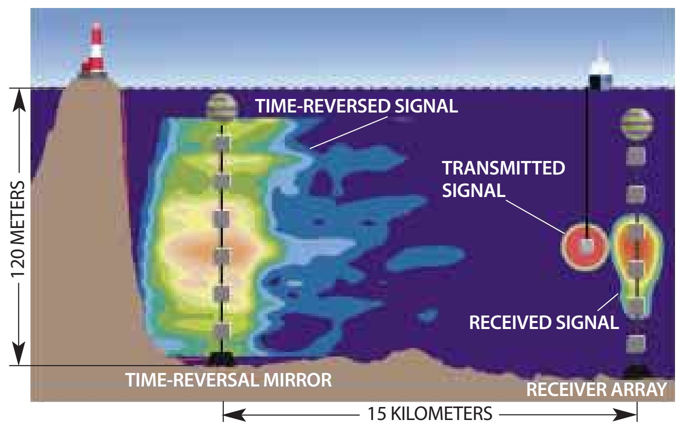
A very impressive re-creation of the original pulse occurred at point A, focused within a radius of about half the wave's wavelength with a duration on the order of a microsecond. Using reflections at the boundaries, the time-reversed wave field converged toward the origin from all directions to produce a circular spot. The two-millisecond time-reversed waveform (corresponding to nearly 2,000 complicated oscillations) is the code needed to focus exactly on point A from point B. One can imagine cryptography based on this principle, using signals from point B to generate pulses at different points in the cavity.

TRMs can also compensate for the multipath propagation that is common in ocean acoustics and that limits the capacity of underwater communications systems. The problem occurs in shallow water where sound travels as if in a waveguide, bouncing off the seabed and the ocean surface, so that a single transmitted pulse generates multiple copies of itself at the receiver, much as in the ergodic cavity. The boundaries of a sea channel are not ergodic, however, so a TRM must contain a significant number of transducers. Re-



ALFRED T. KAMAJIAN; LAURIE GRACE (*inset*)

UNDERWATER COMMUNICATIONS can be enhanced by using time-reversed acoustics to focus a signal. This technique was demonstrated in water 120 meters deep near the island of Elba off the coast of Italy. A sound pulse was sent from the target location and recorded up to 30 kilometers away by an array of transponders, distorted by refraction and multiple reflections (*red*) from the surface and the seabed. The time-reversed signal sent by the array was well focused at the target location.

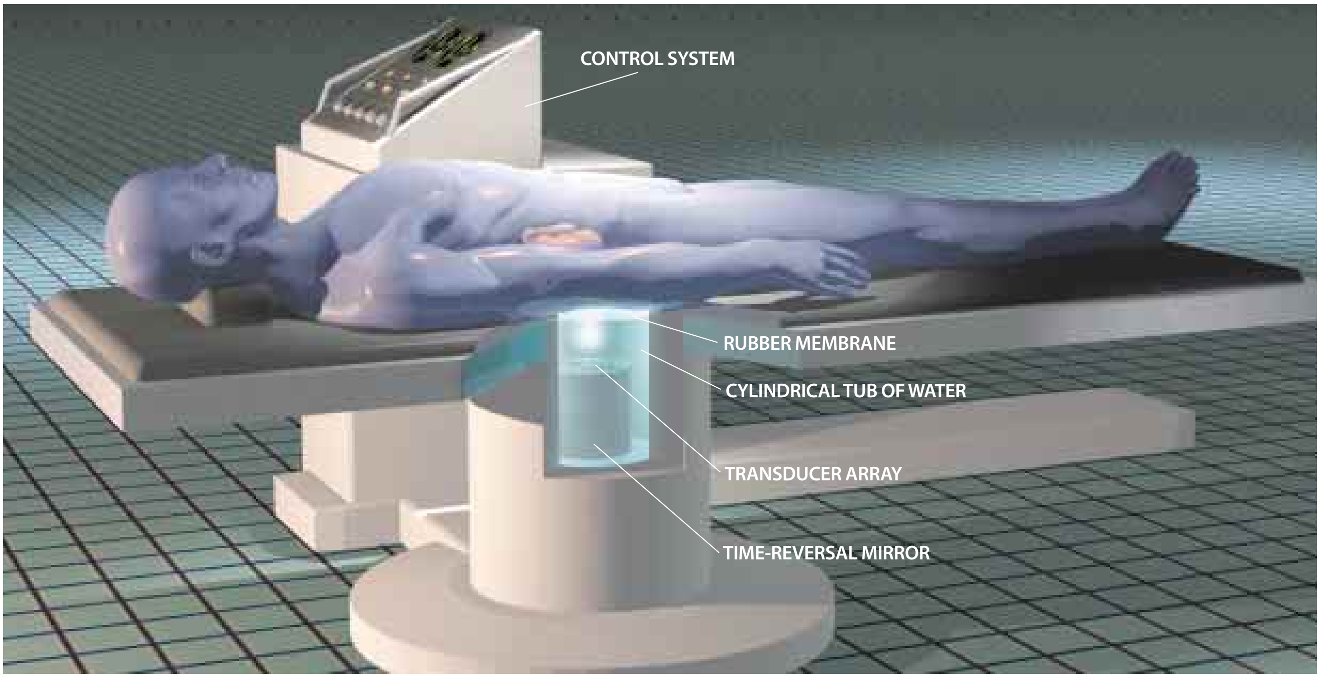


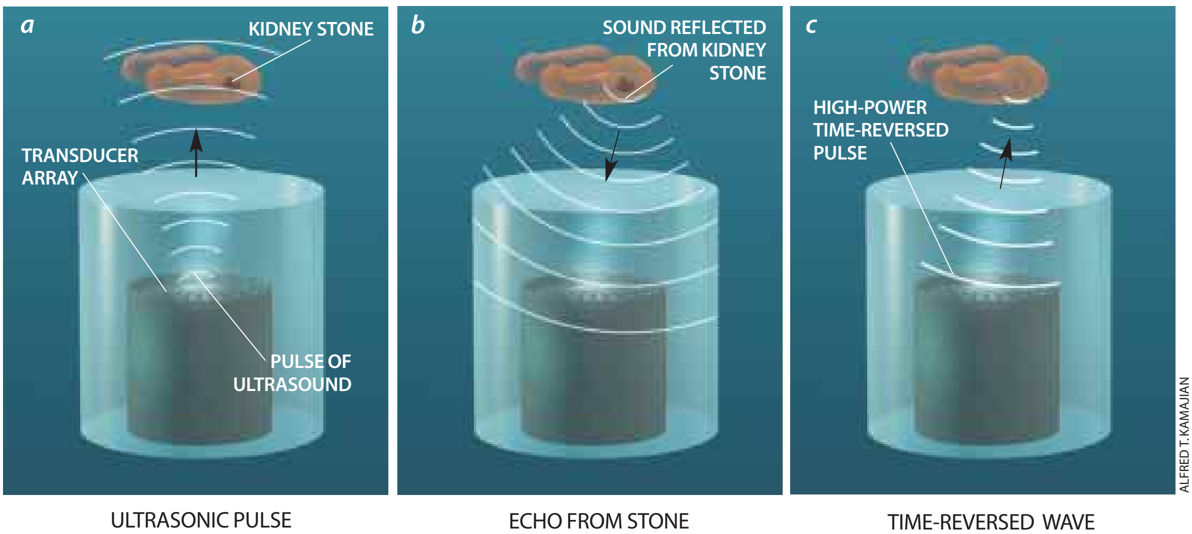
ALFRED T. KAMAJIAN; DATA FROM TUNCAY AKAL *SACLANT Undersea Research Center* AND HEECHUN SONG *Scripps Institution of Oceanography*

RESULTS from an underwater experimental run. Color contours indicate intensity of sound. The transmitted signal pulse (*red circle*) is greatly distorted at the time-reversal mirror, but when the time-reversed signal is played back (*at left*) it reproduces a focused pulse at the receiver array (*at right*).

cently researchers from the Scripps Institution of Oceanography in La Jolla, Calif., and the SACLANT Undersea Research Center in La Spezia, Italy, built and tested a 20-element TRM in the Mediterranean Sea off the coast of Italy [*see illustration above*]. Led by Tuncay Akal, William Hodgkiss and William A. Kuperman, they showed in water about 120 meters deep that their mirror could focus sound waves up to 30 kilometers away. In a result similar to the sixfold enhancement in the scattering rod experiment, the time-reversed beam was focused onto a much smaller spot than the one observed with standard beam-forming sonar. Roux and I have conducted similar studies using ultrasonic waveguides, in which multiple reflections occur. The focusing and the strong time recompression of the time-reversed wave let us create a very high power acoustic pulse that can be used for shock-wave generation.

A particularly rich field for applications of TRMs is pulse-echo detection, in which one sends out a short pulse and detects the echoes from one or more targets. The possible scenarios are diverse, ranging from medical imaging to nondestructive evaluation (inspecting materials such as industrial components for cracks and defects) to underwater acoustics (searching for mines, submarines or buried objects). The common element needed for high-quality detection is a sharp acoustic beam, and in each application the intervening medium makes it difficult to achieve this at the target location. The problem is perhaps most evident in the case of





KIDNEY STONES can be targeted and broken up with ultrasound by using the self-focusing property of a time-reversal mirror. An ultrasonic pulse emitted by one part of the array (*a*) produces a distorted echo from the stone (*b*). A powerful time-reverse of this echo passes through intervening tissues and organs, focuses back on the stone (*c*) and breaks it up. Iterating the procedure improves the focus and allows real-time tracking as the stone moves because of the patient's breathing.

medical imaging, where one wishes to send the ultrasound through fat, bone and muscle to targets such as tumors or kidney stones. Pulse-echo detection with a TRM can circumvent this problem.

Pulse-Echo Detection

First, one part of the array sends a brief pulse out through the distorting medium to illuminate the region of interest. Next, the wave that is reflected back to the array by a target is recorded, time-reversed and reemitted. The time-reversal process ensures that this reversed wave focuses on the target despite all the distortions of the medium.

When the region contains only one target, this self-focusing technique is highly effective. If there are several targets, the problem is more complicated, but a single target can be selected by repeating the procedure. Consider the simplest multitarget case, in which the medium contains two targets, one more reflective than the other. The echoes produced by the initial pulse will have a somewhat stronger component from the brighter target than from the weaker one. Therefore, the first time-reversed signal will focus a wave on each target but with a more powerful wave on the brighter target. The echoes from these waves will have an even greater bias toward the brighter target, and after a few more iterations one will have a signal that focuses primarily on that target. More complex techniques let one select the weaker reflectors.

Among the medical applications of pulse-echo TRM, the closest to fruition is the destruction of stones in kidneys and gallbladders [*see illustration on opposite page*]. Conventional ultrasonic or x-ray imaging can accurately locate such stones, but it is difficult to focus ultrasonic waves through the surrounding tissues to destroy the stones. Also, the movement of stones during breathing is hard to track. Only an estimated 30 percent of the shots reach the stone, and it takes several thousand shots to destroy one. Ultrasonic time-reversal techniques can solve these problems.

After several iterations of the pulse-echo time-reversal process, the ultrasonic beam focuses tightly on the most reflective area of a stone. Intermittent amplified pulses can then be applied to shatter the stone. This process can be repeated to track the stone in real time as it moves. Jean-Louis Thomas, François Wu and I have developed a TRM 20 centimeters in diameter for this application. The tracking procedure and in vitro stone destruction have been demonstrated in two French hospitals.

Another promising application is ultrasonic medical hyperthermia, in which high-intensity ultrasound heats up tissues. Temperatures above 60 degrees Celsius (140 degrees Fahrenheit) can destroy tissues within seconds. Devices that use conventional techniques to focus ultrasound are already on the market but only for static tissues, such as a cancerous prostate gland. Abdominal and cardiac applications are limited by the motions of breathing and heartbeat. At the University of Michigan, Emad Ebbini and his group are developing self-focusing arrays to solve this problem. My group is working on brain hyperthermia. The challenge is to focus through the skull, which severely refracts and scatters the ultrasonic beam. The porosity of the skull produces a strong dissipation—absorbing energy from the wave—and thus breaks the time-reversal symmetry of the wave equation. We have developed a new focusing technique that adds a correction of these dissipative effects to standard time-reversal. It allows us to send an ultrasonic beam through the skull and focus it on a 1.5-millimeter spot [*see illustration above*].


VO TRUNG DUNG

POROUS BONE IN THE SKULL presents an energy-sapping challenge to focusing ultrasound waves on a brain tumor to heat and destroy it. A time-reversal mirror with a modified playback algorithm can nonetheless focus ultrasound through skull bone onto a small target.

Another important application of TRMs is flaw detection in solids by nondestructive evaluation. Small defects are hard to find in an object with a complicated geometry or one made of heterogeneous or anisotropic material. Usually the sample and the ultrasonic transducers are immersed in water, but refraction can alter the beams at the water-solid interface, making it even harder to detect small defects. Furthermore, the ultrasound can produce a variety of wave polarizations and types in the solid. We have demonstrated that self-focusing techniques using TRMs can automatically compensate for these problems. In a joint program with the French National Society for the Study and Construction of Aircraft Engines, we have developed a 128-element time-reversed mirror to detect low-contrast defects in the titanium alloys used in jet engines. Titanium has a highly heterogeneous microstructure that produces a lot of scattering noise, which can hide the echo of a defect. We have shown that the iterative pulse-echo method can detect defects as small as 0.4 millimeter in 250-millimeter-diameter titanium billets and offers a better signal-to-noise ratio than the alternative techniques do.

The process of acoustic time-reversal is now readily achievable in the laboratory, and the challenge is to perfect its application in real-life clinical and industrial settings. Reversing a person's "hello" is a bit like a party trick, but the same principles that focus the "olleh" on the speaker's mouth can be used, with a little more computer processing, to generate acoustic holograms in the room. For example, the transducers can be programmed to focus the sound "hello" near one person and "*bonjour*" near another, simultaneously.

Time-reversal techniques may also be extended to types of waves other than sound waves. Some researchers in the radar community are exploring their possible application to pulsed radar, using electromagnetic waves in the microwave range. Another type of wave occurs in quantum mechanics: the quantum wavefunctions that describe all matter. Indeed, a type of retroreflection can occur when an electron wavefunction hits the boundary between a normal conductor and a superconductor. One can only speculate on what kinds of tricks would be possible if time reversal were applied to the waves of quantum mechanics. SA

The Author

MATHIAS FINK developed acoustic time-reversal mirrors at École Supérieure de Physique et de Chimie Industrielles de la Ville de Paris. He is director of the Waves and Acoustics Laboratory and professor of physics at Denis Diderot University (University of Paris VII). He received his Ph.D. in solid-state physics and his *doctorat d'état* in ultrasonic medical imaging from the University of Paris. He is a member of the Institut Universitaire de France.

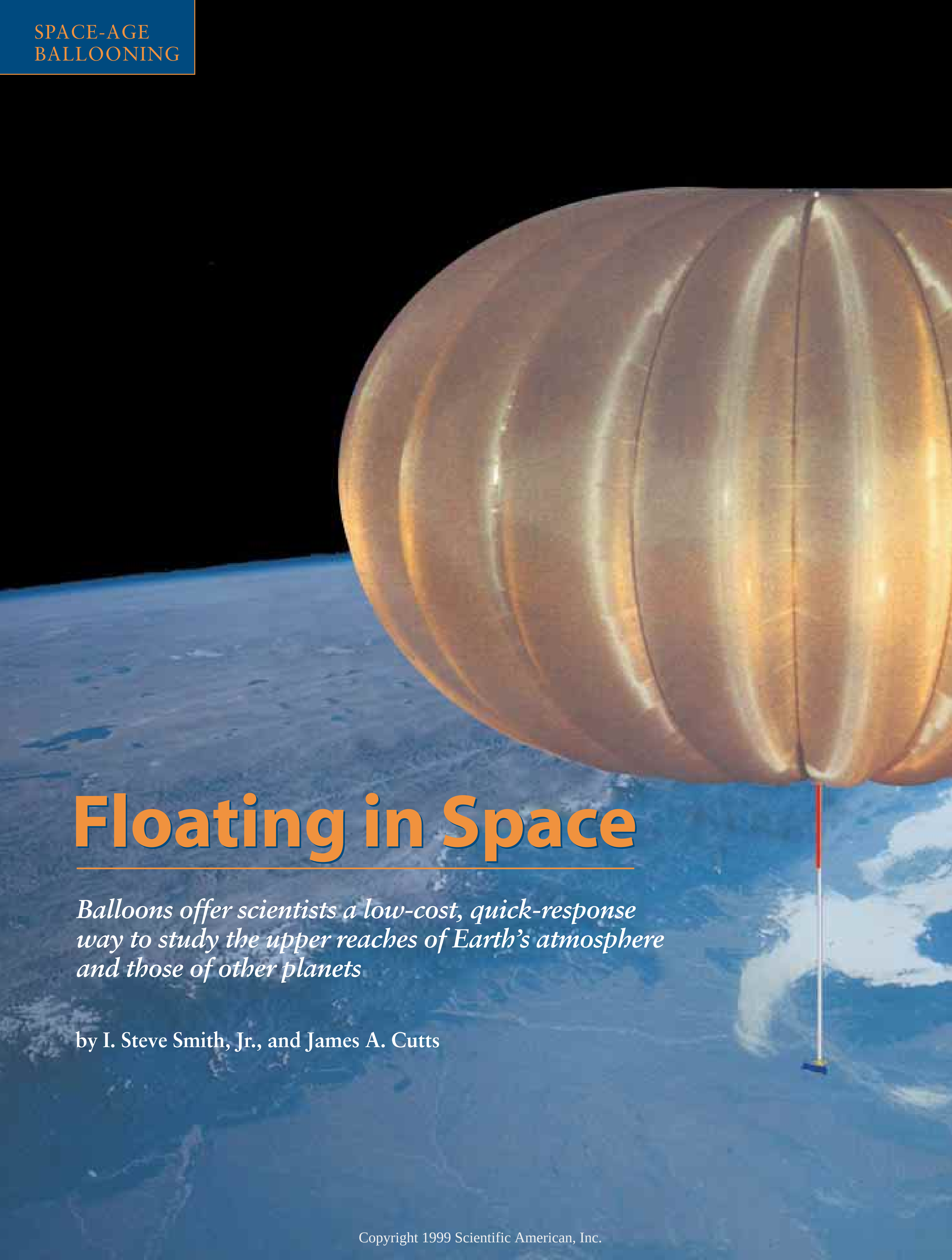
Further Reading

ULTRASONIC FOCUSING WITH TIME-REVERSAL MIRRORS. M. Fink and C. Prada. Advances in Acoustic Microscopy Series. Edited by A. Briggs and W. Arnold. Plenum Press, 1996.

TIME-REVERSED ACOUSTICS. M. Fink in *Physics Today,* Vol. 50, No. 3, pages 34–40; March 1997.

PHASE CONJUGATION IN THE OCEAN: EXPERIMENTAL DEMONSTRATION OF AN ACOUSTIC TIME-REVERSAL MIRROR. W. A. Kuperman, W. Hodgkiss, H. C. Song, T. Akal, C. Ferla and D. R. Jackson in *Journal of the Acoustical Society of America,* Vol. 102, No. 6, pages 1–16; December 1997.

ULTRASOUND PUTS MATERIALS TO THE TEST. M. Fink in *Physics World,* Vol. 11, No. 2, pages 41–45; February 1998.



Floating in Space

Balloons offer scientists a low-cost, quick-response way to study the upper reaches of Earth's atmosphere and those of other planets

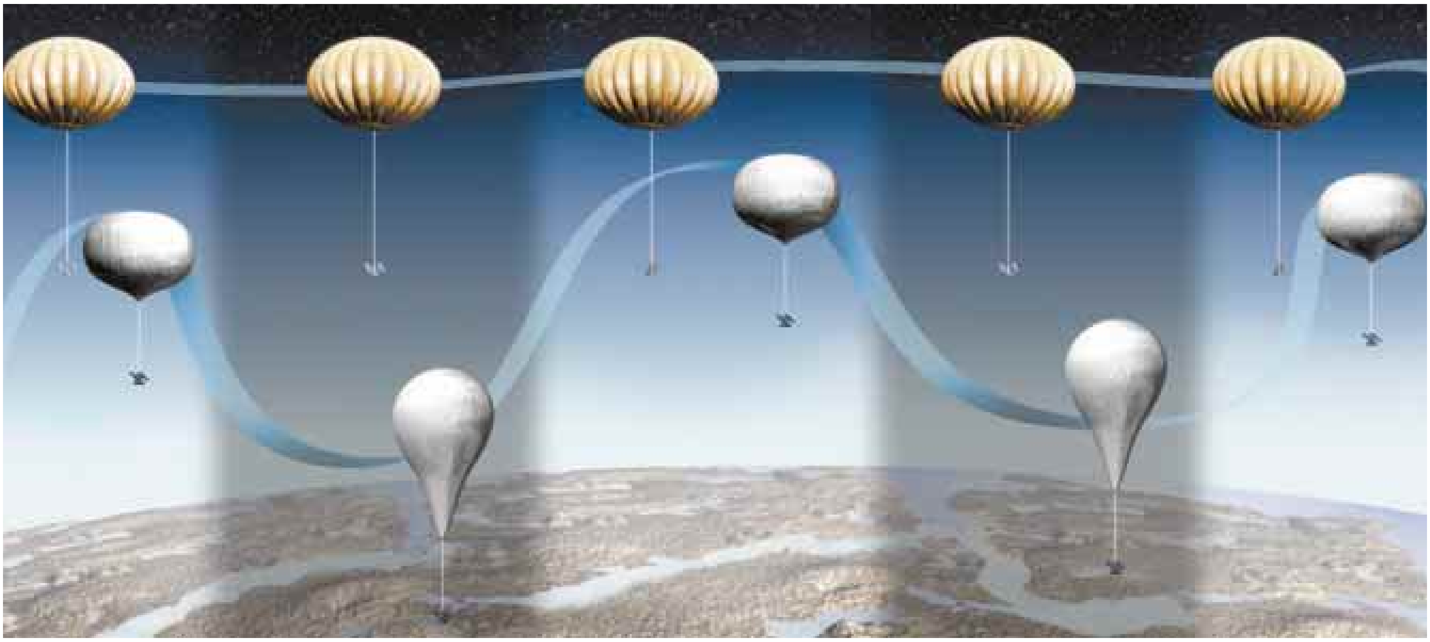
by I. Steve Smith, Jr., and James A. Cutts

Rejecting the idea that an old dog can't be taught new tricks, scientists and engineers at the National Aeronautics and Space Administration are revolutionizing the size, shape, durability and stamina—indeed, just about everything—of the balloon, humankind's oldest flight vehicle. Although balloons have been flying for more than 200 years and scientists have long used them for a variety of research missions, the length of time balloons can stay aloft has always constrained their efforts. Now, thanks to greatly enhanced computer technologies, high-tech materials and advanced designs, longer-range balloons are poised to open a new frontier for high-altitude research and even space exploration. Guided by a "better, faster, cheaper" philosophy in an era of shrinking budgets, NASA is encouraging scientists and engineers to become more innovative in their work on scientific ballooning.

Researchers today are focusing on the uppermost regions of Earth's atmosphere, designing balloons that can stay aloft for as many as 100 days. In December 2001 a huge, pumpkin-shaped balloon being developed by the NASA Goddard Space Flight Center in Maryland will take off from somewhere in either Australia or New Zealand and float to the outer edges of Earth's atmosphere—four times higher than passenger jets can fly—where it will stay for several months. Because the balloon is linked via global satellite to the Internet through a ground station, scientists back on Earth will have access to data from its instruments, including the Trans-Iron Galactic Element Recorder (TIGER), which measures the amounts of elements in galactic cosmic rays.

The Ultra Long Duration Balloon (ULDB) project will also carry the hopes of many scientists who see balloon technology as an economical means of studying the upper atmosphere and outer space. Balloons can be flown for a small fraction of the cost of rockets, and their instruments can be retrieved, tweaked and flown again. Scientific balloons have attained heights of 52 kilometers (32.3 miles) and carried payloads of

ULTRA LONG DURATION BALLOON, floating in the upper reaches of the stratosphere for up to 100 days, will allow scientists to view the universe and its contents at far less cost than spacecraft.



SUPER-PRESSURE BALLOON (*orange*) is made of strong fabric that can maintain a pressure difference between the inside and the outside. As a result, the balloon maintains a constant volume and, by Archimedes' principle, stays at the same altitude. Older, zero-pressure balloons expand during daytime because of heating by the sun and shrink at night; therefore they constantly change altitude. Altitude is controlled by dropping ballast, and so the life of these balloons is limited by the amount of ballast they carry.

up to 3,600 kilograms. With the ability to attain the limits of the stratosphere, where atmospheric interference is virtually nil, the ULDB may one day carry a high-powered telescope that rivals the Hubble Space Telescope in its ability to see the universe—a telescope far too large to transport on a rocket.

Balloons transported by rocket can also take science beyond the terrestrial atmosphere to those of other planets and their moons. Planetary scientists who hope to use balloons for their research are interested in areas such as atmospheric chemistry and dynamics, paleomagnetic mapping, geologic reconnaissance and ultrahigh-resolution imagery.

Floating above Earth

Archimedes first discovered, in 240 B.C., the principle of buoyancy or flotation that enables balloons to fly, but another 2,000 years passed before it was put to practical use in the late 1700s. Scientific ballooning began in the late 1800s, when the new technology was employed to measure temperature and moisture in early attempts at understanding the atmosphere. Balloons were first introduced for military purposes during the American Civil War, as observation platforms for watching troop movements. In the late 1940s and early 1950s, a U.S. Navy project involving the use of polyethylene ushered in the era of modern ballooning, allowing the craft to reach the stratosphere, 15 to 50 kilometers (9.4 to 31.3 miles) high, carry greater weight and stay aloft longer. Manned balloon missions helped the manned U.S. space program by testing space suits and assessing human reactions to a near-space environment. In 1960 a NASA rocket launched the first balloon experimental communications satellite, Echo I, which orbited Earth for nearly eight years at an altitude of approximately 1,600 kilometers. Twenty-five years later an international team led by the Soviet Union and involving France and the U.S. built and successfully flew two balloons in the clouds of Venus just 54 kilometers above its surface.

Aside from their limited cargo capacity (only the space shuttle can carry as much as larger balloons), spacecraft have the added disadvantage that it takes years to prepare their sensors for flight. In 1987 balloon-borne sensors observed Supernova 1987A—the kind of galactic stellar explosion that comes along once every 400 years or so—within three months of its discovery. For this reason, many of the instruments flown on modern spacecraft are based on technologies first flown and demonstrated on balloon missions.

Today's scientific balloons are usually one of two types: zero-pressure and super-pressure. Most NASA balloons are the former variety. A zero-pressure balloon leaves the ground when it is filled with enough helium to offset its total weight, including payload. For the balloon to rise, helium must provide "free lift"—a ballooning term meaning a lift force greater than the weight of the balloon and payload combined. (The lift is determined by Archimedes' principle, which states that an object immersed in a fluid experiences a buoyant force that is equal in magnitude to the force of gravity on the displaced fluid.) As the balloon rises, atmospheric density decreases and the volume of gas inside expands until the balloon's envelope is completely filled. The pressure inside and outside the balloon's envelope is then the same (hence, zero-pressure), but the balloon floats because its weight is less than that of the displaced air. Once the desired altitude of 36 to 40 kilometers is reached, usually in two to three hours, ducts at the base of the balloon vent excess gas to keep it stable and prevent rupturing of the thin polyethylene envelope. Because the balloon releases some of its gas to the atmosphere, this zero-pressure design is said to be "open" to the atmosphere.

During the day, gas is vented as the sun heats the balloon; as night approaches and solar heating abates, the gas cools, the volume of the balloon contracts, and it starts to descend. To maintain altitude, ballast—usually amounting to between 7 and 10 percent of total system mass—is dropped. The next day the process of solar heating and cooling is repeated, so the number of days an open balloon can stay aloft is limited by the amount of ballast it can carry.

Because typical scientific balloon flights last only one or two days, numerous flights are often required to finish experiments. One way to "cheat" is to fly balloons near the polar regions in virtually perpetual daylight or darkness. NASA conducts a limited number of flights from Fairbanks, Alaska, and McMurdo Station in Antarctica, where the constant daylight during the summer allows balloons to stay aloft for two to three weeks.

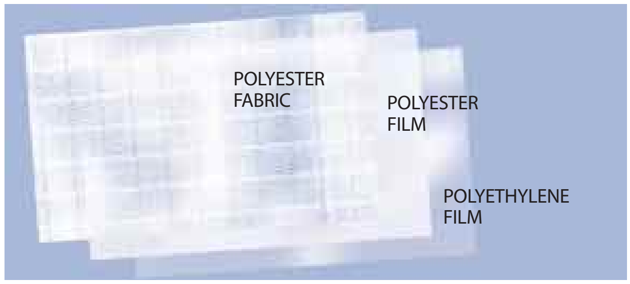
Once a balloon experiment has been completed, a radio command separates the balloon from the payload, which parachutes back to Earth to be recovered and, often, used again. The balloon also falls to Earth and is discarded.

Staying Aloft Longer

For balloon flights of significant duration and for interplanetary balloons, researchers need far different—and vastly improved—capabilities. The goal of the Ultra Long Duration Balloon project, initiated in 1997 by the NASA Office of Space Science and managed by the Goddard Space Flight Center Wallops Flight Facility, is to create a balloon that can fly for up to 100 days above 99 percent of Earth's atmosphere. The ULDB is a super-pressure, or "closed," balloon, which is not vented to the atmosphere like conventional balloons. Usually fabricated from stronger materials such as polyester, super-pressure balloons are inflated like their zero-pressure counterparts and then sealed. Once a super-pressure balloon reaches the desired altitude, the sun's heat forces the internal pressure to rise until it exceeds the outside ambient pressure. As a result, the differential pressure between the inside and outside increases. At night, when the gas cools, the differential pressure drops, but if enough gas has been put into the balloon the differential cannot drop below zero. In this way, the balloon remains full and at a stable altitude without having to drop ballast. So long as the balloon remains impervious to helium or hydrogen molecules, it can stay aloft. Accordingly, super-pressure balloons can be used for flights of far greater duration than zero-pressure systems.

Because long flights require balloons to fly in the most extreme environmental conditions—over oceans, deserts or polar ice caps—the material used to make them must be both strong and adaptable. It must resist fractures, tears and pinholes, withstand ultraviolet degradation and allow for manufacture at low cost. Small, spherical super-pressure balloons made of polyester film have been flown for up to several hundred days at low altitudes. Balloon scientists tried in the 1970s to make these balloons larger and capable of carrying bigger payloads to higher altitudes, but problems with the polyester films, including very low resistance to tears, kept scientists from significantly advancing the super-pressure concept.

For the ULDB project, officials decided that a composite possessing the desirable properties of diverse materials was the best bet for flights of many months. Many different substances, including films, woven and nonwoven fabrics, scrims, polyester, polyethylene, nylon, polypropylene and polyurethane, as well as composites of these, were evaluated. The composite finally chosen involves three layers: a 30-denier, high-tenacity polyester fabric made in Japan; a polyester film; and a polyethylene film. The polyester film is the primary barrier to the helium; the polyester fabric provides much of the composite's strength, whereas the polyethylene contains the gas, resists pinholes and yields additional toughness. Both the polyester fabric and film have some ability to withstand damage by ultraviolet rays. The three ingredients are bonded together by a soft adhesive that allows for some realignment of fabric fibers to compensate for weave defects and changing conditions. The end result is a material with a density of 55 grams per square meter and a yield strength of 2,600 newtons per meter.



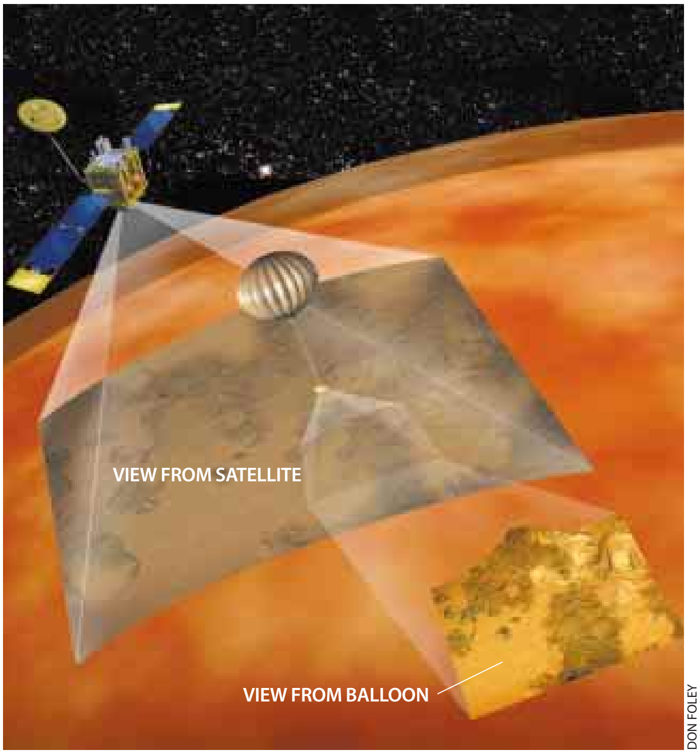
JANA BRENNING

COURTESY OF RAVEN INDUSTRIES, INC.

COMPOSITE FABRIC for the Ultra Long Duration Balloon, to be launched in December 2001, consists of three bonded layers (*top*). A polyester fabric provides strength; a polyester film prevents helium molecules from leaking out; and a polyethylene film further contains the gas and provides added toughness. The photograph (*bottom*) shows the final seam being made in a smaller model of the balloon, slated to fly this year.

Despite the composite's increased strength, engineers decided a new material alone was not enough for flights of long duration in extreme and varying conditions. A new design was also needed. Building on balloon projects in the U.S., France and Japan, ULDB officials chose a pumpkin-shaped design over the typical spherical design of most super-pressure balloons. Spherical balloons suffer from stresses along both the meridian and the circumference because the balloon envelope carries most of the load. A pumpkin-shaped balloon relies more on the meridional "tendons" that bind sections of material (called gores) together. The pumpkin shape reduces material strength requirements to only 600 newtons per meter, well below the yield strength of the composite. This fact is significant because the stress along the circumference is the product of the local pressure and the local radius caused by the pumpkin's lobes. As a result, the size of the balloon plays no role in determining the stress in the balloon envelope. (The improved design has in turn inspired engineers to search for a lighter version of the material, which will allow a heavier scientific payload to be lofted.)

When the balloon takes off in December 2001, the TIGER payload it carries will measure the elemental abundances of galactic cosmic rays with atomic numbers between 26 (iron) and 40 (zirconium) and with energies exceeding 300 million



CAMERA ON A BALLOON can view objects on a planet's surface—in this drawing, Mars—up to 10,000 times closer than can a camera on an orbital spacecraft, allowing for greater detail.

electron volts per nucleon. This is not the first time balloons have helped researchers study cosmic rays. In fact, cosmic rays and astrophysical gamma rays—as well as the stratosphere itself—were discovered by balloon-borne sensors. The rays are of great interest to some scientists because they offer a sample of galactic matter either freshly synthesized in supernovae or originating in the interstellar medium.

The TIGER mission is just the beginning. Scientists have proposed building on the effort with optical and infrared telescopes that will search for extrasolar planets or image the sun and other stars; with hard x-ray, gamma-ray, cosmic-ray and cosmic microwave background telescopes for looking at the universe; and with stratospheric chemistry experiments.

Ballooning the Planets

What scientists learn from projects such as the ULDB may one day be put to use in the exploration of other worlds. Six planets—Mars, Venus, Jupiter, Saturn, Uranus and Neptune—and Titan, one of Saturn's nine moons, have atmospheres that can support balloon flights. But each atmosphere presents challenges different from those on Earth. Space researchers hope balloons can provide low-cost platforms for exploring the composition and circulation of those atmospheres, as well as for observing planetary surfaces using remote sensors. A balloon can also be used as a platform for launching exploratory drones, including ones that retrieve samples from a planet's surface. These samples could be returned to Earth for detailed analysis.

Mars's atmosphere provides perhaps the earliest opportunity for applying recent developments in balloon technology. Because the atmospheric density at Martian sea level is about what it is at Earth's stratosphere, a balloon operating globally only a few kilometers above the surface of Mars must be, like the ULDB, a stratospheric, super-pressure balloon, which can remain aloft for months.

What could a balloon floating above Mars provide that other platforms, including orbiting satellites, landers and rovers (like the Mars Pathfinder), cannot? A surface-based rover can reach a small portion of a planet's surface, but a balloon can travel much farther and observe much more. And although balloons cannot carry instruments with the global reach of satellite sensors, they can provide far better images of a planet's surface and allow for observations of critical factors such as remanent magnetism and subsurface water.

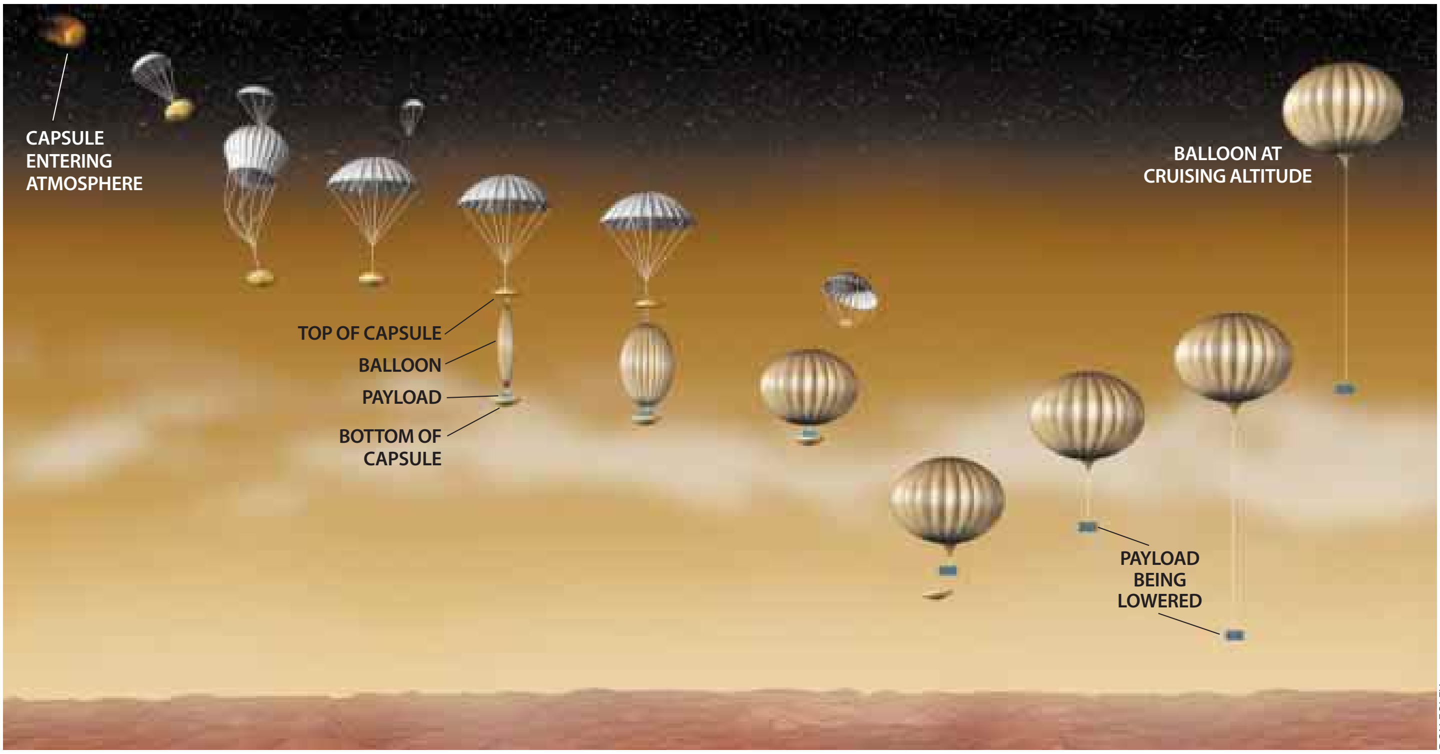
In the late 1980s France and Russia collaborated on the Mars aerostat mission, an ambitious attempt to deploy a balloon that would carry an imaging system and drop a guide rope to drag along the planet's surface, acquiring chemical samples and taking physical measurements. The project was canceled in 1995 because of Russia's financial problems. Two years later, though, NASA began work on key technologies needed for a much smaller Mars balloon or aerobot—a robotic aerostat—based on work conducted by CNES, the French space agency. This project has yielded a low-mass aerial inflation system, which began a series of stratospheric tests this past spring.

Venus, with a hotter, thicker atmosphere than Earth's, has already been explored by balloon. In 1985 the Soviet Union, in collaboration with France and the U.S., deployed two balloons 54 kilometers above the planet's surface, where they operated for approximately 48 hours; both traveled halfway around the planet. Using instruments on these craft, scientists were able to confirm strong high-altitude winds above Venus and to gauge atmospheric temperature and pressure. NASA coordinated a system of global tracking stations to measure the position and speed of the two balloons.

Because of its thick atmosphere, Venus can be viewed from space only with radio and certain infrared wavelengths, whereas the planet's surface temperatures and atmospheric densities are too high for rovers or landers to operate for more than a few hours. Consequently, one option for scientists interested in exploring the surface of Venus may be the balloon. The concept, called the Venus Aerobot Multisonde, envisages a balloon floating in the upper reaches of the planet's atmosphere and sending several small probes, called sondes, to the surface; there they would obtain high-resolution images and spectroscopic data that would help unravel Venus's evolution. This concept is feasible even with today's technology. A more ambitious mission, a "reversible-fluid" aerobot, could make short, repeated excursions from the cool upper atmosphere to the surface of Venus, where the temperature is 460 degrees Celsius (860 degrees Fahrenheit). After retrieving samples, the aerobot would return to the upper atmosphere to allow its instruments and electronics to cool. Some of the essential capabilities for such a mission—such as a miniature gondola that can tolerate high surface temperatures and sulfuric acid clouds—have already been developed by NASA.

Two teams, one at NASA and one at the European Space Agency, are studying a mission to bring a sample of Venus's surface back to Earth. They agree that high-temperature balloons will play a key role in such a project. The balloons could be used to lift rocks and soil to an altitude of approximately 60 kilometers, where the planet's atmosphere is thin enough for them then to launch rockets toward other spacecraft that would retrieve the contents and return to Earth.

Titan is a primary target for space exploration missions be-



DEPLOYMENT on a distant planet requires a balloon to be ejected from a spacecraft. The balloon is packaged in a capsule able to withstand a high-velocity entry into the atmosphere. It opens and inflates during a parachute descent toward the surface and then rises to its cruising altitude. Balloons of the future will carry probes that will retrieve samples from a planet's surface.

cause it may still preserve prebiotic organic chemicals found nowhere else in the solar system. Photochemical reactions in the atmosphere generate an orange haze of organic materials that obscured the moon's surface when the Voyager spacecraft flew by in the 1980s. Titan is thought to have large seas of hydrocarbons as well as solid surface areas. Its atmosphere is composed primarily of nitrogen and is four times as dense as Earth's, but much colder—just warm enough to prevent it from liquefying. Here, too, balloons may be ideal platforms for exploration. Titan aerobots could make multiple descents to the surface to take close-up images and even to conduct in situ measurements of prebiotic chemicals—which scientists think could hold answers to questions surrounding the origins of life. Someday a balloon mission could help a Titan ascent vehicle send samples from its surface to Earth.

Before balloons can be deployed for many of the space exploration missions envisioned today, a number of challenges, including some unique to the different planets, must be overcome. New balloon materials, so crucial to the development of the ULDB, are even more important for planetary research missions. Stronger fabrics mean lighter weight, which will allow for more payload. The envelopes will also have to withstand severe environments, such as the Venusian atmosphere, which features high temperatures and sulfuric acid clouds. Scientific instruments carried by balloons must be further shrunk. And scientists will also have to figure out how to manage balloon flights by expending minimal energy.

Another challenge involves the means by which balloons are delivered to distant planets. On Earth, balloons rise from the ground; in space, the process is reversed. Spacecraft deliver balloons packaged in capsules designed to withstand the stress of entering the atmosphere. The balloons are then opened and inflated during descent toward the planet's surface. Accordingly, NASA is developing simple, lightweight deployment and inflation systems for space missions.

No matter where they fly, balloons offer tremendous advantages for the scientists who use them. With the availability of money being so important to the future of space exploration, those who use the least may get ahead faster. In many cases, balloons can provide far greater return on investment than spacecraft, a major reason why scientists are lining up to take humankind's first means of flight to new heights. SA

The Authors

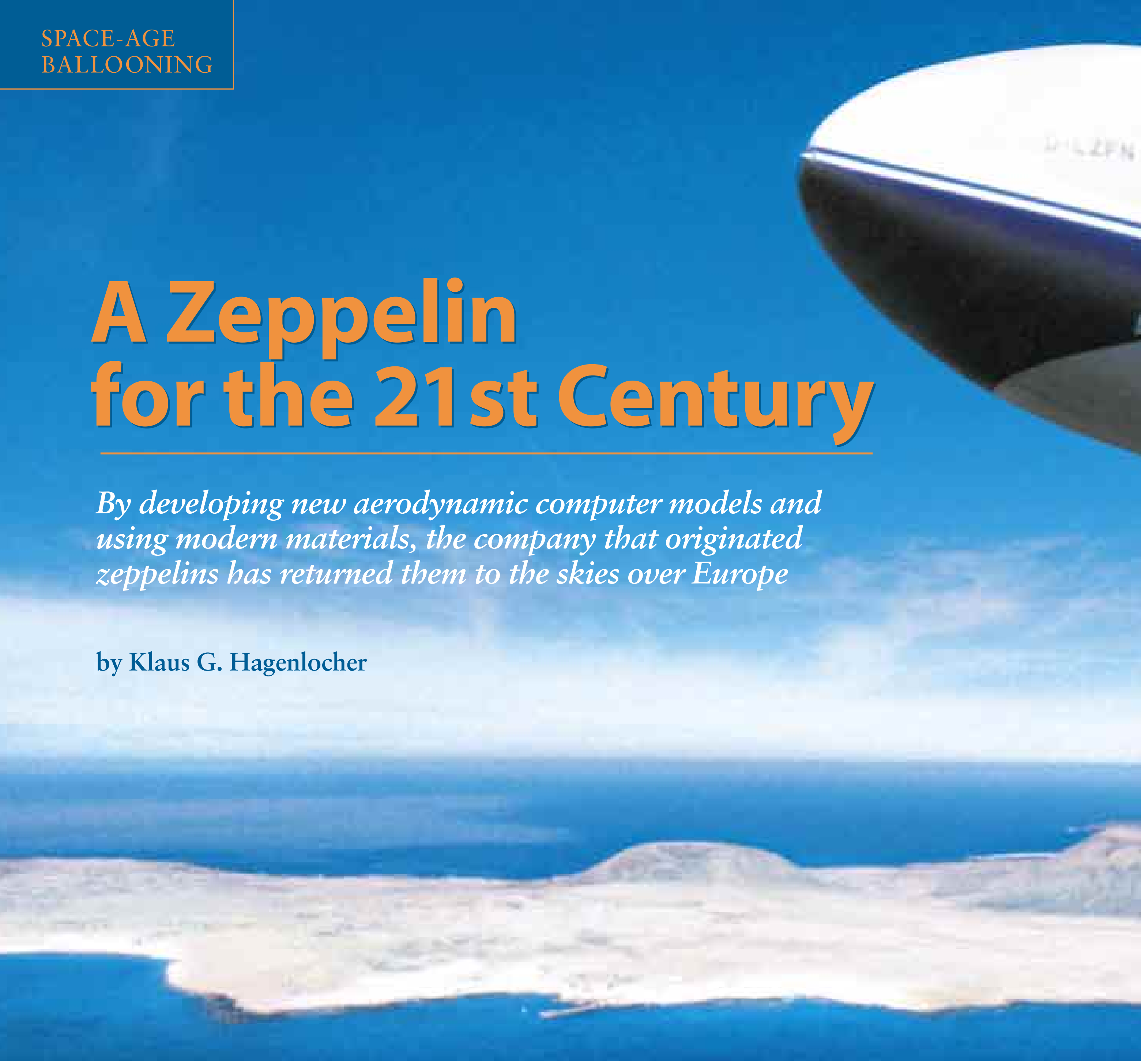
I. STEVE SMITH, JR., and JAMES A. CUTTS have collaborated on extraterrestrial balloon technologies for several years. Smith, the Ultra Long Duration Balloon project manager for the NASA Goddard Space Flight Center, studied aerospace engineering at Texas A&M University and has worked on balloon design concepts for a quarter-century. Cutts studied physics, geophysics and planetary science at the University of Cambridge and at the California Institute of Technology; he later participated in the Mariner 6, 7 and 9 and Viking Orbiter Mars missions. Until recently manager of the special projects office at the Jet Propulsion Laboratory in Pasadena, Calif., Cutts is now with the Mars Exploration Office.

Further Reading

The Eagle Aloft: Two Centuries of the Balloon in America. Tom D. Crouch. Smithsonian Institution Press, 1983.

Race to the Stratosphere: Manned Scientific Ballooning in America. David H. DeVorkin. Springer-Verlag, 1989.

For more on the Ultra Long Duration Balloon project, visit the NASA site at www.wff.nasa.gov/~uldb/ on the World Wide Web.



A Zeppelin for the 21st Century

By developing new aerodynamic computer models and using modern materials, the company that originated zeppelins has returned them to the skies over Europe

by Klaus G. Hagenlocher

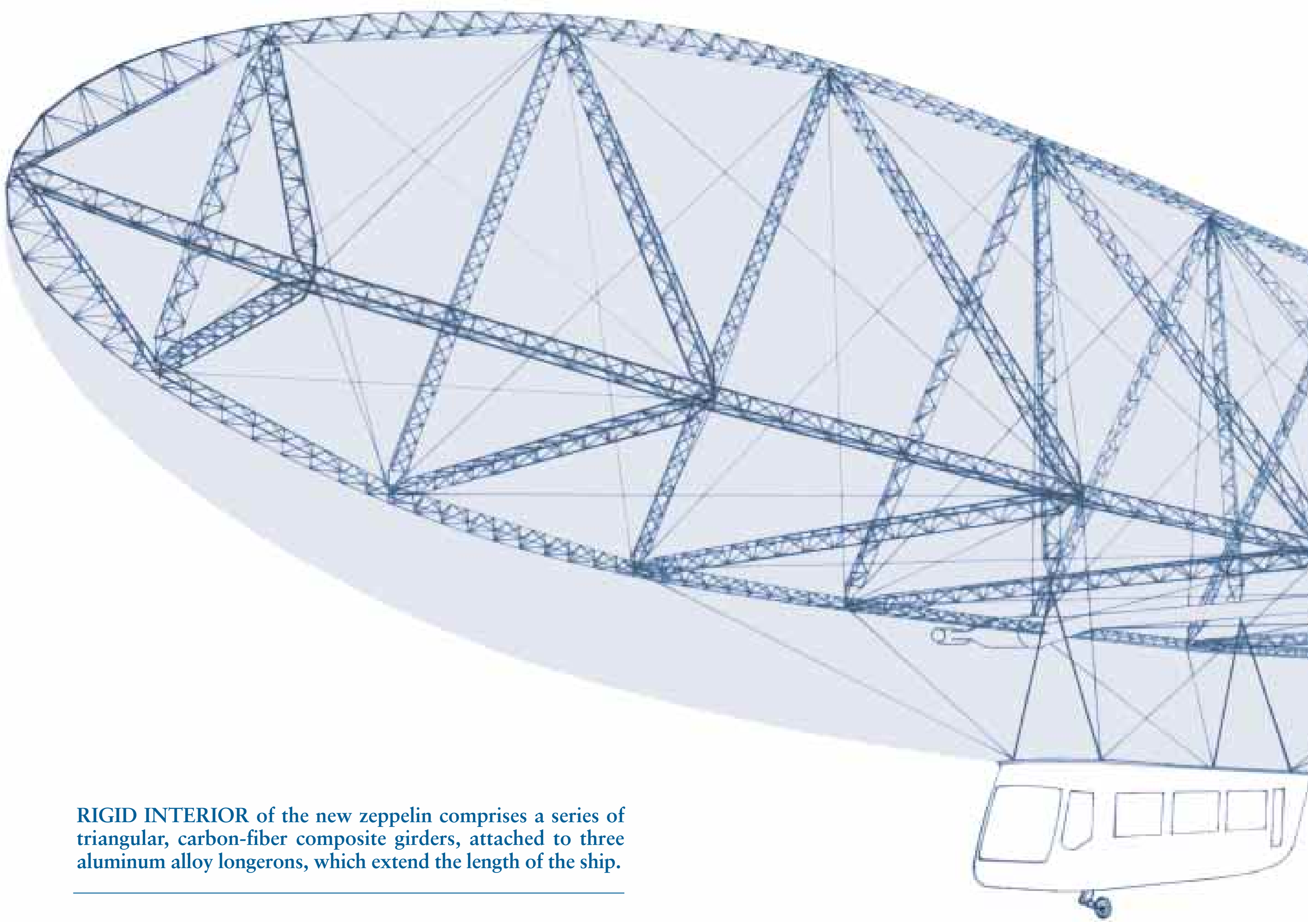
The course of true love never did run smooth. This Shakespearean sentiment certainly holds for one of the 20th century's most romantic forms of transportation—the zeppelin. On August 5, 1908, the German city of Echterdingen celebrated the first landing of a zeppelin. The elegant, floating airship must have seemed the very embodiment of the promise of a new age. As if to foreshadow the future demise of zeppelins in general, however, disaster struck almost immediately. The evening of the maiden voyage, a gust of wind tore the ship from its hangar. Suddenly, the battered zeppelin's hydrogen-filled envelope burst into flames. The ship was totally destroyed.

NEW ZEPPELIN is the first of its kind in some six decades. Thanks to a rigid internal structure [*see illustration on next two pages*], the zeppelin's engines can attach to surfaces other than the gondola, where blimps' engines must sit. Distancing the engines from the gondola makes the ship more maneuverable and decreases cabin noise and vibration.

COURTESY OF ZEPPELIN LUFTSCHIFFTECHNIK

Undaunted, the eponymous Count Ferdinand von Zeppelin continued to build his airships, until more than 100 of them had proved airworthy. But the disastrous 1937 explosion of the *Hindenburg* in Lakehurst, N.J., the advent of World War II and the rise of jet air travel turned the zeppelin into a symbol of a bygone era. People still see the occasional blimp, with its simple inflated body, patrolling sporting events. But the more complex zeppelins, with rigid internal structures within their gas-filled envelopes, became extinct. Or so it seemed, until August 8, 1998.

Almost exactly 90 years after the Echterdingen incident, the skies above that city once again welcomed a zeppelin. Although this one retained the same general ap-



RIGID INTERIOR of the new zeppelin comprises a series of triangular, carbon-fiber composite girders, attached to three aluminum alloy longerons, which extend the length of the ship.

pearance as its long-departed ancestors, it was in every other way a new creation. Dubbed the LZ N07, it combines the grace and bearing of the airships of old with state-of-the-art aeronautic and electronic technology. This is not your grandfather's zeppelin.

Back to the Drawing Board

By the late 1980s the company founded by Ferdinand von Zeppelin, Luftschiffbau Zeppelin, had been engaged for some 50 years in other technical pursuits, such as the manufacture of radar antennas and construction equipment. At that time, company executives Max Mugler and Heinz Kollmann came to the conclusion that modern airships might have a niche. Specifically, they thought that high-tech zeppelins could find roles in advertising and sight-seeing as well as in environmental protection, serving as stable platforms for monitoring environmentally sensitive areas. Engineers and researchers from other divisions were chosen to work in a Lockheed skunk works–type atmosphere—a small team, housed separately, free of all external influences and united in a single purpose. This group, which I was assigned to lead, carried out studies examining the feasibility of creating modern zeppelins and determining their market potential.

Review of the extensive archives of Luftschiffbau Zeppelin informed the group's decisions regarding design. Foremost, of course, was safety. This concern led to the obvious conclusion that nonflammable helium would be the gas of choice. In addition, the craft would need some degree of flight-worthiness even in the event that envelope pressure became compromised. Another safety focus was ballast that would not require jettisoning. A blimp, lighter after dropping its ballast, can be more easily bandied about by winds when returning to its base. The airship, therefore, would need a constant, robust heft.

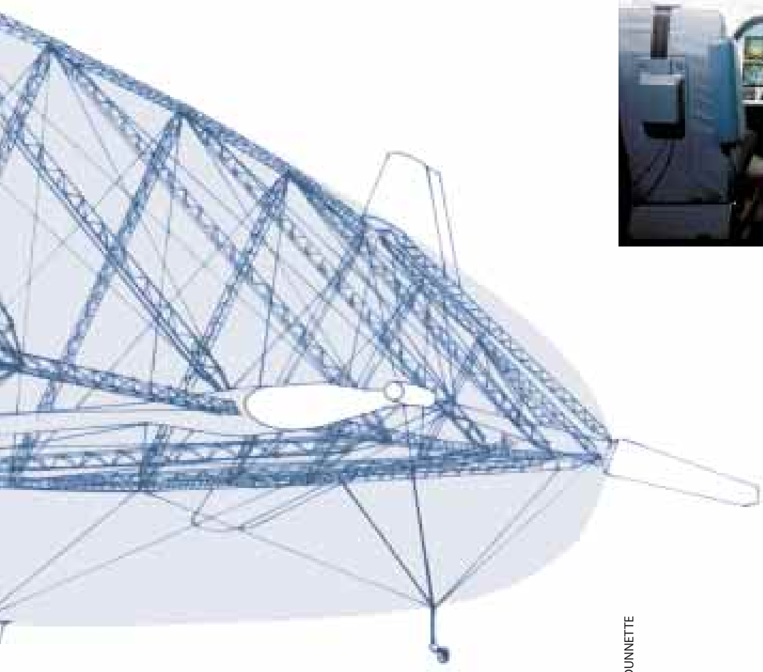
Also on our wish list was a reduction in support staff. Blimps require ground crews of 15 or more to literally catch the floating behemoth and pull it to the ground. This work is strenuous and sometimes dangerous—and the maintenance, including transportation, of a large ground crew can be a major cost in blimp operations. We wanted the new zeppelin to function with a much sparser support team of only three or four people. To attract customers, the new zeppelin would also need obvious performance advantages over blimps: higher speed, the ability to fly in rougher weather, decreased cabin noise and vibration, and easier operation for the pilots.

In 1990 the skunk works team finished a design. With management's approval, we then set out to build a proof-of-concept model. When this 10-meter-long (33-foot-long) miniature zeppelin passed its simple flight tests in the spring of 1991, we began to grapple with the realities of designing a full-size prototype. This effort involved some detective work and the invention of new technology.

One of our greatest challenges was performing the kinds of

PHOTOGRAPHS COURTESY OF ZF FRIEDRICHSHAFEN AG

HIGH-TECH COCKPIT (*left*) incorporates state-of-the-art navigation instrumentation and "fly-by-wire" controls that electronically operate the ship. The tail (*right*) includes a rear propeller, which can pivot down 90 degrees and push the ship up, and a side propeller that can drive the zeppelin in a circle, the center point of which is the craft's nose.



LEE DUNNETTE

calculations common in the aircraft design industry—estimates of aerodynamics, stresses and electronic functions for various design options. With today's computer technology, we knew the potential existed for vast improvements over classical zeppelin design. But airship development basically ended in 1940, and no theoretical or scientific advancement had occurred since. We searched the world for computer programs capable of calculating loads and stresses for various aerodynamic maneuvers and found nothing. We would have to create our own theory and practice of zeppelin design.

Two mathematical engineers from our group gleaned whatever seemed useful from the existing literature. Along with members of the Institute for Aerodynamics and Gas Dynamics at the University of Stuttgart, they then developed from scratch computer programs to calculate zeppelin functions. The task was complicated by the fact that the typical full-size cigar-shaped zeppelin is more than just a larger version of smaller test prototypes that might be used in preliminary wind-tunnel tests to generate data. The bulky shape translates to an array of different behaviors at the larger size. For example, the flow of air over the ship during turns remained difficult to calculate, even after wind-tunnel tests. Airplanes are actually simpler to model, with the smaller wind-tunnel versions presenting a reasonable approximation to larger craft. The full-size LZ N07 is therefore both the result of our initial programming and calculations and, with 400 flight-hours now on the books, a test vehicle for generating the kind of real-world data that are helping to improve our computer models.

In September 1993 a separate company, Zeppelin Luftschifftechnik, was founded to construct a zeppelin according to our design and to seek and protect patents for the numerous inventions that would enable the modernistic craft to take flight. (All members of a future fleet of zeppelins would bear the generic name "Zeppelin NT," for new technology. Each would also have a "species" designation, such as the LZ N07, where the 07 refers to its original gas volume of 7,000 cubic meters [247,000 cubic feet], although we later expanded the design to accommodate 8,200 cubic meters.)

The Body of a New Machine

The rigid internal structure that makes an airship a zeppelin rather than a blimp would be central to the realization of many of our requirements. For example, engines could be fixed at more propitious positions than are available with blimps, in which they are limited to the underhanging gondola. Such positioning limits maneuverability and increases noise. The new zeppelin's engines appear to be attached to the exterior of the envelope but are actually connected to the hidden internal framework just underneath the skin.

The legendary airships of old, such as the *Hindenburg* and *Graf Zeppelin,* had complex internal structures, necessary to support their enormity: each stretched 245 meters long, with a diameter of 41 meters and a volume of 200,000 cubic meters. Thirty-six lengthy beams, called longerons, extended from nose to tail, and "ring stiffeners" every five meters served as reinforcing ribs. We wanted to greatly streamline this kind of anatomy, which would have been too heavy and expensive for the 75-meter-long ships we had in mind. In addition, a minimal internal structure affords less opportunity for damage in rough landings.

In the LZ N07, therefore, the elaborate skeleton of ancestral craft is replaced by a simple triangular framework, consisting of three aluminum alloy longerons and only 12 sets of light, strong carbon-fiber composite girders. This arrangement gives the airship traditional zeppelin stiffness but only along its length. Radial stiffness is maintained by the internal gas pressure. All external components—engines, gondola and control surfaces such as fins and rudders—are connected to the frame.

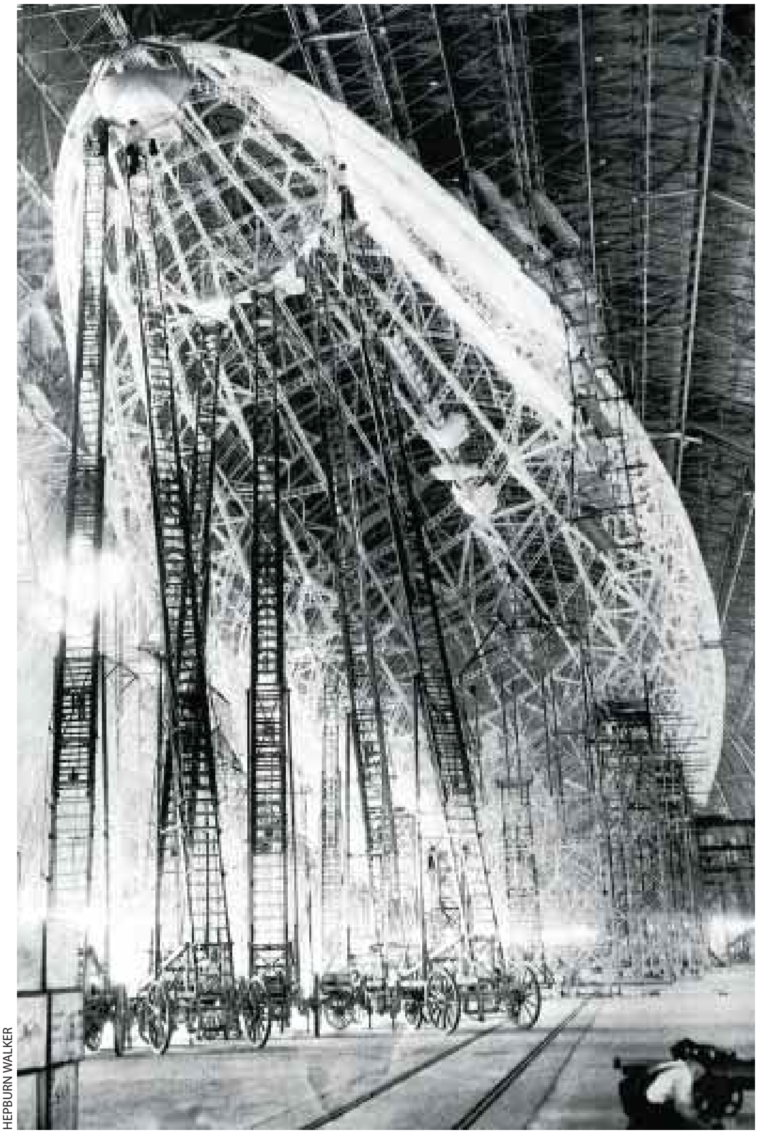
The envelope, a multilayer laminate, attaches continuously to the three longerons and surrounds both helium gas and ballonets, compartments of adjustable volume filled with air. These ballonets can take in air from outside the ship, or release air, to maintain a constant internal pressure in the hull during ascents or descents. The fore and aft placement of the ballonets also enables attitude adjustments—pumping air from the aft ballonet to the front one, for example, pushes the nose down relative to the tail.

The entire helium-air system also maintains a constant, slight "overpressure" within the envelope about 4 percent higher than the external atmospheric pressure. As in blimps, keeping the overpressure low is a safety feature. If the pressure within an envelope is significantly higher than the external pressure, a tiny puncture will lead to catastrophic failure, as when a pin explodes a balloon. With a low overpressure, a similar puncture leads only to slow leakage of internal gas; the pilot has ample time to land the airship safely. In the LZ N07 the frame and envelope also back each other up; the envelope has its own integrity in the event of any frame breaks, and the frame still provides support and some airworthiness if the envelope loses pressure.

The desire for unparalleled maneuverability resulted in the decision to use three engines. Two are installed left and right of the fuselage, just in front of the center of buoyancy. These engines drive propellers capable of delivering thrust over their entire 120-degree range of positions. The third engine powers a tail propeller, which has a 90-degree range of movement; it can supply thrust anywhere from straight down to directly backward. The rear unit also contains a small lateral propeller, which can push the rear of the airship sideways—this zeppelin can make a circle with its nose at the center. The blades of all four propellers can be hydraulically shifted to face either forward or backward, effectively giving each propulsion unit the capability of shifting into reverse.

Carbon-fiber housings of all the engine/propeller units help to dampen noise. Also helping to quiet the ride is a gearing system that takes the engines' 2,750 revolutions per minute (rpm) down to a more leisurely 1,250 rpm for the propellers. The engines are most efficient at the higher speed, but the long blades of the propellers produce sufficient thrust at their slower, and quieter, pace.

The new zeppelin's nimble handling and ability to take off and land virtually vertically make possible the limited ground crew we sought. A truck with a telescoping mast, reaching 12 meters high, moors the airship. The ground crew chief catches a line from the ship's nose and snaps it into place within a winch system attached to the mast. No other physical contact with lines is necessary. The winch tows the ship to the mast, which then telescopes down to ground level. The crew chief, truck driver and winch operator make up the entire ground team.



HEPBURN WALKER

The View from the Bridge

One of the triumphs of the new airship is the cockpit. A 1930s-vintage zeppelin pilot, transported to the new ship, would probably feel comfortable with the basic stick controls (although the computer screens might distract at first). Back in his own time, that pilot manipulated sticks or wheels that pushed or pulled cables attached directly to rudders or elevators or that increased or decreased engine power. The modern flight-control system looks similar but feels a bit different. Although the new ship's stick performs the same kind of functions, the old pilot might be surprised at the stick's smooth movement. The ease of operation is explained by examination of the guts of the control system—the cables have been replaced by electronics. Stick movement produces digital signals that tell, for example, the rudder to swivel. Rather than forcing heavy cables, the pilot's stick actions could be part of a living video game: Zeppelin Aviator 1.0.

Adding to that video game feel are the state-of-the-art features of the command center. Liquid-crystal displays reveal the status of all the airship's functions, such as the position of every rudder and elevator and the pitch of every propeller blade. The cockpit also includes a weather radar screen, a Global Positioning System and an Electronic Flight Information System; the last incorporates a small panel with a quick listing of the major items of interest to the pilot: heading, speed, vertical speed, altitude, pitch, yaw and roll. The pilots sit at the front of the gondola, which can accommodate as many as 12 passengers who can enjoy cruising at speeds up to 130 kilometers per hour (about 80 miles per hour).

COURTESY OF ZF FRIEDRICHSHAFEN AG

ZEPPELIN EVOLUTION is visible in these views of the interiors of the new airship (*left*) and the *Macon* (*far left*), a pre–World War II U.S. Navy airborne aircraft carrier. The simple skeleton of the LZ N07 performs the role once played by the baroque internal structure of the 240-meter-long *Macon.*

The first flight of the new zeppelin took place on September 18, 1997, exactly 69 years after that of the *Graf Zeppelin.* The 47-minute maiden voyage of the LZ N07 began at a parking lot near its construction hangar—an exhibition hall in the city of Friedrichshafen. The entire population of the city seemed to have gathered to witness this historic event, which only added to the nervousness of the team that had devoted eight years of ingenuity and effort in the hope of making this day a reality. The airship may have left the ground with far less Sturm und Drang than a Saturn V engine commands, but our reactions were easily as joyful as those of the members of a moon trip's mission control after a successful launch.

The ship will soon have sisters. Customers have ordered five zeppelins to date, four to be used in advertising and tourism and one earmarked for scientific measurement. The success of this enterprise has allowed us to contemplate a return to even larger zeppelins built with our new technology. Although intermediate-size ships would be built first, the LZ N20, with seating for perhaps 50 passengers, is a possibility. In the near future, thousands may enjoy the most buoyant tourist experience of their lives, gliding serenely over scenic vistas in the cabin of a 21st-century zeppelin. SA

The Author

KLAUS G. HAGENLOCHER has been managing director of Zeppelin Luftschifftechnik since 1997. He headed the team that developed the new zeppelin and the technology that made it possible. After receiving a mechanical engineering degree in 1962 from the Technical College in Karlsruhe, Germany, he then joined one of Luftschiffbau Zeppelin's affiliated companies, Zeppelin GmbH Friedrichshafen, working on the development of lightweight construction. He became head of development and design for that company in 1972, a position he retained until 1989, when he was named chief engineer for development of the Zeppelin NT.

Further Reading

GOLDEN AGE OF THE GREAT PASSENGER AIRSHIPS; GRAF ZEPPELIN AND HINDENBURG. Harold G. Dick and Douglas H. Robinson. Smithsonian Institution Press, 1992.

COMPANY TOWN. William Garvey in *Air & Space Smithsonian,* Vol. 11, No. 6, pages 60–67; February/March 1997.

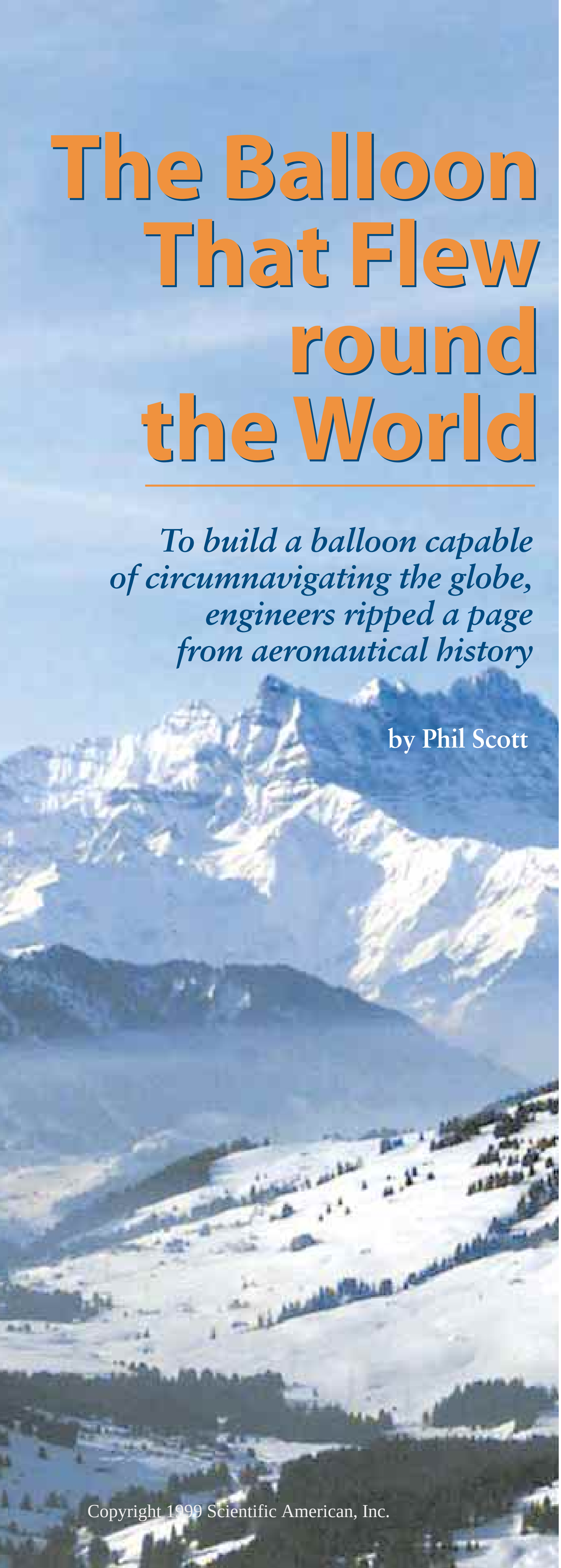
The Zeppelin Luftschifftechnik GmbH home page is available at www.zeppelin-nt.com/ on the World Wide Web.


BREITLING
ORBITER 3

The Balloon That Flew round the World

To build a balloon capable of circumnavigating the globe, engineers ripped a page from aeronautical history

by Phil Scott



What do you do once you've been to the moon? As the 20th century crept somewhat ungracefully toward its twilight years, the remaining aeronautical milestones clustered mainly around humankind's oldest contrivance for flight: the humble balloon. And once aeronauts in balloons had done the impossible by spanning the Atlantic Ocean in 1978 and then the Pacific in 1981, there was but one last hurrah: nonstop global circumnavigation.

Circling the earth in a balloon was hardly the stuff of superpower competitions. (Imagine a president exhorting, "We do not choose to float around the world because it is easy but because it is hard!") So for the past two decades it has been up to a handful of millionaire sportsmen/adventurers to grab the final gold ring—not for their countries but for themselves. And at last, in March 1999, two intrepid balloonists captured the prize: Bertrand Piccard and Brian Jones flew around the globe in the *Breitling Orbiter 3*.

As a technological achievement, a globe-girdling gasbag lies well below the lunar module (or even a moderately reliable passenger jet), though quantum leaps above the rainbow-colored nylon teardrop attached to a wicker basket that you'll find at the county fair. The typical sport balloon stands 18 meters (60 feet) tall, its 2,550-cubic-meter (90,000-cubic-foot) volume heated by a propane burner. There's enough fuel on board to keep the balloon floating placidly for up to two hours at the exact speed and direction of the wind. Its larger, long-duration cousins can stay up much longer, but each night the heat in the envelope radiates into space, forcing the aeronaut to throw away between 10 and 20 percent of the balloon's gross weight in ballast and fuel simply to stay out of the ocean or above the mountaintops. That translates into a natural endurance limit of between four and eight days, which simply wouldn't work for a voyage of global proportions (38,600 kilometers, or 24,000 miles, minimum) lasting up to three weeks.

To design a vessel likely to survive such a trip, engineers took a page from ballooning's early history: late 1783, to be exact.

AP KEYSTONE

***BREITLING ORBITER 3* flies over the Alps after launching from Château d'Oex, Switzerland, on March 1, 1999, at the start of its historic round-the-world flight.**

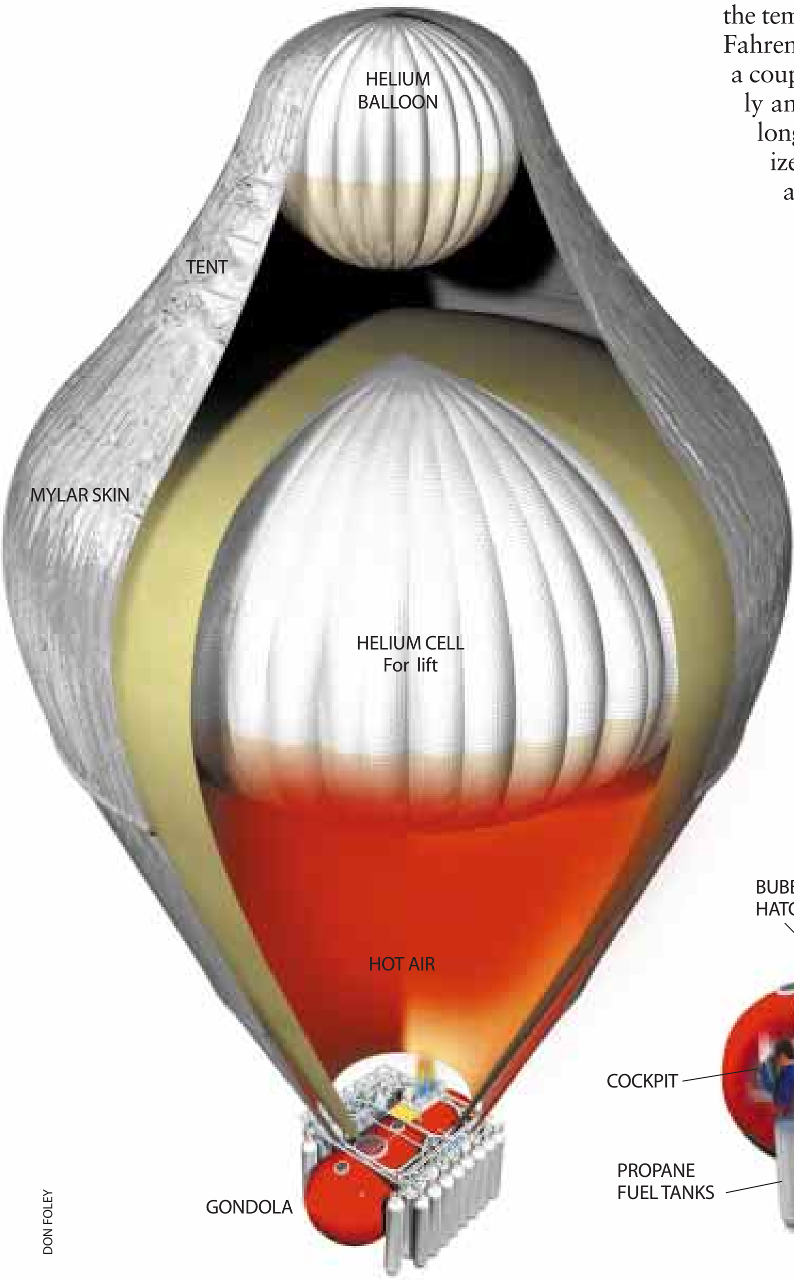
Only days after Pilâtre de Rozier and the Marquis d'Arlandes became the first men to rise in a hot-air balloon, fellow Frenchman Jacques Charles flew the first balloon filled with hydrogen gas. Just 18 months after that, Rozier attempted a long-distance flight across the English Channel in a hybrid balloon, which combined flame-heated air and a cell filled with explosive hydrogen. He soon became aeronautics's first fatality.

Nevertheless, aeronautical engineer Don Cameron, whose Bristol, England–based Cameron Balloons has become a leading manufacturer of sport balloons, saw promise in Rozier's dual-gas configuration. Unlike air, a light gas such as hydrogen—or the more recently discovered and less explosive helium—remains light without the constant expenditure of fuel. Yet it, too, rises when heated and sinks when cooled. That's where burners and hot air can come in handy.

"The secret of making a gas balloon fly long periods is to keep the helium the same temperature day and night," says Alan Noble, director of special projects for Cameron Balloons. "The problem is that during the day the sun is trying to warm it and at night it wants to radiate heat into the blackness of space. Our job is to keep the temperature as stable as possible." Cameron's so-called Rozier design places a helium cell above an inverted cone of air heated by propane. To ascend, the aeronauts heat the air cone, which in turn heats and expands the helium. The balloon's outer envelope consists of two layers, and the dead air space between the layers cuts heat loss at night by 50 percent. During the day the sun takes over to warm the helium, but should the balloon want to rise to an undesirable altitude, solar-powered fans can draw in cool air so that the temperature inside remains stable. "It's what we call air conditioning and double glazing," Noble says. It's also what you would call a success: the majority of distance and duration flights have been flown in Cameron-built Roziers, including the *Breitling Orbiter 3*.

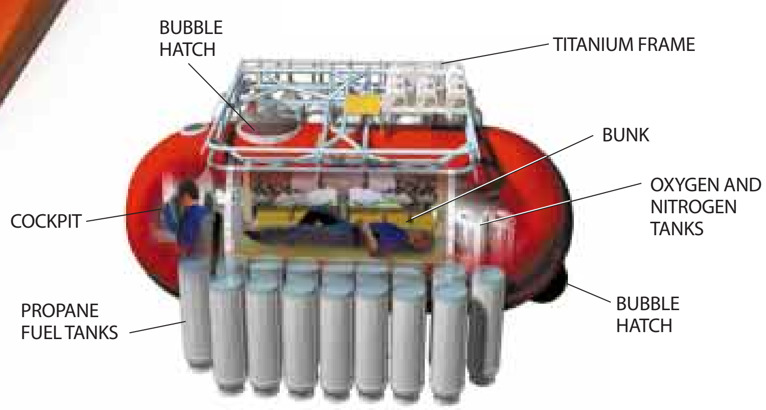
Suspended beneath this complex bag is a gondola, which must provide all the comforts of a space capsule: sleeping quarters, food storage, a toilet and life support. Inside the more than 115-kilometer-per-hour (70-mile-per-hour) jet stream, which resides at between 6,000 and 15,000 meters, the temperature hovers near −56 degrees Celsius (−69 degrees Fahrenheit). There an unprotected human can survive about a couple of minutes. *Breitling Orbiter 3*'s gondola, essentially an airtight Kevlar and carbon-fiber cylinder 5.5 meters long and just over 2.75 meters in diameter, was pressurized to 2,500 meters (nearly the same pressure altitude as an airliner's cabin) simply by being sealed at that altitude. Oxygen tanks gave the crew something to breathe, and lithium filters scrubbed their carbon dioxide exhalation. In the event of a noncatastrophic loss of cabin pressure, the crew could repressurize with an onboard nitrogen reserve.

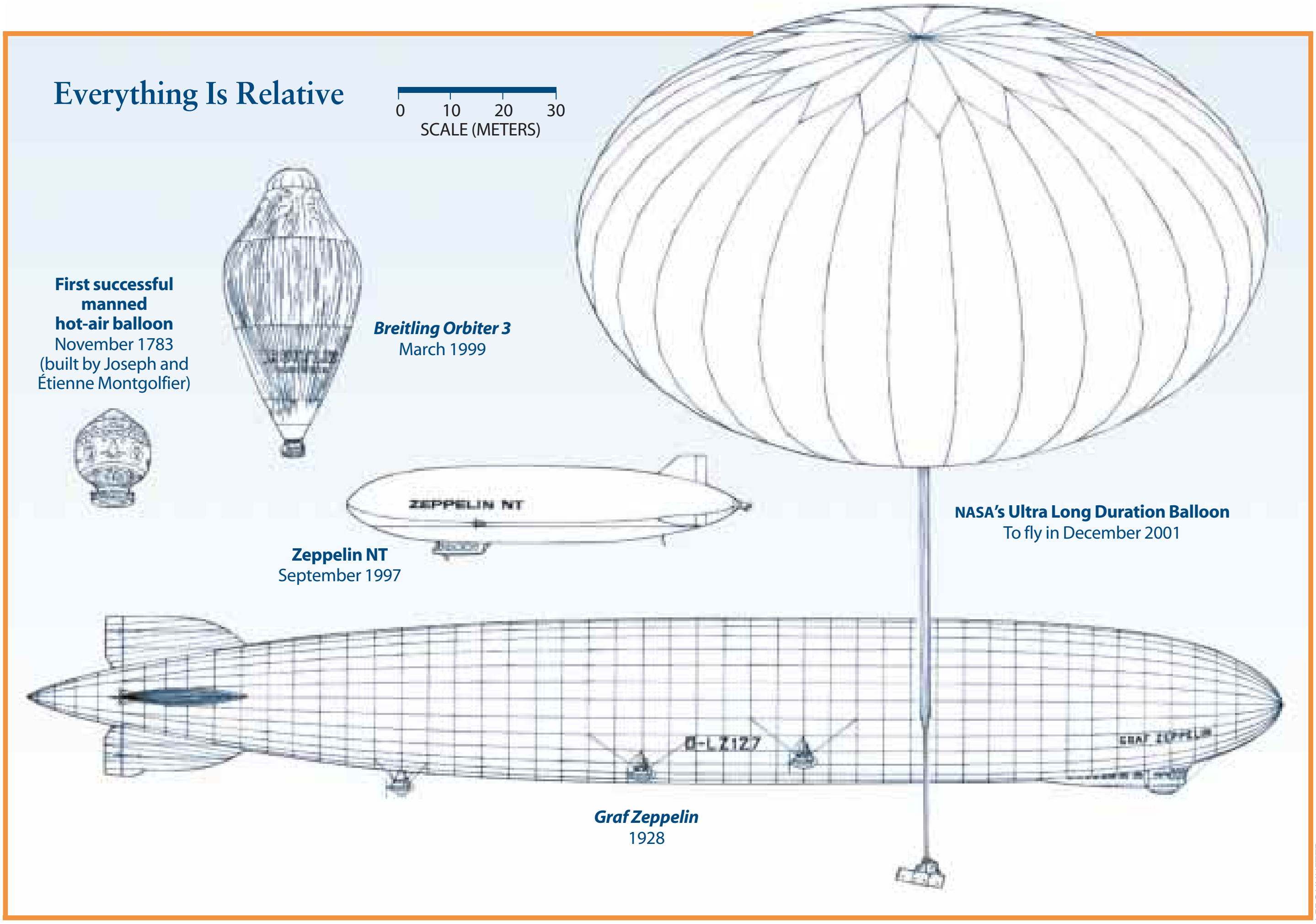
Instrumentation is minimal: dual VHF airband radios and dual HF shortwave radios for communicating with air traffic control, Inmarsat C for keyboarding messages to mission control ("You can't misunderstand a written message," Noble says), Inmarsat M for voice,



DON FOLEY

INSIDE *ORBITER 3:* The Rozier design used for this balloon (*left*) is fairly complex. The small helium balloon at the top stakes up the "tent," which helps to insulate the larger helium cell. Life inside the gondola (*below*) was cramped: the crew took turns sleeping in the single bunk. Oxygen and nitrogen tanks were stowed aft, while the cockpit housed the few necessary instruments and radios. For a look outside, the crew had to peek through bubble hatches.





LEE DUNNETTE

triple-redundant Global Positioning System receivers coupled to the Inmarsat C for navigation, redundant altimeters and vertical speed indicators, plus the burner controls. A double necklace of propane cylinders flanks the exterior.

Dumb luck, however, remains the most vital component in any successful circumnavigation by a vessel meant to ride the fickle winds. During any given winter in recent years (all balloon circumnavigations start in the winter, when the jet stream is at its strongest), half a dozen parties were preparing to launch. But the tenacity award should go to American Steve Fossett. His circumnavigation career began in January 1995, when he piloted his Cameron-built Rozier from Seoul to Saskatchewan, at the time an absolute world distance record of 9,878 kilometers. In early 1996 he launched from South Dakota but alighted soon after when his balloon's outer envelope started shredding. In 1997 his *Solo Spirit* got him from St. Louis to India (16,674 kilometers), where he landed low on fuel; then in 1998 he made it from Missouri to Krasnodar, Russia (11,748 kilometers), before being forced down by technical problems. The following August Fossett tried again—from the Southern Hemisphere—but this time his Rozier ruptured during a thunderstorm, and he ditched in the ocean. Richard Branson, of Virgin entertainment and airline empire fame, himself a two-time circumnavigational bridesmaid, offered the then balloonless Fossett a seat in his 1998 ICO Global balloon. But this attempt, too, ended low on fuel after 21,450 kilometers.

Only slightly less tenacious, the Breitling Orbiter crew, captained by Piccard, ditched six hours into its 1997 attempt, when a tiny clip came loose and caused the gondola to become flooded with fuel. In January 1998 Piccard was at the helm of the *Breitling Orbiter 2,* which left Switzerland and got as far as Myanmar (Burma) when the Chinese refused the balloon permission to enter their airspace. This year's *Breitling Orbiter 3,* with Piccard and co-pilot Jones, was the charm: weather, technology and international politics all conspired happily for a flight covering 42,714 kilometers from Switzerland to Egypt and lasting 19 days, 1 hour and 49 minutes.

But now that humans have blasted through that last goal, what more could await the rarefied Roziers and big-money ballooning in general? Noble has an answer ready. "For our next outing we are planning on getting a ladies' [circumnavigation] team together—next year," he says. "And the Fédération Aéronautique Internationale has announced it will run an around-the-world balloon race circa 2001." Of course, there's also that 38-year-old world altitude record of 34,668 meters, set back in 1961 by U.S. Navy commanders Malcolm Ross and Victor Prather, which just screams for someone to break it.

"There are only three absolute records in aeronautics: distance, duration and altitude," Noble says. "My company holds the distance and duration for the Breitling flight. We'd like to add the third."

And perhaps Captain Piccard will be along to make it so. SA

The Author

PHIL SCOTT is a freelance journalist who frequently writes about flight. His most recent book is *The Pioneers of Flight: A Documentary History* (Princeton University Press, 1999).

The Grameen Bank

A small experiment begun in Bangladesh has turned into a major new concept in eradicating poverty

by Muhammad Yunus

Over many years, Amena Begum had become resigned to a life of grinding poverty and physical abuse. Her family was among the poorest in Bangladesh—one of thousands that own virtually nothing, surviving as squatters on desolate tracts of land and earning a living as day laborers.

In early 1993 Amena convinced her husband to move to the village of Kholshi, 112 kilometers (70 miles) west of Dhaka. She hoped the presence of a nearby relative would reduce the number and severity of the beatings that her husband inflicted on her. The abuse continued, however—until she joined the Grameen Bank. Oloka Ghosh, a neighbor, told Amena that Grameen was forming a new group in Kholshi and encouraged her to join. Amena doubted that anyone would want her in their group. But Oloka persisted with words of encouragement. "We're all poor—or at least we all were when we joined. I'll stick up for you because I know you'll succeed in business."

Amena's group joined a Grameen Bank Center in April 1993. When she received her first loan of $60, she used it to start her own business raising chickens and ducks. When she repaid her initial loan and began preparing a proposal for a second loan of $110, her friend Oloka gave her some sage advice: "Tell your husband that Grameen does not allow borrowers who are beaten by their spouses to remain members and take loans." From that day on, Amena suffered significantly less physical abuse at the hands of her husband. Today her business continues to grow and provide for the basic needs of her family.

Unlike Amena, the majority of people in Asia, Africa and Latin America have few opportunities to escape from poverty. According to the World Bank, more than 1.3 billion people live on less than a dollar a day. Poverty has not been eradicated in the 50 years since the Universal Declaration on Human Rights asserted that each individual has a right to:

> A standard of living adequate for the health and well-being of himself and of his family, including food, clothing, housing and medical care and necessary social services, and the right

KAREN KASMAUSKI *Matrix*

WEEKLY VILLAGE MEETING of Grameen Bank borrowers ends with a recitation of pledges for better living, along with a salute. The gatherings are venues in which members request, receive or repay loans, as well as relate the status of the businesses they have set up. This revolutionary bank, based in Bangladesh, now boasts 39,000 such village centers and 2.4 million borrowers, most of them women. Even though the recipients are too poor to offer collateral, the repayment rate for the loans varies between 96 and 100 percent.

to security in the event of unemployment, sickness, disability, widowhood, old age or other lack of livelihood in circumstances beyond his control.

Will poverty still be with us 50 years from now? My own experience suggests that it need not.

After completing my Ph.D. at Vanderbilt University, I returned to Bangladesh in 1972 to teach economics at Chittagong University. I was excited about the possibilities for my newly independent country. But in 1974 we were hit with a terrible famine. Faced with death and starvation outside my classroom, I began to question the very economic theories I was teaching. I started feeling there was a great distance between the actual life of poor and hungry people and the abstract world of economic theory.

I wanted to learn the real economics of the poor. Because Chittagong University is located in a rural area, it was easy for me to visit impoverished households in the neighboring village of Jobra. Over the course of many visits, I learned all about the lives of my struggling neighbors and much about economics that is never taught in the classroom. I was dismayed to see how the indigent in Jobra suffered because they could not come up with small amounts of working capital. Frequently they needed less than a dollar a person but could get that money only on extremely unfair terms. In most cases, people were required to sell their goods to moneylenders at prices fixed by the latter.

This daily tragedy moved me to action. With the help of my graduate students, I made a list of those who needed small amounts of money. We came up with 42 people. The total amount they needed was $27.

I was shocked. It was nothing for us to talk about millions of dollars in the classroom, but we were ignoring the minuscule capital needs of 42 hardworking, skilled people next door. From my own pocket, I lent $27 to those on my list.

Still, there were many others who could benefit from access to credit. I decided to approach the university's bank and try to persuade it to lend to the local poor. The branch manager said, however, that the bank could not give loans to the needy: the villagers, he argued, were not creditworthy.

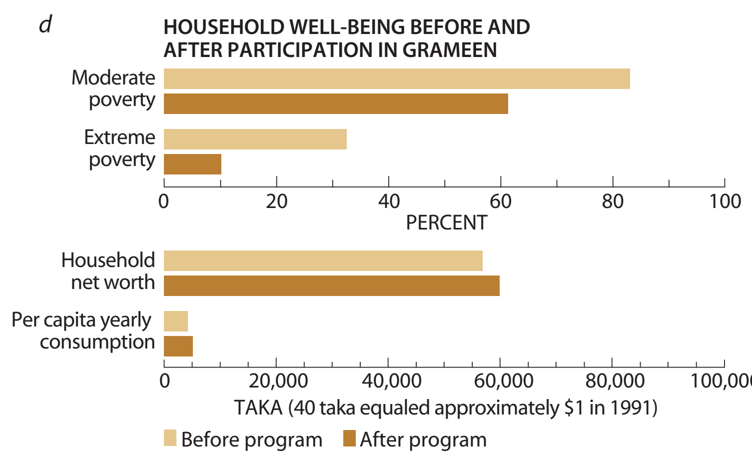
I could not convince him otherwise. I met with higher officials in the banking hierarchy with similar results. Finally, I offered myself as a guarantor to get the loans.

In 1976 I took a loan from the local bank and distributed the money to poverty-stricken individuals in Jobra. Without exception, the villagers paid back their loans. Confronted with this evidence, the bank still refused to grant them loans directly. And so I tried my experiment in another village, and again it was successful. I kept expanding my work, from two to five, to 20, to 50, to 100 villages, all to convince the bankers that they should be lending to the poor. Although each time we expanded to a new village the loans were repaid, the bankers still would not change their view of those who had no collateral.

Because I could not change the banks, I decided to create a separate bank for the impoverished. After a great deal of work and negotiation with the government, the Grameen Bank ("village bank" in Bengali) was established in 1983.

From the outset, Grameen was built on principles that ran counter to the conventional wisdom of banking. We sought out the very poorest borrowers, and we required no collateral. The bank rests on the strength of its borrowers. They are required to join the bank in self-formed groups of

PHOTOGRAPHS BY SALAHUDDIN AZIZEE *Grameen Bank*; LISA BURNETT (*graphs*)



LOANS RECEIVED from the bank (*a*) are used for a variety of small ventures, including raising chickens (*b*) and making the earthen pots that villagers use to store drinking water (*c*). The income from such a business has a significant effect on the well-being of a borrower's household (*d*). Before joining the bank, 83 percent of the members were moderately poor and 33 percent were extremely poor. But a fifth of the members were able to lift themselves out of poverty after participating in the bank.

five. The group members provide one another with peer support in the form of mutual assistance and advice. In addition, they allow for peer discipline by evaluating business viability and ensuring repayment. If one member fails to repay a loan, all members risk having their line of credit suspended or reduced.

The Power of Peers

Typically a new group submits loan proposals from two members, each requiring between $25 and $100. After these two borrowers successfully repay their first five weekly installments, the next two group members become eligible to apply for their own loans. Once they make five repayments, the final member of the group may apply. After 50 installments have been repaid, a borrower pays her interest, which is slightly above the commercial rate. The borrower is now eligible to apply for a larger loan.

The bank does not wait for borrowers to come to the bank; it brings the bank to the people. Loan payments are made in weekly meetings consisting of six to eight groups, held in the villages where the members live. Grameen staff attend these meetings and often visit individual borrowers' homes to see how the business—whether it be raising goats or growing vegetables or hawking utensils—is faring.

Today Grameen is established in nearly 39,000 villages in Bangladesh. It lends to approximately 2.4 million borrowers, 94 percent of whom are women. Grameen reached its first $1 billion in cumulative loans in March 1995, 18 years after it began in Jobra. It took only two more years to reach the $2-billion mark. After 20 years of work, Grameen's average loan size now stands at $180. The repayment rate hovers between 96 and 100 percent.

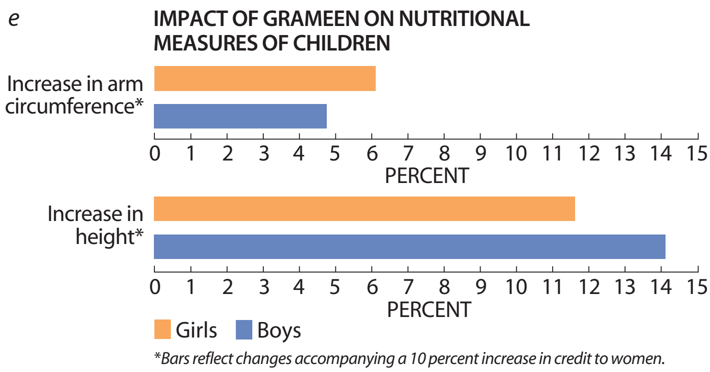
A year after joining the bank, a borrower becomes eligible to buy shares in Grameen. At present, 94 percent of the bank is owned by its borrowers. Of the 13 members of the board of directors, nine are elected from among the borrowers; the rest are government representatives, academics, myself and others.

A study carried out by Sydney R. Schuler of John Snow, Inc., a private research group, and her colleagues concluded that a Grameen loan empowers a woman by increasing her economic security and status within the family. In 1998 a study by Shahidur R. Khandker, an economist with the World Bank, and others noted that participation in Grameen also has a significant positive effect on the schooling and nutrition of children—as long as women rather than men receive the loans. (Such a tendency was clear from the early days of the bank and is one reason Grameen lends primarily to women: all too often men spend the money on themselves.) In particular, a 10 percent increase in borrowing by women resulted in the arm circumference of girls—a common measure of nutritional status—expanding by 6 percent. And for every 10 percent increase in borrowing by a member, the likelihood of her daughter being enrolled in school increased by almost 20 percent.

Not all the benefits derive directly from credit. When joining the bank, each member is required to memorize a list of 16 resolutions. These include commonsense items about hygiene and health—drinking clean water, growing and eating vegetables, digging and using a pit latrine, and so on—as well as social dictums such as refusing dowry and managing family size. The women usually recite the en-

SALAHUDDIN AZIZEE *Grameen Bank*

SALAHUDDIN AZIZEE *Grameen Bank*



LISA BURNETT

EMPOWERMENT OF WOMEN is one consequence of providing caregivers with capital. A woman's income—whether it be from weaving baskets (*a*), run-

tire list at the weekly branch meetings, but the resolutions are not otherwise enforced.

Even so, Schuler's study revealed that women use contraception more consistently after joining the bank. Curiously, it appears that women who live in villages where Grameen operates, but who are not themselves members, are also more likely to adopt contraception. The population growth rate in Bangladesh has fallen dramatically in the past two decades, and it is possible that Grameen's influence has accelerated the trend.

In a typical year 5 percent of Grameen borrowers—representing 125,000 families—rise above the poverty level. Khandker concluded that among these borrowers extreme poverty (defined by consumption of less than 80 percent of the minimum requirement stipulated by the Food and Agriculture Organization of the United Nations) declined by more than 70 percent within five years of their joining the bank.

To be sure, making a microcredit program work well—so that it meets its social goals and also stays economically sound—is not easy. We try to ensure that the bank serves the poorest: only those living at less than half the poverty line are eligible for loans. Mixing poor participants with those who are better off would lead to the latter dominating the groups. In practice, however, it can be hard to include the most abjectly poor, who might be excluded by their peers when the borrowing groups are being formed. And despite our best efforts, it does sometimes happen that the money lent to a woman is appropriated by her husband.

Given its size and spread, the Grameen Bank has had to evolve ways to monitor the performance of its branch managers and to guarantee honesty and transparency. A manager is not allowed to remain in the same village for long, for fear that he may develop local connections that impede his performance. Moreover, a manager is never posted near his home. Because of such constraints—and because managers are required to have university degrees—very few of them are women. As a result, Grameen has been accused of adhering to a paternalistic pattern. We are sensitive to this argument and are trying to change the situation by finding new ways to recruit women.

Grameen has also often been criticized for being not a charity but a profit-making institution. Yet that status, I am convinced, is essential to its viability. Last year a disastrous flood washed away the homes, cattle and most other belongings of hundreds of thousands of Grameen borrowers. We did not forgive the loans, although we did issue new ones and give borrowers more time to repay. Writing off loans would banish accountability, a key factor in the bank's success.

Liberating Their Potential

The Grameen model has now been applied in 40 countries. The first replication, begun in Malaysia in 1986, currently serves 40,000 poor families; their repayment rate has consistently stayed near 100 percent. In Bolivia, microcredit has allowed women to make the transition from "food for work" programs to managing their own businesses. Within two years the majority of women in the program acquire enough credit history and financial skills to qualify for loans from mainstream banks. Similar success stories are coming in from programs in poor countries everywhere. These banks all target the most impoverished, lend to groups and usually lend primarily to women.

The Grameen Bank in Bangladesh has been economically self-sufficient since 1995. Similar institutions in other countries are slowly making their way toward self-reliance. A few small programs are also running in the U.S., such as in inner-city Chicago. Unfortunately, because labor costs are much higher in the U.S. than in developing countries—which often have a large pool of educated unemployed who can serve as managers or accountants—the operations are more expensive there. As a result, the U.S. programs have had to be heavily subsidized.

SALAHUDDIN AZIZEE *Grameen Bank*

KAREN KASMAUSKI *Matrix*

ning a village store (*b*), crafting handloom textiles (*c*) or providing phone service to her neighbors (*d*)—enhances her status within her family, gives her more control over her fertility and allows her to take better care of her children (*e*). Women are also more conscientious about repaying the loans. For all these reasons, microcredit programs lend primarily to women.

In all, about 22 million poor people around the world now have access to small loans. Microcredit Summit, an institution based in Washington, D.C., serves as a resource center for the various regional microcredit institutions and organizes yearly conferences. Last year the attendees pledged to provide 100 million of the world's poorest families, especially their women, with credit by the year 2005. The campaign has grown to include more than 2,000 organizations, ranging from banks to religious institutions to nongovernmental organizations to United Nations agencies.

The standard scenario for economic development in a poor country calls for industrialization via investment. In this "top-down" view, creating opportunities for employment is the only way to end poverty. But for much of the developing world, increased employment exacerbates migration from the countryside to the cities and creates low-paying jobs in miserable conditions. I firmly believe that, instead, the eradication of poverty starts with people being able to control their own fates. It is not by creating jobs that we will save the poor but rather by providing them with the opportunity to realize their potential. Time and time again I have seen that the poor are poor not because they are lazy or untrained or illiterate but because they cannot keep the genuine returns on their labor.

Self-employment may be the only solution for such people, whom our economies refuse to hire and our taxpayers will not support. Microcredit views each person as a potential entrepreneur and turns on the tiny economic engines of a rejected portion of society. Once a large number of these engines start working, the stage can be set for enormous socioeconomic change.

Applying this philosophy, Grameen has established more than a dozen enterprises, often in partnership with other entrepreneurs. By assisting microborrowers and microsavers to take ownership of large enterprises and even infrastructure companies, we are trying to speed the process of overcoming poverty. Grameen Phone, for instance, is a cellular telephone company that aims to serve urban and rural Bangladesh. After a pilot study in 65 villages, Grameen Phone has taken a loan to extend its activities to all villages in which the bank is active. Some 50,000 women, many of whom have never seen a telephone or even an electric light, will become the providers of telephone service in their villages. Ultimately, they will become the owners of the company itself by buying its shares. Our latest innovation, Grameen Investments, allows U.S. individuals to support companies such as Grameen Phone while receiving interest on their investment. This is a significant step toward putting commercial funds to work to end poverty.

I believe it is the responsibility of any civilized society to ensure human dignity to all members and to offer each individual the best opportunity to reveal his or her creativity. Let us remember that poverty is not created by the poor but by the institutions and policies that we, the better off, have established. We can solve the problem not by means of the old concepts but by adopting radically new ones. SA

The Author

MUHAMMAD YUNUS, the founder and managing director of the Grameen Bank, was born in Bangladesh. He obtained a Ph.D. in economics from Vanderbilt University in 1970 and soon after returned to his home country to teach at Chittagong University. In 1976 he started the Grameen project, to which he has devoted all his time for the past decade. He has served on many advisory committees: for the government of Bangladesh, the United Nations, and other bodies concerned with poverty, women and health. He has received the World Food Prize, the Ramon Magsaysay Award, the Humanitarian Award, the Man for Peace Award and numerous other distinctions as well as six honorary degrees.

Further Reading

GRAMEEN BANK: PERFORMANCE AND SUSTAINABILITY. Shahidur R. Khandker, Baqui Khalily and Zahed Khan. World Bank Discussion Papers, No. 306. ISBN 0-8213-3463-8. World Bank, 1995.

GIVE US CREDIT. Alex Counts. Times Books (Random House), 1996.

FIGHTING POVERTY WITH MICROCREDIT: EXPERIENCE IN BANGLADESH. Shahidur R. Khandker. Oxford University Press, 1998.

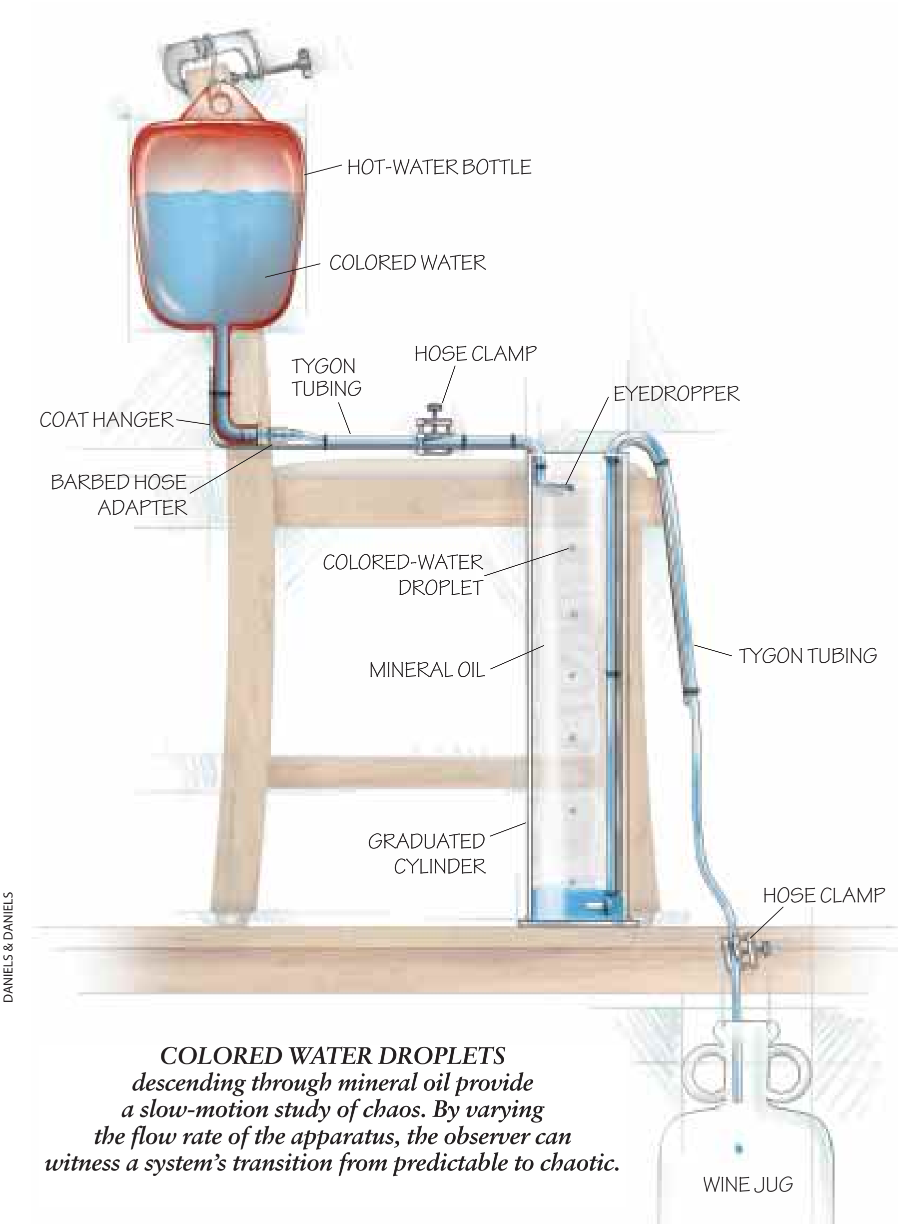
Grameen Bank site is available at www.grameenfoundation.org on the World Wide Web.

by Shawn Carlson

Falling into Chaos

When I was a physics student, I spent most of my time studying things that didn't exist—frictionless pulleys, massless springs, gravitational fields that don't change with height. Scientists have recognized for some time that real systems interact with their environment in ways that elude practical measurements, and over time these effects accumulate. So we've known that idealized solutions can describe systems for only so long. What we didn't realize was just how brief this time period could be.

In the 1980s researchers learned that for many real systems the myriad uncooperative complications of nature cause observations to disagree with predictions extremely quickly. You can, for example, take all the temperature, pressure and wind-speed readings you want, but you just won't have enough information to forecast the weather accurately more than seven days ahead. The reason is that the effects of tiny perturbations, even a jet flying over Salt Lake City, can build much more rapidly than scientists had realized, altering the weather in unforeseen ways. Systems that tumble rapidly into unpredictability are aptly termed "chaotic."



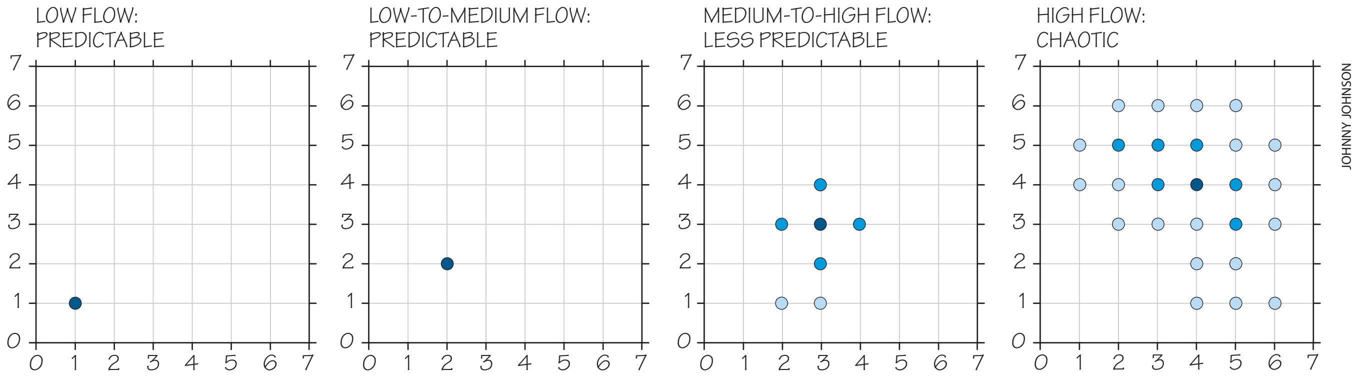
***COLORED WATER DROPLETS** descending through mineral oil provide a slow-motion study of chaos. By varying the flow rate of the apparatus, the observer can witness a system's transition from predictable to chaotic.*

Now, thanks to a delightful device developed by Mahlon Kriebel, a professor of neuroscience and physiology at the SUNY Health Science Center at Syracuse, you can explore the subtleties of chaos at your own kitchen table. Kriebel's apparatus is a slow-motion version of another chaos classic—the dripping faucet. By dropping colored water droplets through mineral oil, Kriebel slows them enough that the onset of chaos can be readily observed and studied.

A graduated cylinder with a volume of 1,000 cubic centimeters makes an ideal chimney to hold the mineral oil, but a tall, clear flower vase would also work well. For the reservoir to hold the colored water, you can use a hot-water bottle with tubing attached. Cut the tubing and mate it with a barbed hose adapter to some Tygon tubing. You'll need a hose clamp to control the flow rate through the tubing and nozzle. Almost any hardware store should have the necessary hose adapter, clamps and tubing. To keep the hot-water bottle well above the nozzle, I fastened the bottle to the back of a chair and placed it on top of my kitchen table.

Kriebel fashions his nozzle from the tip of a pipette, but eyedroppers are easier to come by. The opening on mine was too wide, so I filled the tip with candle wax and then used a heated sewing needle to melt a tiny hole in the wax. Hold the tip of the needle against the wax with a pair of pliers and touch a hot soldering iron to the needle right near the dropper. Applying firm and steady pressure will quickly bore the needle through the wax plug. After that's done, insert your nozzle into the Tygon tubing and secure the connection with a liberal dose of aquarium cement.

Next, to keep the tubing in place after you've situated it, tie it to a length of coat hanger. Use sewing thread and not twine, because the latter sheds fibers that will contaminate the oil. Then install the



***RETURN MAPS** plot a series of numbers in terms of their sequence. For the first point, the* x *coordinate is the first number in the series and the* y *coordinate is the second number. For the next point, the* x *coordinate is the second number and the* y *coordinate is the third number, and so on. From left to right, the graphs are for increasing flow rates of the experiment (darker dots indicate a greater number of instances of that event). Note that as the flow rate is increased, the system becomes less predictable. At the highest rate, shown in the rightmost graph, the system has become chaotic.*

assembly into the cylinder with the nozzle's exit hole centered about 10 centimeters (four inches) below the top of the cylinder.

Lash a second length of Tygon tubing to another coat hanger and install one end at the bottom of the cylinder. Pinch off the other end of the tube with a hose clamp and set it in an empty wine jug. This setup will enable you to siphon some of the colored water that collects at the bottom so that you can periodically return it to the hot-water bottle.

Fill the cylinder with mineral oil from your local drugstore until the liquid just covers the nozzle. Then dye some water with food coloring and pour the solution into the hot-water bottle. Loosen the upper clamp just a bit to allow droplets to form slowly on the nozzle and fall through the oil. You're now ready to begin your excursion into chaos.

The slowest flow rates produce droplets that are all about the same size, and so they fall at nearly the same rate. They reach the bottom one after another, resulting in a pattern that can be recorded as 1, 1, 1, 1,…

At some slightly higher flow rate, the drops fluctuate in size. The larger drops fall faster in the mineral oil than the smaller ones do (the former have a higher terminal velocity because of their greater mass per surface area), and so they catch up and push into the smaller drops, thus falling in clumps of two. At this flow rate, the pattern is 2, 2, 2, 2,… If you increase the flow rate a bit more, you may find a setting at which they will tend to fall in groups of three.

At even faster rates, all heck breaks loose, with data that are not predictable but aren't random either. To understand why, consider the rolling of dice, which is similar to the falling of droplets in that both depend on intractable factors. Change the spin rate or the trajectory of a die slightly as it leaves your hand, and you completely change how it rolls. Likewise, the size of a droplet and its rate of descent depend on uncontrollable variables such as its vibration as it pulls away from the water stream and the fluctuating pressures inside the nozzle.

A truly random process, however, is *completely* unpredictable; whatever you observe one instant has no relation to what came before and no effect on what comes after. In this sense, rolling a die is random, because the odds of getting a "1," for instance, are always one sixth, regardless of how the die has rolled before. But falling drops behave differently, because although one state may not determine the next, it can affect it.

For example, if I continue rolling a die I will eventually roll two consecutive 1s. But at a fast flow rate I never observed two single drops arriving one after another. I thus concluded that creating a single drop always caused the system to enter a state that produced only multiple drops. In other words, the arrival of a single drop guaranteed that a cluster would follow. At least that was some information. And I knew even less about what was coming after that. The fact that each state affected the next but that the outcomes became rapidly less certain is the hallmark of chaos. Chaos inhabits the gap between the perfect predictability of a frictionless pendulum and the pure randomness of rolling dice.

Chaotic systems are easy to spot with the help of a special graph called a return map. For the water-drop data, plot your first point by taking the first number in the series as the *x* coordinate and the second number as *y*. For the second point, use the second datum in the series as *x* and take the third as *y*. Keep going until you've run out of data. For the steady drip of the low-flow faucet, the points all cluster near a single location. For random data, all pairs are equally likely, so the points would be scattered over the map. A chaotic system, on the other hand, is not random. Because each event affects the one that follows, some combinations are more likely than others. If the connection is strong enough, some areas on the map will contain no points at all.

Return maps can open up a universe filled with chaotic delights. Indeed, countless everyday phenomena are chaotic, such as the time between pedestrians passing by on a busy street, the distance between blossoms on a vine and the spacings between stripes on a cat. Plot these variables to discover how truly chaotic our world is. SA

For a good primer on chaos theory, read Chaos, *by James Gleick. More information about this and other projects can be found on the Society for Amateur Scientists's Web site at earth.thesphere.com/sas/WebX.cgi. You may write to the society at 4735 Clairemont Square, PMB 179, San Diego, CA 92117, or call 619-239-8807.*

by Ian Stewart

Most-Perfect Magic Squares

Readers of this column are probably familiar with magic squares. Take, say, the consecutive whole numbers from 1 to 16 and arrange them in a four-by-four array so that every row, every column and the two diagonals all add up to the same total. If you succeed, you've made a magic square of order 4, and the common total is called its magic constant. If you do the same with the numbers 1 to 25 in a five-by-five array, you've created a magic square of order 5, and so on.

Magic squares are a favorite topic of recreational mathematics, and it always seems possible to put a fresh spin on the concept. What is much harder, though, is to make a new contribution to the basic mathematics of the subject. Just such a contribution was published in 1998 by Kathleen Ollerenshaw and David S. Brée in a wonderful book with the slightly forbidding title *Most-Perfect Pandiagonal Magic Squares: Their Construction and Enumeration*. (The publisher is the Institute of Mathematics and Its Applications, Southend-on-Sea, England.)

The book presents the first significant partial solution of one of the biggest unsolved problems in the subject: to count how many magic squares there are of any given order. The main result is a formula for the number of so-called most-perfect squares, a special subset of magic squares with particularly remarkable properties. In case this sounds like an easy problem, it is worth pointing out that the number of such squares of order 12 is more than 22 billion. The number for order 36 is roughly 2.7×10^{44}. Obviously, you can't count these squares by writing them out individually.

Ollerenshaw and Brée tackled the problem using an area of mathematics known as combinatorics, which is the art of counting things "by the back door"—that is, without listing them. A noteworthy feature of the research is that neither author is a typical mathematician. Ollerenshaw, who is 87, spent much of her professional life as a high-level administrator for several English universities. Brée has held university positions in business studies, psychology and, most recently, artificial intelligence.

64	92	81	94	48	77	67	63	50	61	83	78
31	99	14	97	47	114	28	128	45	130	12	113
24	132	41	134	8	117	27	103	10	101	43	118
23	107	6	105	39	122	20	136	37	138	4	121
16	140	33	142	0	125	19	111	2	109	35	126
75	55	58	53	91	70	72	84	89	86	56	69
76	80	93	82	60	65	79	51	62	49	95	66
115	15	98	13	131	30	112	44	129	46	96	29
116	40	133	42	100	25	119	11	102	9	135	26
123	7	106	5	139	22	120	36	137	38	104	21
124	32	141	34	108	17	127	3	110	1	143	18
71	59	54	57	87	74	68	88	85	90	52	73

ILLUSTRATIONS BY SARAH L. DONELSON

MAGIC SQUARE
of order 12 is most-perfect because the numbers in any two-by-two block (black squares) *add up to the same total: 286.*

For mathematical purposes, it is convenient to build a magic square of order n from the integers 0, 1, 2, . . . , $n^2 - 1$, and both the book and this column employ that convention. Traditional magic squares, however, do not include 0; instead they use the integers 1, 2, 3, . . . , n^2. There is no essential difference between the two conventions—if you add 1 to every entry in a mathematician's magic square, you get a traditional square, and conversely if you subtract 1 from every entry in a traditional magic square, you get a mathematician's square. The only thing that changes is the square's magic constant, which is increased or diminished by n.

There is a single magic square of order 1, namely, the number 0 standing alone. There is no magic square of order 2 (the only order that never occurs), because the conditions force all four entries to be equal. There are eight magic squares of order 3, but they are all rotations or reflections of just one square with a magic constant of 12:

1	8	3
6	4	2
5	0	7

A rotation or a reflection of a magic square remains magic, so all magic squares of order 3 are essentially the same. There are lots of different magic squares of order 4, however, and the number explodes as the order increases. No exact formula is known.

One way to make progress is to impose further conditions on the magic squares. For our purposes, the most natural such condition is that the square should be pandiagonal—all the square's "broken diagonals" must also sum to the magic constant. (Broken diagonals wrap around from one edge of the square to the opposite edge.) An example of a pandiagonal magic square with a magic constant of 30 is:

0	11	6	13
14	5	8	3
9	2	15	4
7	12	1	10

Examples of the broken diagonals here are 11 + 8 + 4 + 7 and 11 + 14 + 4 + 1, both of which do indeed add up to 30. The order 3 square is not pandiagonal: for example, 8 + 2 + 5 = 15, not 12. In fact, a magic square cannot be pandiagonal unless its order is doubly even—that is, a multiple of 4.

Most-perfect squares are even more restricted. As well as being magic and pandiagonal, they also have the property that any two-by-two block of adjacent entries sum to the same total, namely, $2n^2 - 2$, where n is the order. (It can also be shown that any magic square with this two-by-two property is necessarily pandiagonal.) The order 4 square shown above is most-perfect—for example, the entries in the two-by-two block consisting of 0, 11, 14 and 5 add up to 30. Note that we include two-by-two blocks that wrap around from one edge of the square to the opposite edge, such as the block consisting of 3, 4, 14 and 9. More ambitiously, the order 12 square shown on the opposite page is also most-perfect.

The key to Ollerenshaw and Brée's counting method is a connection between most-perfect squares and "reversible squares." To explain what these are, we need some terminology. A sequence of integers has reverse similarity if, when the sequence is reversed and the corresponding numbers are added, the totals are all the same. For example, the sequence 1, 4, 2, 7, 5, 8 has reverse similarity, because its reversal is 8, 5, 7, 2, 4, 1 and the sums of the corresponding numbers—1 + 8, 4 + 5, 2 + 7, 7 + 2, 5 + 4 and 8 + 1—are all equal to 9.

A reversible square of order n is an n-by-n array formed by the integers 0, 1, 2, . . . , $n^2 - 1$ with the following properties: every row and column have reverse similarity, and in any rectangular array of integers from the square, the sums of entries in opposite corners are equal. For instance, the four-by-four array of the integers 0 to 15 in ascending order is reversible, as shown below. In the third row, for example, 8 + 11 = 9 + 10 = 19. The same pattern holds for all other rows and all columns. Moreover, equations such as 5 + 11 = 7 + 9 and 1 + 15 = 3 + 13 verify the second condition:

0	1	2	3
4	5	6	7
8	9	10	11
12	13	14	15

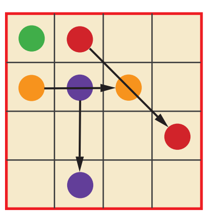
Reversible squares are generally not magic, but Ollerenshaw and Brée prove that every reversible square of doubly even order can be changed to a most-perfect magic square by a specific procedure and that every most-perfect magic square can be produced in this manner. We show the procedure on the order 4 reversible square above. First, reverse the right-hand half of each row:

0	1	3	2
4	5	7	6
8	9	11	10
12	13	15	14

Reverse the bottom half of each column:

0	1	3	2
4	5	7	6
12	13	15	14
8	9	11	10

Now break up the square into two-by-two blocks. Move the four entries in each block as shown below:



That is, the top left entry stays fixed, the top right moves diagonally two squares, the bottom left moves two spaces to the right, and the bottom right moves two spaces down. If any number falls off the edge of the four-by-four square, wrap the edges around the square to find where it should go. (This particular method works only for order 4 squares. For the general case of order n, there is a similar recipe expressed by a mathematical formula.) The result here is a most-perfect magic square:

0	14	3	13
7	9	4	10
12	2	15	1
11	5	8	6

The transformation process sets up a one-to-one correspondence between most-perfect magic squares and reversible squares of doubly even order. Therefore, you can count the number of most-perfect magic squares by counting the number of reversible squares of the same order. At first sight, this change in the nature of the problem doesn't seem to get you very far, but it turns out that reversible squares have several nice features that make it possible to count them.

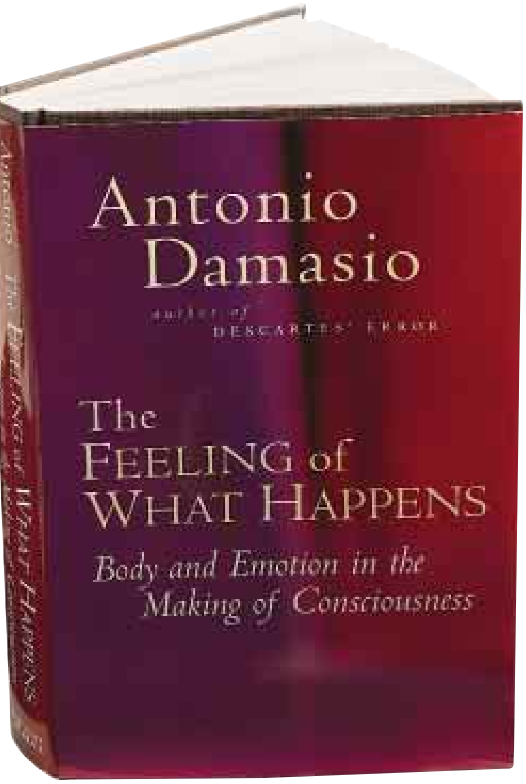
In particular, reversible squares fall into classes. Within each class, all members are related to one another by a variety of transformations, such as rotations, reflections and a few more complicated maneuvers. To construct all members of such a class, it is enough to construct one of them and then routinely apply the transformations. Furthermore, each class contains precisely one "principal" square. Finally, the size of each class is the same. The number of essentially different squares in each class is precisely $2^{n-2}((n/2)!)^2$, where the exclamation point indicates a factorial. (For example, $6! = 6 \times 5 \times 4 \times 3 \times 2 \times 1 = 720$.)

It thus remains only to count how many principal reversible squares there are of a given order and to multiply that number by the above formula. The result will be the number of essentially different most-perfect magic squares of that order. It turns out that the number of principal reversible squares can itself be given as a formula, though a rather complex one. The discovery of this formula, and its proof, leads deeper into combinatorics, so I'll stop here, except to say that for the doubly even orders n = 4, 8, 12 and 16, the numbers of different most-perfect magic squares are 48, 368,640, 2.22953×10^{10} and 9.322433×10^{14}. SA

THE HINT HALF GUESSED

Review by Thomas Metzinger

The Feeling of What Happens: Body and Emotion in the Making of Consciousness
BY ANTONIO DAMASIO
Harcourt Brace, New York, 1999 ($28)



BETH PHILLIPS

As you read the first sentence of this review—trying to find out whether this will be an interesting book, one you might like to read yourself—what exactly is the content of your conscious experience? Is it formed by the letters and their white background, which make up your visual experience? By the feel of the paper in your hands? By thoughts, now slowly beginning to bubble up as you continue to read? Or is it, rather, the experience of *a self in the act of trying to understand?*

In his new book, Antonio Damasio investigates the deep representational structure of consciousness. He argues that it always portrays a relation between an organism and an object and that the basic format of this portrayal is not thought but feeling. Damasio, head of the department of neurology at the University of Iowa College of Medicine and adjunct professor at the Salk Institute, won international acclaim for his 1994 book, *Descartes' Error*. It is easy to predict that *The Feeling of What Happens* will have a similar impact. The book is clearly aimed at a broad, nonscientific audience; in fact, a large part of its strength lies in the elegance of its language and the seeming ease with which it makes difficult issues accessible to readers with highly divergent backgrounds.

In the introductory section, Damasio presents two different notions of consciousness: core consciousness and extended consciousness. Core consciousness is what we share with some nonhuman animals—a simple biological phenomenon, the scope of which is the Here and Now. This basic, integrated representation of one moment and one place is independent of language and reasoning, of conventional as well as of working memory. Essentially, it stays stable across the whole lifetime of an organism. What evolves in the course of a life, subtly flowering from the Here and Now through many levels and grades of content, is an awareness of being situated within an individual history—the conscious experience of anticipated future possibilities and of a lived past. This is extended consciousness. Human beings share it only with a much smaller number of other animals.

Intimately related to this difference between basic and extended consciousness are two distinct notions of self-consciousness: the core self and the autobiographical self. They are central to the new approach to the problem of consciousness that Damasio presents. Again, the richer version—autobiographical self-consciousness—is closer to what we usually refer to when discussing our selves. Its content is a systematic record of the organism's memories of past situations, of its name, and of its likes and dislikes—in short, of the more invariant properties that this organism has discovered about itself. It generates the subjective experience of possessing a transtemporal identity. Interestingly, what it grows out of is a much more transient entity—the core self, which is "ceaselessly re-created for each and every object with which the brain interacts."

This new idea of anchoring our traditional self-concept in a more fundamental notion of continuously changing bodily processes is the central motive of this exciting book. Incessantly pulsating, like a heart pumping blood, the core self swiftly and constantly generates new states in which images of objects and a basal model of the self are integrated into an overarching representation of "a self in the act of knowing."

Answer to a Question Never Asked

For Damasio, solving the problem of consciousness has two aspects. The first is to narrow down the neural correlates of conscious image generation, of what he calls the phenomenal "movie-in-the-brain." The second aspect, which has been widely neglected in the past, is more subtle: it consists of advancing our understanding of how "the *appearance* of an owner and observer for the movie *within the movie*" can be created. We have to understand how a phenomenal self can be generated and perceived as being external to the brain while being fully immersed in a complex, multimodal scene. Damasio points out that, phenomenologically, the presence of the self is often subtle and implicit but that, nevertheless, it is the key ingredient in transforming mere wakefulness into consciousness in the true sense of the word.

The presence of self centers the flow of your interactions with perceptual objects on itself, thereby making them your own experiences. It is here that the author for the first time employs one of many beautiful literary metaphors to come. He writes about the self, silently flickering in the background:

> The presence is quiet and subtle, and sometimes it is little more than a "hint half guessed," a "gift half understood," to borrow words from T. S. Eliot. Later I shall propose that the simplest form of such a presence is also an image, actually the kind of image that constitutes a feeling. In that perspective, the presence of you is the feeling of what happens when your being is modified by the acts of apprehending something. The presence never quits, from the moment of awakening to the moment sleep begins. The presence must be there or there is no you.

My own favorite metaphor, however, is another one: The self, says Damasio, is an answer to a question that was never posed.

In the second part of the book, Damasio explores the relation between emotion and feeling at length, analyzing emotions as bioregulatory devices. Their experiential content expresses the logic of survival *to* the organism, enabling it to feel this logic directly from an inward perspective. As it turns out, consciousness and wakefulness, as well as consciousness and low-level attention, can be separated. Interestingly, what *cannot* be separated are consciousness and the emotions. Damasio now introduces the notion of an unconscious proto-self. Changes in the proto-self, caused by the perception of external images, underlie a high-level mapping in the brain that depicts an ongoing relation between organism and object. This relation is, then, the crucial step into core consciousness, including a conscious core self.

Those readers hungry for some nuts-and-bolts ideas about possible neural underpinnings of the proto-self, the core self and organism-object mapping finally get their fill in part 3 (especially chapter 8, "The Neurology of Consciousness"). The cingulate cortex, a massively somatosensory structure also involved in attention, emotion and the generation of movements, turns out to be a prime candidate for implementing the crucial mapping needed to create the "self in the act of knowing." It is telling that bilateral anterior damage to the cingulate disrupts core and extended consciousness, while preserving wakefulness. On the other hand, because the correlates of the unconscious proto-self and the core self are concentrated in certain nuclei in the upper brain stem and the hypothalamus, damage to those areas causes the most profound and irreversible losses of phenomenal experience. Damasio makes a number of testable predictions, and one can only hope that they will engender a flood of empirical research, leading to a fine-grained mapping of the actual functional matrix realized by those brain regions.

Consciousness and wakefulness, as well as consciousness and low-level attention, can be separated. Interestingly, what cannot *be separated are consciousness and the emotions.*

The Survival Value of Consciousness

Being a philosopher, I will remain mute about empirical details and refrain from further speculation. Most intriguing is how this research supports a certain theoretical intuition that I have long found attractive myself: not only is the human self-model firmly anchored in ancient bioregulatory processes that secure the physical coherence of the organism, but it also builds a bridge. This bridge reaches first to higher-order forms of mental self-organization as seen in the mental simulation of possible worlds or possible selves, and second, and more important, to the universe of social cognition and cultural evolution. We are not machines. The simple fact of our own present existence affects us. Imagination, future plans and the mental states of other living beings *matter* to us, because our cognitive, autobiographical and social selves are riding on the internal dynamics of bodily homeostasis and emotion. In Damasio's words: "Consciousness is valuable because it introduces a new means of achieving homeostasis."

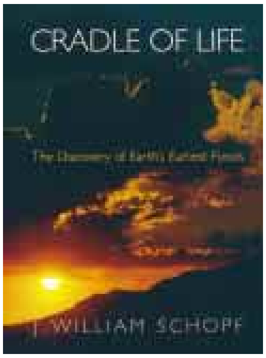
In trying to assess the primary virtue of this book, I would offer its sensitivity to the subtleness of real phenomenology and to the deeper philosophical issues associated with the ongoing search for a convincing theory of consciousness. In particular, and in the jargon of my own theory, Damasio has discovered the central feature of the representational deep structure of conscious experience: "the phenomenal model of the intentionality relation." Put simply, this amounts to the claim that the content of consciousness is a dynamic, transient relation—namely, the relation between a perceiving self and an object. If the internal image of this relation is what philosophers call "transparent"—the organism has no chance of recognizing that all this is just an internal model—then, by necessity, a rudimentary first-person perspective will emerge. The organism will suddenly be phenomenally situated in the movie in his own brain, seamlessly immersed in a biologically grounded virtual reality and simultaneously having an "out-of-brain experience."

It may be that I am blinded to weaknesses in Damasio's approach because our respective theories converge in a number of points. But even aside from this happy convergence of ideas, I believe that the book's clear, beautiful language, its fascinating case studies and the way in which it brings difficult scientific issues to life for readers with many different interests may actually make it a landmark in the interdisciplinary project of consciousness research.

THOMAS METZINGER, a former fellow at the Hanse Institute for Advanced Study in Germany, is a visiting scholar in the philosophy department of the University of California at San Diego. The author of Subjekt und Selbstmodell *(Paderborn: mentis), he has edited two major collections of texts on consciousness,* Conscious Experience *(Paderborn: mentis/Thorverton; UK: Imprint Academic) and* Neural Correlates of Consciousness: Empirical and Conceptual Questions *(forthcoming, MIT Press).*

Cradle of Life: The Discovery of Earth's Earliest Fossils. J. William Schopf. Princeton University Press, Princeton, N.J., 1999 ($29.95).

Schopf's gripping tale describes the birth and growth of "a new field of science, Precambrian paleobiology." The field arose from "the discovery of a vast, ancient, missing fossil record that extends life's roots to the most remote reaches of the geologic past." Schopf, professor of paleobiology at the University of California at Los Angeles and director of the Center for the Study of Evolution and the Origin of Life there, has had quite a bit to do with the development of the field. His account of the work embraces such arresting topics as Darwin's dilemma (the question, as Darwin put it, of "why we do not find rich fossiliferous deposits belonging to these assumed earliest periods" of life and evolution), the origin of life, the roots of human intelligence and the evolution of evolution. Schopf also has a good deal to say about scientists and the way science is done. It all makes for a book that bears out his assertion that "science is enormously good fun!"



Has Feminism Changed Science? Londa Schiebinger. Harvard University Press, Cambridge, Mass., 1999 ($27.95).

Schiebinger's answer to the question can be summarized as "Yes, but...." Since the 1950s, "expectations about who will become scientists have undergone a sea change" favorable to women. "More important, feminism has in many instances changed the content of human knowledge." But women still face many forms of discrimination—in hiring, promotion, respect for their contributions to science and expectations about how they will handle the tension between career and family.

Schiebinger, professor of the history of science at Pennsylvania State University, marshals an abundance of historical data about the education of women, women in science and the discrimination that women who take up careers in science have confronted. She also deals with another question related to her title: "Do women do science differently?" The notion that they might, she says, "is a hypothesis in need of testing." So is "its antithesis—that women will not do science differently."

Code Breaking: A History and Exploration. Rudolf Kippenhahn. Overlook Press, Woodstock, N.Y., 1999 ($29.95).

Code breaking must be preceded by code making, and Kippenhahn discusses that ably, too, even though he does not include it in his title. He has assembled what is more a collection of anecdotes and explanations than a standard history book, but it makes for interesting and hugely informative reading.

Kippenhahn says it took him a while to catch on to the fascination of cryptology. "Even as a student of mathematics I was unaware of the close relation between my subject and the art of encoding and decoding." Now, after a career as professor of astronomy and astrophysics at the University of Göttingen and director of the Max Planck Institute for Astrophysics in Garching, Germany, he is a cryptology master.

He tells of simple codes, such as Julius Caesar's messages based on a three-place displacement of the letters in the alphabet, and complex ones, including the symmetrical encryption based on coding keys. Here, too, is the long-secret story of how the Allies in World War II cracked the codes produced by the Germans with their Enigma cipher machine. And, for the reader who becomes hooked on the subject, Kippenhahn provides in one appendix instructions for making an encrypting machine at home and in another appendix the procedure that turns a computer into an Enigma.

The Pleasure of Finding Things Out: The Best Short Works of Richard Feynman. Richard P. Feynman. Perseus Books, Reading, Mass., 1999 ($24).

Feynman's distinctive voice rings out in this book, doubtless because most of the 13 chapters are transcripts of talks and interviews he gave, mainly to general audiences. On the Nobel Prize in Physics, which he shared in 1965 with Julian Schwinger and Sin-Itiro Tomonaga for their fundamental work on quantum electrodynamics: "I don't like honors ... I've already got the prize. The prize is the pleasure of finding the thing out, the kick in the discovery...." On the computer as compared with the brain: "This new machine may in fact work very well. But, I must warn you that that does not tell us anything about how the brain actually works, nor is it necessary to ever really know that, in order to make a computer very capable." On science: "Learn from science that you *must* doubt the experts." On breadth of interests: "I don't know anything, but I do know that *everything is interesting* if you go into it deeply enough." On these subjects and all the others he treats, Feynman is both interesting and quotable.

Howard Aiken: Portrait of a Computer Pioneer. I. Bernard Cohen. MIT Press, Cambridge, Mass., 1999 ($34.95).
Makin' Numbers: Howard Aiken and the Computer. Edited by I. Bernard Cohen and Gregory W. Welch. MIT Press, Cambridge, Mass., 1999 ($40).

These companion volumes—the first a biography of Aiken and the second a collection of essays and interviews related to his work—paint a detailed portrait of the man described by his former student Anthony Oettinger as "the crusty, demanding, remarkable, and ultimately lovable s.o.b. whose influence has shaped my life and that of millions ever since he publicly ushered in the information age in 1944." That event was the introduction of the giant calculator, or computer, designed by Aiken and variously named the ASCC (for Automatic Sequence Controlled Calculator) and the Mark I.


FROM HOWARD AIKEN: PORTRAIT OF A COMPUTER PIONEER

Even though computer technology eventually took a different path, Cohen (emeritus professor of the history of science at Harvard University, where Aiken did most of his work) calls Aiken "one of the major innovators of the computer age." His other achievements include inaugurating Harvard's program in what is now called computer science and being among the first people to explore possible applications of the new machines to business. Cohen describes the work in detail and concludes that Aiken was "a giant of a man in force of will, in originality of mind, and in achievement" who judged others rigorously and invited similar judgment of himself. Mary Aiken, the computer pioneer's widow, summed up his life as "colorful, inventive, stormy, and changing."

THE FIRST SEX: THE NATURAL TALENTS OF WOMEN AND HOW THEY ARE CHANGING THE WORLD. Helen Fisher. Random House, New York, 1999 ($25.95).

Exactly 50 years ago Simone de Beauvoir wrote in her celebrated book, *The Second Sex,* that "one is not born, but rather becomes, a woman." In *The First Sex,* Fisher points out that over the past half a century a great deal of scientific evidence (not the least of which involves circuits in the brain) has accumulated to show that in some fundamental respects a woman is, indeed, born a woman. Fisher, who is an anthropologist at Rutgers University, draws on her own research and on findings from a range of other fields—biology, psychology, politics, demography, popular culture—to shape an intriguing argument. She maintains that the distinctive skills of women are particularly well suited to the global society of the 21st century. Among those natural talents she includes a preference for cooperation and leading via egalitarian teams, a gift for networking and negotiating, a penchant for long-term planning, an ability to do and think several things simultaneously, an impulse to nurture, emotional sensitivity, and empathy.

Fisher's own provocative ideas and research, a wide sampling of anecdotes, and quotations from the pithy to the poetic bring her case to life. Provocative though this case is, the book is not a diatribe; she acknowledges men's many talents and concludes with these wise words: "This world, I believe, will go beyond the idea of the first sex or the second sex.... The twenty-first century may be the first in the modern era to see the sexes work and live as equals—the way men and women were designed to live, the way men and women did live for so many millennia of our distinguished human past."

MERDE: EXCURSIONS IN SCIENTIFIC, CULTURAL, AND SOCIOHISTORICAL COPROLOGY. Ralph A. Lewin. Random House, New York, 1999 ($19.95).

Lewin has chosen an unlikely subject, "the feces, the matter of coprology," and made a grand run with it. Inasmuch as he is a marine biologist (professor of marine biology at the Scripps Institution of Oceanography of the University of California at San Diego), the subject is some distance from his usual line of work, but he has researched it thoroughly. The result is that the reader will learn as much as, or perhaps more than, she might want to know about coprology and will be entertained while doing it. Examples: Camel dung makes a fine fuel because it is so dry that it will ignite instantly. Hippocrates asserted that pigeon droppings were an effective remedy for baldness, "although whether this claim was based on personal experience is not recorded." An adult salmon, on a protein-rich diet, produces about a kilogram (dry weight) of feces in a year; an elephant excretes almost 50 times that much every day.

FASTER: THE ACCELERATION OF JUST ABOUT EVERYTHING. James Gleick. Pantheon Books, New York, 1999 ($24).

Travel, communication, technology and most other things keep speeding up. "We are in a rush. We are making haste. A compression of time characterizes the life of the century now closing." That is science writer Gleick's snapshot of today's hurried citizens. He gives many examples: the DOOR CLOSE button on elevators, routinely pushed by type A people; the Rush Hour Concerts offered by the New York Philharmonic; the remote control devices that have led to a frenzy of channel surfing.

But is the incessant hurry gaining us anything? Gleick cites several common time-consuming irritants, suggesting that the answer is "Not much." Tollbooths, he says, "are monuments of civic ineptitude—along with the telephone lotteries at city agencies and queues at unemployment and passport offices." The telephone, supposedly a saver of time, is the source of some spectacular delays, notably for callers put on hold. "And before you get on hold, you must get past the busy signal." The Texas Transportation Institute's Urban Mobility Study found that in Los Angeles alone, more than 2.3 million person-hours were lost to traffic delay in 1994. What can the hurried and harried soul do about all this? At least, Gleick says, "recognize that neither technology nor efficiency can acquire more time for you, because time is not a thing you have lost.... It is what you live in. You can drift or you can swim, and it will carry you along either way."

UNDUE RISK: SECRET STATE EXPERIMENTS ON HUMANS. Jonathan D. Moreno. W. H. Freeman, New York, 1999 ($24.95).

The infamous Nazi medical experiments on human subjects represent an extreme of government arrogance. But many other nations, including the U.S., have done similar if less egregious things, usually in the name of national security. Radiation, chemical agents and disease-causing agents are tested on people who have not given informed consent and may not even know they were test subjects. Moreno, professor of biomedical ethics at the University of Virginia and director of the Center for Biomedical Ethics there, decided to pursue the subject after his service on the presidential Advisory Committee on Human Radiation Experiments, appointed by President Bill Clinton in 1994 to investigate allegations of government-sponsored radiation research on unknowing citizens during the cold war. He tells of secret medical experiments, some ancient but most during and since World War II, by many nations. "If there is a single lesson to be gleaned from the story of military-medical human experiments," he says, "it is that we can expect them to continue in the future.... I believe it is also true that these experiments can be done ethically."

THE ARCHITECTURE OF SCIENCE. Edited by Peter Galison and Emily Thompson. MIT Press, Cambridge, Mass., 1999 ($65).

The question before the house during a two-day conference at Harvard University in 1994 was, "How do the buildings of science literally and figuratively configure the identity of the scientist and scientific fields?" Perhaps it has no categorical answer, but the conferees—architects, scientists, sociologists and historians—offered plenty of possibilities. Galison (a professor of the history of science and physics at Harvard) and Thompson (an assistant professor of the history and sociology of science at the University of Pennsylvania) assemble in this book several of the papers delivered

PROPOSED SUPERCONDUCTING SUPER COLLIDER LABORATORIES, FROM *THE ARCHITECTURE OF SCIENCE*

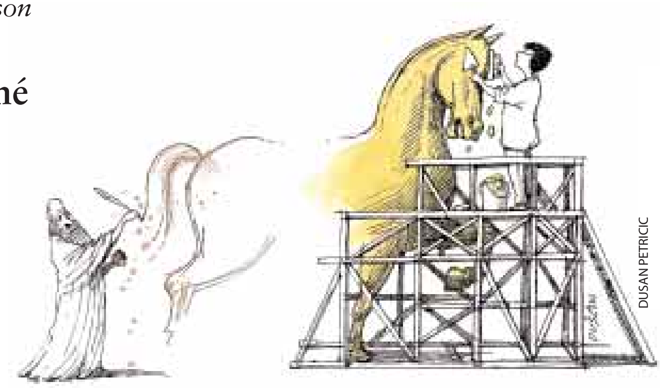
at the conference, plus a few others. Among the subjects discussed are 19th-century science buildings, modern space, whether or not architecture is a science, hospitals, the Fermi National Accelerator Laboratory in Batavia, Ill. ("a scientific project in which architecture was of crucial importance," according to its former director, Robert R. Wilson), and the Lewis Thomas Laboratory at Princeton University as compared with the nearby Center for Advanced Biotechnology and Medicine in Piscataway, N.J. Illustrations, many of them eye-catching as well as apposite, abound. "It is our collective hope," the editors say, "that this volume will encourage a great deal more inquiry into the encounters between architecture and science." SA

COMMENTARY

WONDERS

by Philip and Phylis Morrison

The Surefire Résumé



DUSAN PETRICIC

Ruler of the wealthy city-state of Florence, banker Lorenzo di Medici was First Patron of its arts. A costly settlement had averted a losing war, so in 1472 even the Magnificent was cutting back. One wonderfully versatile Florentine artist at 30 began to think of the future. The duke of fast-rising Milan was eager to lure artists northward. Time to send him a good résumé! Leonardo da Vinci quickly won an offer, to work fruitfully 17 years in Milan, until displaced by occupation troops.

Da Vinci's résumé was neither modest nor exaggerated. Sample it, much cut: "Most illustrious Lord...I shall endeavor...to explain myself...showing...my secrets and offering ... to work with effect...on all these things.... I have plans of bridges.... I have plans for destroying every fortress...even if it were founded on rock. I will make covered cars, safe and unassailable.... In times of peace...can give perfect satisfaction...in architecture...sculpture...and I can do in painting whatever can be done, as well as any other, be he who he may. Moreover, the bronze horse may be taken in hand, which shall endow with immortal glory...the happy memory of the Prince your Father and of the illustrious house of Sforza."

In Milan after 1482, Leonardo painted his *Virgin of the Rocks, Lady with an Ermine* and more and paid much heed to courtly pageants, the Cathedral dome, studies of water, air and light, even the mechanics of Milanese industry. "I started this notebook," he wrote in 1490, "and restarted on the Horse." He designed and produced an over-the-top gala at Duke Ludovico's 1491 wedding to Beatrice d'Este, a lady Leonardo painted very well. A few years later he completed with enormous energy his renowned painting *Last Supper.*

He worked at realizing the Horse as he did on the *Supper*. In 1493 he showed a full-scale clay model of his 24-foot colossus and designed intricate schemes for casting this biggest of all bronze horses. The duke set aside an 80-ton stock of bronze, largely old cannon and bells, to be recast someday into the Horse. But all too soon that stockpile of bronze was requisitioned again for artillery. Sforza's duplicitous maneuvers brought on defeat, and the forces of France's king, Louis XII, took Milan. A company of elite archers destroyed the clay Horse, a most satisfying target, on one bitter day, now reckoned as September 10, 1499. Leonardo soon left the occupied city, and Sforza himself was taken to France as prisoner of war for life.

The duke set aside an 80-ton stock of bronze, largely old cannon and bells, to be recast someday into the Horse.

Although the artist often recorded steps of his work in progress, not even a drawing of the final horse remains. Freelance Leonardo worked in many cities afterward, finally for Louis XII and his successor, still sovereign of Milan. For years the old master lived on the Loire's green banks, adjoining the royal dwellings. He died at 67, a white-bearded sage, an honored trophy at the French court, where they called him "divine Leonardo." He lies buried in France.

Poignancy has always surrounded Leonardo's unfulfilled determination to create that Horse. Half a millennium is time enough for strange events to unfold. Thus, on September 10, 1999, 500 years to the day since Leonardo lost his last hope, a 24-foot spirited stallion in golden-brown bronze was unveiled near the Hippodrome in Milan, a gift to the people of Italy from the people of America, a new work of art in homage to the nonpareil from Leonardo.

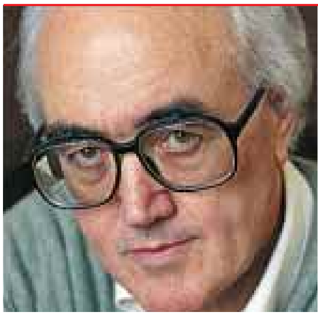
The unfolding began with two big notebooks of Leonardo's that were a bequest to the palace library in Madrid in 1642. Private and ignored, then misfiled for 150 years, they came to light by chance in the National Library there in 1965. The find made a sensation and was discussed and excerpted everywhere. One drawing was a vigorous stamp-size sketch in red ocher, perhaps the first of many studies for the Horse. Retired airline pilot and amateur sculptor Charles C. Dent of Allentown, Pa., was moved as he saw the images and read of genius frustrated. He conceived the gift and dedicated himself toward its realization until his death in 1994, having created in 1982 a nonprofit organization to carry out his plan.

The sculptor of the clay horse finally chosen to be cast in heroic bronze is an American, Nina Akamu of Cold Spring, N.Y., who had studied in Italy and devoted much time to animal forms. "Perhaps," she wrote, "the modern... Horse can be seen as a symbol for... creative energy...focused on a distant goal. The...awesome size stands as a testament to the magnitude of Leonardo's...creation."

The Horse was made in the Tallix Art

Continued on page 131

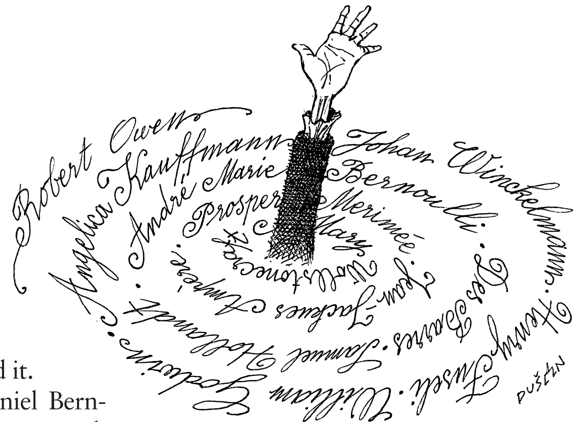
COMMENTARY



CONNECTIONS

by James Burke

Various, Unrequited



DUSAN PETRICIC

Recently, in the beautiful Italian coastal town of Lerici, near La Spezia, I was staring out the window of the Hotel Shelley at the bay where the eponymous poet drowned overboard in 1822 and thinking of his hard-done-by wife.

A year after the incident, pale and interesting Mary, passing through Paris on her way back to London, was enraptured to see a drama production of something she'd written after being inspired by Sir Humphrey Davy's chemistry lectures, although maybe not the way Davy might have intended. The play was *Frankenstein,* and the French reaction was "rave." Mary herself was having roughly the same effect on a local Romantic novelist, frequently unrequited lover and Parisian culture-vulture, name of Prosper Mérimée. (Leaf through a few pages of his *A Chronicle of the Time of Charles IX*—it'll cure your insomnia.) I've spoken of Mérimée before—you can't cross the French 19th century without bumping into him—because he made it his business to know everybody who was anybody.

One being a school pal. Jean-Jacques Ampère, Scandinavian-mythology freak, philologist and son of André-Marie, the electrical whiz who gave his name to yet one more aspect of electricity I don't fully understand. Poor old Ampère *père* had a rotten life: guillotined father, died-young first wife, runaway second wife, and a mother-in-law who must have triggered the original jokes. So André-Marie buried himself in his work. Ended up shocking the intellectual livewires of Europe with the science of electrodynamics. You get a feel for the man from the fact that while he was still a bookish child prodigy, some librarian in Lyons told him the mathematical text that he wanted to study that day was in Latin, so he went home and learned it.

Mind you, reading Daniel Bernoulli's math in *any* language must have been daunting. One of eight mathematicians produced by three generations of Bernoullis, each more incomprehensible than the next, Daniel turned out weighty stuff like the explanation for why your airplane's wings keep you up in the air (a.k.a. Bernoulli's principle: with a curved aerofoil, the air over the top goes faster than the air under the bottom, the over-the-top air pressure drops, and you get sucked into the sky). Daniel also dipped into spheres rolling down inclined planes, the math of oscillating organ pipes and (a fascinating glimpse into 18th-century high-tech) the optimal shape of sand-filled hourglasses. And his experimental physics classes in Basel laid 'em in the aisles.

> *Bernoulli's math in* any *language must have been daunting.*

One face in the student crowd was that of Joseph Frederick Wallet Desbarres, who later moved to England and in 1756 was commissioned as a lieutenant in the British Royal American Regiment. Desbarres had the job of recruiting American colonials (who would be better than the Redcoats at fighting the French in the Canadian backwoods) and also of hiring anybody who could survey. He gave the latter job to Samuel Holland, ex-Dutch-army engineer and triangulator extraordinaire. Desbarres and Holland (and a few helpers) began with local survey work in preparation for the British attack on Québec and ended with production of the great Atlantic Neptune charts. These gave the British navy the triangulated lowdown on every creek and inlet along the entire (potentially revolutionary) American eastern seaboard. Alas, by the time the last triangle had been dotted, so to speak, and the great work was ready for publication, it was already 1777. Too much, too late.

Back in 1759 Desbarres and Holland had taught most of what they knew about surveying (and its cousin skill, navigation) to a young naval nobody, who then went back home and became a somebody, ending up in command of HMS *Endeavour* on the 1768 Tahiti expedition to observe the transit of Venus. After which, during three Pacific expeditions, he (Capt. James Cook) charted much of New Zealand and discovered New Caledonia, the South Sandwich Islands and South Georgia. In Britain, between voyages, he was a big enough exploratory name to have his portrait painted by Sir Nathaniel Dance-Holland, whose main claim to fame (not much) was his brother, George, a minor member of the new Neoclassical fraternity of architects. Once, that is, the two bros had taken the obligatory trip to Italy in the 1750s to ogle the recently uncovered and mind-boggling views of classical Pompeii, Herculaneum et al.

Another local ogleworthy sight, with whom Nathaniel became unrequitedly infatuated (another one!), was a Swiss painter named Angelica Kauffman. At this time, expatriate *dolce vita* types in Rome (Ms. Kauffman included) sat at the feet of a gay Prussian art maven (he invented the study of art history), Johann Winckelmann, the oracle you went to hear (as did Nat and George) to find out what to see. And then what to say. Winckelmann wrote a massive analysis of ancient Greek art and architecture and was the first to suggest you had to understand a period to understand its art. Historical relativism, I believe it's called now. Good stuff, except that it laid the ground rules for the vacuous chatter that passes for cultural programming on TV and radio these days.

Anyway, one of Winckelmann's many admirers was another Swiss, Henry Fuseli, a dauber who ended up in London and at one point edited a book by the Swiss divine Johann Lavater. This influential volume, entitled *Physiognomy,* featured the latest pseudoscientific stuff on how to read psychological traits from facial characteristics. Fuseli's own physiognomy must have been pretty good, because every woman he met fell for him. But the only meaningful—though (wait for it) unrequited—relationship he seems to have aimed at (except for his marriage, of course) was with a woman named Mary Wollstonecraft.

She was probably one of the first true feminists, in 1792 writing a powerful emancipatory article called "A Vindication of the Rights of Woman." In 1796 she had an affair with, became pregnant by and married (in that order) one of the foremost liberal thinkers of the time: William Godwin. In 1793, when Godwin's "Political Justice" was published, it had made him an overnight celeb among free thinkers of every stripe. Godwin advocated what sounds like an early form of Communism and came down heavily on the side of nurture rather than nature, fingering education as the key to shaping character. This went over very big with enlightened industrialists such as Robert Owen, the first mill owner in Scotland to provide schooling for his workers' children (his future workers).

William Godwin was the radical's radical, even going so far as to say that women were capable of reason, a statement so outrageous it did the trick with Mary. Alas (in the final moments of this tale of woe), it must be added that Godwin's passion, too, was fairly unrequited, because Mary Wollstonecraft Godwin died of a fever shortly after giving birth to their daughter. Leaving the child (named after her) to grow up without a mother's care and protection. Possibly as a result of which she was eventually to elope with a ne'er-do-well poet.

Who wrote good enough verse but couldn't sail to save his life. SA

Wonders, *continued from page 129*

Foundry in Beacon, N.Y., on the Hudson, one of the finest modern art foundries. First a team of young sculptors took key dimensions from the clay pattern, point by measured point for enlargement, each length increased by a factor of three. Then they modeled the complex surface forms. Over 60 distinct bronze pieces were individually cast, most of them elegant plates averaging 400 pounds, four feet square and under half an inch thick. That is not at all unlike the antique practice, although now the lift cranes handle 50 tons, the alloy is precisely chosen, and the pouring and welding are high skills augmented by apt instrumentation. The pieces, supported on an interior armature of stainless-steel plates and tubes, were then welded, seams burnished, into the full Horse. After its public display in Beacon this past June, the Horse was cut tenderly apart and flown to Milan in seven crates, for rewelding and meticulous refinishing.

Bronze has made castings for weaponry and for wonder over more than 5,000 years, in cultures from the Mediterranean to ancient China and Thailand. (The biggest of all bronzes is in Nara, Japan, a reclining Buddha of above 500 tons. Our Statue of Liberty is of thin hammered copper sheet supported by an iron and steel tower.) The casting alloy now in use—mostly copper, about one-tenth tin and varying small amounts of other metals—was familiar to the armorers of both Greeks and Trojans. Its virtues are clear: the alloy melts at lower temperatures than copper, and its fluidity fills the molds with ease. Its expansion on solidification is enough to guarantee the reproduction of fine molded detail and yet not so large that it threatens the basic form of the piece. Copper is mined widely, but it was never cheap, a metal for rulers, priests, warriors—and artists!

Visit Milan. Nearer home, admire a duplicate casting of the bronze Horse in Grand Rapids, Mich., at the sculpture park given by Frederik Meijer to that city. No real horses have ever stood so tall, although 20 million years ago four-legged steppe creatures of flesh and bone came close to the stature of the Horse of metal. They were giant hornless rhinos and heavy of build.

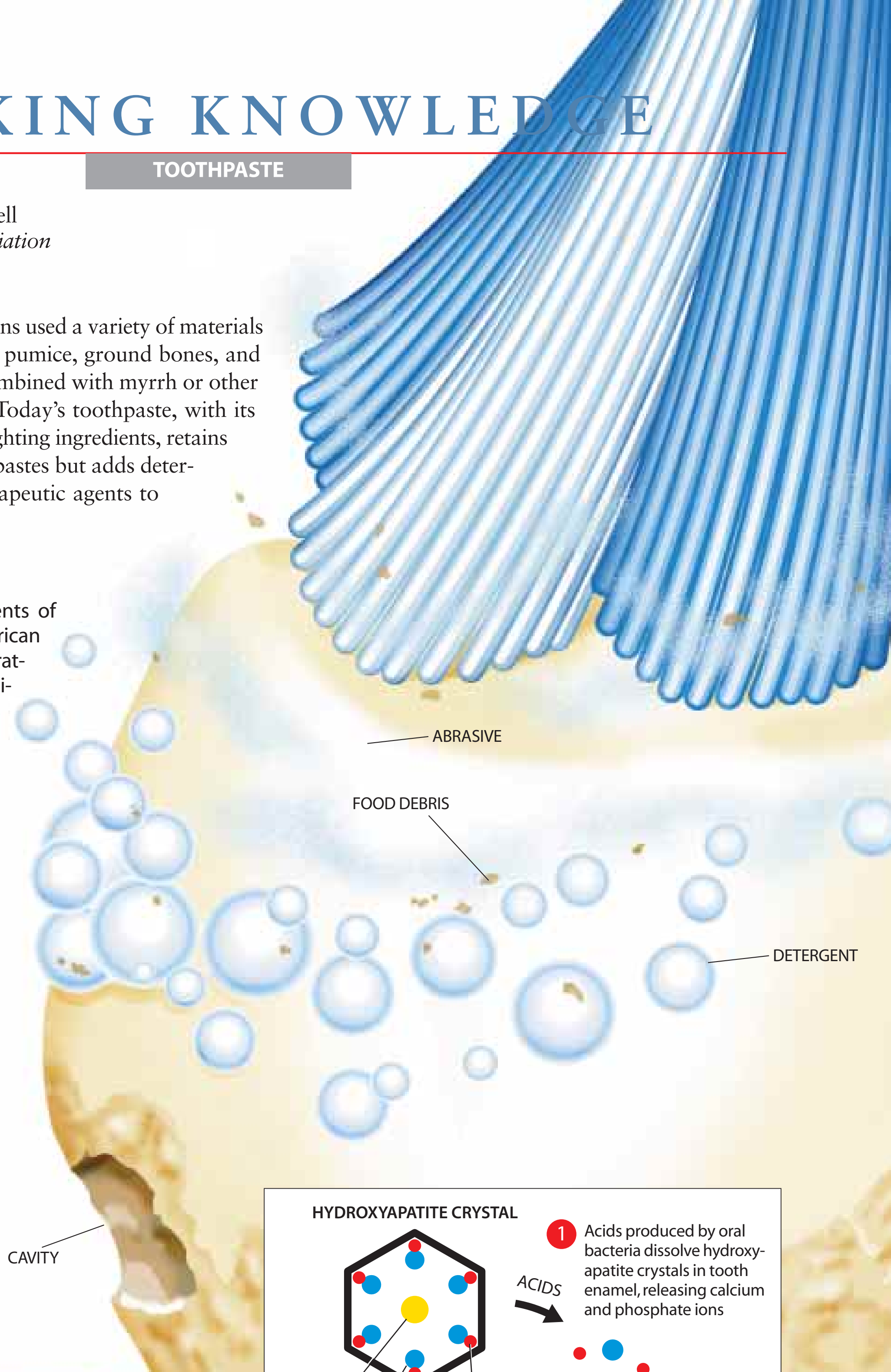
Leonardo da Vinci's Horse, Inc., invites Web viewers to check out www.leonardoshorse.org and its many links. SA

WORKING KNOWLEDGE

TOOTHPASTE

by Kenneth H. Burrell
American Dental Association

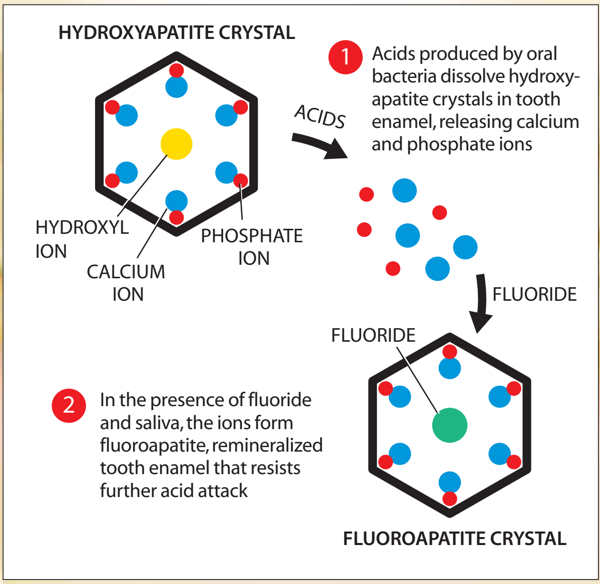
The ancient Greeks and Romans used a variety of materials to clean the teeth, including pumice, ground bones, and oyster shells or eggshells, combined with myrrh or other substances that acted as astringents. Today's toothpaste, with its breath-freshening flavors and cavity-fighting ingredients, retains the function of the ancient prototype pastes but adds detergents for enhanced cleaning and therapeutic agents to help keep the teeth and gums healthy.



ABRASIVES remain principal components of toothpaste. Almost all modern American toothpaste contains mildly abrasive hydrated silica particles, measuring four to 12 microns in diameter. Other agents such as calcium carbonate, dicalcium phosphate and alumina trihydrate may also be incorporated. The level of abrasivity is critical: the toothpaste must be abrasive enough to help remove stains and dental plaque without damaging tooth surfaces.

DETERGENTS, usually sodium lauryl sulfate, are used as foaming agents. They loosen food particles and other debris and ease movement of the abrasive across the teeth and gums.

THERAPEUTIC AGENTS such as fluoride help keep the teeth and oral soft tissues healthy. U.S. toothpastes commonly contain three fluoride compounds—sodium fluoride, sodium monofluorophosphate and stannous fluoride—to fight dental caries (tooth decay). In a process known as demineralization, acids produced by bacteria in the mouth dissolve tooth enamel, but fluoride aids in reversing this process. Saliva serves as a reservoir for calcium and phosphate, which along with fluoride, remineralize tooth enamel (*1*, *2*).



GEORGE RETSECK; INSET BY BRYAN CHRISTIE