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SCIENTIFIC AMERICAN

APRIL 1998 $4.95

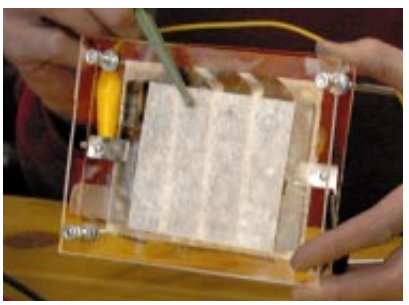
SPECIAL REPORT:

THE UNWIRED WORLD

An Insider's Guide to the Future Technologies of Telecommunications

SCIENTIFIC AMERICAN

April 1998 Volume 278 Number 4



SPECIAL REPORT:

Wireless Technologies 69

Demand for cellular phones and wireless modems is skyrocketing—and they represent only a few of the applications for the new wave in communications-on-the-go technology. In this special report, experts size up the infrastructure being built today for billions of consumers tomorrow.

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About the Cover

A High Altitude Long Endurance (HALE) platform hovering more than 20,000 meters (66,000 feet) over the city of Boston could send and receive millions of telecom signals simultaneously for the metropolitan area. It is one of several types of systems that could provide the wireless infrastructure of the next century (see page 80). Aircraft image by David Fierstein; courtesy of Angel Technologies. High-altitude image by Photo Researchers, Inc./CNES; licensed by SPOT Image Corporation.

Visit the SCIENTIFIC AMERICAN Web site (http://www.sciam.com) for more information on articles and other on-line features.

How *Scientific American* Works

The laboratory is where it starts. Brilliant scientist (A) makes an important discovery. His loud cry of "Eureka!" startles sleep-deprived postdoctoral fellow (B), who drops a cage of laboratory mice (C). The animals, dizzy from running mazes, dash around the room, knocking experimental notes (D) onto the floor along with unfinished grant proposals, flyers for upcoming scientific meetings, the brilliant scientist's blurry vacation photographs, and a half-finished sandwich. Worried graduate student (E), acting on vaguely worded instructions from brilliant scientist, bundles all of the above into a large manila envelope (F) and mails it to *Scientific American*.

Upon arriving at our offices, the envelope is promptly opened by unpaid interns (G) who, desperate, eat the half-finished sandwich. The administrative staff (H) collects the rest of the contents and passes them to the editor in chief (I, that is, me), who immediately reaches for his large bottle of aspirin (J). The string attached to the aspirin bottle opens a valve on the coffeemaker (K), pouring a gallon of hazelnut Colombian directly into the waiting mouth of the article editor (L). Twitching with caffeine, that editor is now ready to begin her work.

Editing is a highly complex process and quite impossible without a lot of heavy machinery. First, we feed the manuscript through the Dejargonizing Passive Phrase Reallocator. Operating on quantum-mechanical principles of wave-particle equivalence, it changes sentences such as "Samples obtained from Site 46 were subjected to analysis by multiple investigators and subsequently reintroduced to the environment from which they had been collected" to "We examined the specimens, then put them back." The Implicit Inflection Remodulator makes sure that sentences carry some form of punctuation at least every 200 words, whether they need it or not. Most awe-inspiring is the Randomizing Optimum Structural Facilitizer, a cross between a paper shredder, a house fan and a sewing machine, which takes apart a manuscript at the subatomic level and reorganizes it.

The Dejargonizing Passive Phrase Reallocator does the real work.

It's roughly at this point in our work that the brilliant scientist (A) contacts us again, informing us that the manuscript we are working on was sent by mistake and that the real one is on its way. Also, he would like his vacation photographs back. I (I) then reach for my aspirin again, and the editing begins anew.

Ahem. Nobody was ever better at describing great mechanical contrivances and the way things ought to work than Rube Goldberg. In the spirit of April Fool's Day, we salute his inventiveness with our Working Knowledge, found on page 108.

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LETTERS TO THE EDITORS

TWIN TOWERS

SPIRE atop Petronas Tower

J. APICELLA *Cesar Pelli & Associates*

The skyscrapers of the 1930s (the Chrysler Building and the Empire State Building) were built just as the Great Depression took hold of the U.S. economy. The World Trade Center and Sears Tower were also leading indicators of the economic malaise of the 1970s. And just as Malaysia completes its showpiece, the Petronas Twin Towers (*right*) ["The World's Tallest Buildings," by Cesar Pelli, Charles Thornton and Leonard Joseph, December 1997], the economy of the region dives into disaster. In retrospect, this should be no surprise; during these periods, symbolism took great precedence over substance.

MEREDITH POOR
San Antonio, Tex.

Had the Petronas Towers been built alongside the Sears Tower, those of us who actually worked on the 102nd floor of the Sears Tower would have laughed looking out at the pip-squeak spires of the new buildings. The Sears Tower is a *building;* the Petronas Towers are buildings with spires.

KERMIT SLOBB
Northbrook, Ill.

Thank you for the wonderful phallic cover on the December issue! The Petronas Towers are a hymn to male bonding and a joy to behold. Lauds to Cesar Pelli and his associates in New Haven and to *Scientific American* for these beautiful images and the fine explanatory articles that they accompany.

LOU HARRISON
Aptos, Calif.

BUILDING THE BIGGEST

To William J. Mitchell's perceptive comments on the demise of the skyscraper ["Do We Still Need Skyscrapers?" December 1997], might I contribute one more bit of evidence that the prestige factor is no longer operative in North America? When one sets out to find the tallest structure in North America, one notices only a minor notation on a highway map announcing the location of a television tower 2,063 feet (629 meters) high—more than 40 percent higher than the Sears Tower. The owners have erected no great sign advertising their prodigy, nor do they even advertise it on the Internet.

One can't help wondering what modesty prevails here. Oh, yes, the tallest man-made structure in North America—the KVLY television transmitter tower—is located about 35 miles northwest of Fargo, N.D.

GERALD DAVIDSON
Red Lodge, Mont.

TRUTH OR DARE

In his article about the polygraph [Working Knowledge, December 1997], Joel Reicherter asserts that "the validity of polygraph tests rests on the theory that someone who is lying will perceive the relevant question ('Did you steal $500 from the office safe?') as more threatening than the vaguer control question ('Have you ever stolen something worth more than $25?')." In fact, the validity of the polygraph test rests on the far more dubious assumption that more pronounced physiological responses to the relevant question rather than the control question are diagnostic of lying per se. Innocent subjects might perceive the first question as more threatening for a variety of reasons that have nothing to do with guilt or lying: for instance, they might be fearful that they will be found guilty, or they are indignant at being unjustly accused. Consequently, the standard polygraph test is biased against the innocent and yields a high rate of false positives.

SCOTT O. LILIENFELD
Emory University

Reicherter replies:

My article was designed to describe only the rudimentary concepts behind polygraph tests; it was not designed to be a comprehensive treatise on the theoretical foundations of the polygraph.

That said, there are several questioning formats available to the examiner administering a polygraph that have been subjected to the rigors of scientific inquiry. Error rates, including false positives, do vary depending on the format of the test, the nature of the issue being tested and the quality of information available to the examiner.

Some of these methodologies meet generally accepted scientific standards, but others do not. For example, the type of polygraph test once commonly used in preemployment screening produces high error rates and does not meet acceptable scientific standards of assessment; such tests are now prohibited for most jobs by the Employee Polygraph Protection Act of 1988. So-called guilty-knowledge tests, which include questions containing information known only to a guilty subject, have very low error rates, particularly false positives.

WILLIAMS SYNDROME

The recent article "Williams Syndrome and the Brain," by Howard M. Lenhoff, Paul P. Wang, Frank Greenberg and Ursula Bellugi [December 1997], was a poignant and insightful piece. How much gentleness, insight and wisdom would be lost from our cultural heritage if we were to screen out such "defects" and narrow the human genome. Although I anxiously await the benefits that modern genetics may bring us, I am perplexed by the thought of how little of human nature we can truly measure with superficial tools such as the Intelligence Quotient.

ROBERT D. SHEELER
Mayo Clinic
Rochester, Minn.

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. Letters selected for publication may be edited for length and clarity.

50, 100 AND 150 YEARS AGO

SCIENTIFIC AMERICAN

APRIL 1948

TECHNOLOGY TRANSFER—"During the past two years, federal investigators have surveyed all German advances which could be of value to American industry. Their reports, available for the price of reproduction, contain descriptions of processes, equipment, formulas, plant layouts and other technical data. Many industries should benefit. For example, shops which do sheet metal stamping will be interested in a process for extruding cold steel, just as we extrude tin, zinc, copper and other non-ferrous metals."

NONINVASIVE MEASURES—"A new X-ray gage measures the thickness of red-hot steel without physically contacting it in any way. The device shoots one X-ray beam through the hot steel strip as it moves off the finishing stands in a rolling mill. Simultaneously, a second X-ray beam from the same source penetrates a standard reference sample of a desired thickness. The instrument then compares the intensity of the two beams; a difference indicates that the strip is either more or less than the desired thickness."

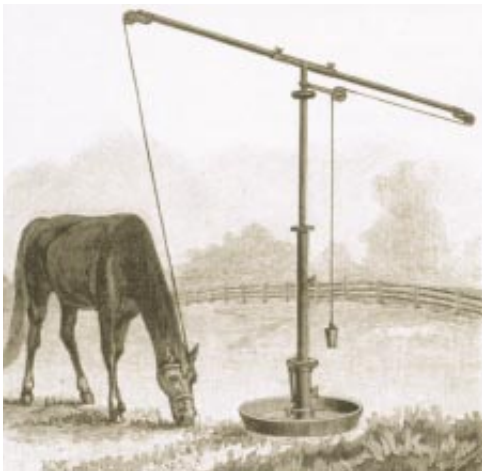
APRIL 1898

SUB SUCCESS—"Extraordinary interest attaches to the trials of the Holland submarine torpedo boat, which are now being carried out in New York Harbor. The John P. Holland submarine boat embodies the results of some twenty years of experimental work on the part of the designer, who firmly believes that this type is destined to become the most deadly weapon of future naval warfare. This is the first submarine boat of its type ever built and tested. The 'Holland' (as she is called) is of 75 tons displacement, 55 feet long and 10 1/4 feet in diameter. The steel hull is cigar-shaped." [*Editors' note: The* Holland *was purchased and commissioned by the U.S. Navy in 1900.*]

WIRELESS TELEGRAPHY—"At a time when relations are strained between Spain and this country, nothing could be more welcome than a practical method of carrying on electrical communication between distant points on land, and between ships at sea, without any prearranged connection between the two points. During the last year Guglielmo Marconi, an Italian student, developed a system of wireless telegraphy able to transmit intelligible Morse signals to a distance of over ten miles. It has been left, however, for an American inventor to design an apparatus suitable to the requirements of wireless telegraphy in this country. After months of experimenting, Mr. W. J. Clarke, of the United States Electrical Supply Company, has designed a complete wireless telegraphy apparatus that will probably come rapidly into use."

MEDITERRANEAN DIET—"Medical authorities are generally agreed as to the value of olive oil medicinally, finding it also a potent agent for any defects of the excretory ducts, especially the skin; eczema has rapidly disappeared upon a discontinuance of starch foods and the substitution of a diet of fresh and dried fruits, milk, eggs and olive oil. It has long been observed that those who use olive oil as a common article of food are generally healthier than those who do not."

CANNIBAL DIET—"According to a French writer named Petrie, twenty per cent of all cannibals eat the dead in order to glorify them; nineteen per cent eat great warriors in order that they may inherit their courage, and eat dead children in order to renew their youth; ten per cent partake of their near relatives from religious motives, either in connection with initiatory rites or to glorify deities, and five per cent feast for hatred in order to avenge themselves upon their enemies. Those who devour human flesh because of famine are reckoned as eighteen per cent. In short, deducting all these, there remains only twenty-eight per cent who partake of human flesh because they prefer it to other means of alimentation."



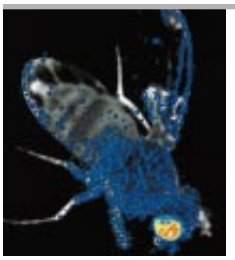
A better tether for animals

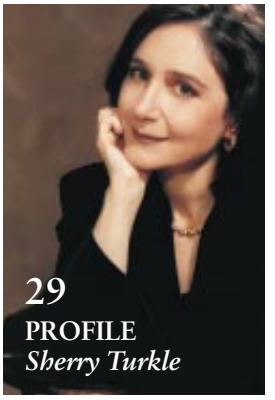
FLEXIBLE TETHER—"The illustration represents a tether made in adjustable sections. It is designed to be comfortable for the feeding animal, while giving the animal great freedom of movement within prescribed bounds without danger of entanglement in the tether rope. Three pulleys afford a guideway for the tether rope or chain, which is attached at one end to the halter or bridle on an animal's head, and the other end to a weight."

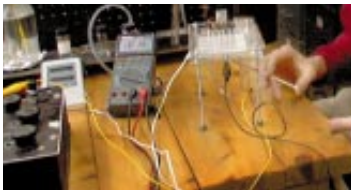
APRIL 1848

EGYPT'S ANCIENT ARTS—"French explorers have exhumed a new 'book' of monumental Egyptian history. Upon the immense walls of the tombs and temples were spread out pictorial or sculptural representations of the entire social economy of the Egyptians, 1,800 years B.C., faithfully represented. These pictorial delineations prove that many arts supposedly unknown to antiquity were well understood: the manufacture of glass, porcelain and fine linen, the imitation of precious stones with glass, and the principle of the Railway and the artesian well. Astronomical tables prove also that the wise men of Egypt possessed the art of bringing scientific instruments to a high degree of perfectness."

NEWS AND ANALYSIS







IN FOCUS

LIVES IN THE BALANCE

Researchers plan to modify HIV and try it as a live AIDS vaccine

An estimated 16,000 people become infected with the human immunodeficiency virus (HIV) every day, according to the United Nations AIDS program, and 90 percent of them are in developing countries where antiviral drugs are unavailable. Although some candidate HIV vaccines made from noninfectious material do stimulate immune responses against the virus in laboratory tests, none has proved it can protect people from AIDS.

In desperation, researchers in Australia and in the U.S. are now pushing for clinical trials of vaccines that are essentially weakened yet still infectious forms of HIV. Within a couple of years, if plans move forward, HIV-negative volunteers in these countries will be vaccinated with an attenuated strain of either HIV itself or a "molecular clone," DNA that can establish a viral infection. The Chicago-based International Association of Physicians in AIDS Care had, as of February, lined up 276 HIV-negative volunteers who are at high risk of acquiring HIV and who are willing to be vaccinated. Charles F. Farthing, a physician who is volunteer number one and medical director of the AIDS Healthcare Foundation in Los Angeles, says, "I think the risk is very, very minimal, and that's what I want to prove."

Proponents of live-virus vaccine studies point to animal tests with HIV's viral cousin, simian immunodeficiency virus (SIV), which causes illness in monkeys. Such experiments suggest that a genetically modified version of HIV might establish in humans a low-level infection capable of protecting against the natural form. Many successful vaccines for other diseases contain live viruses, these advocates note, and the rare cases of illness caused by the vaccine are accepted as the price of mass protection. HIV that has been genetically modified to replicate at a very low rate thus might stop millions of deaths from AIDS.

Critics contend, however, that the danger of spreading deadly disease makes trials with uninfected patients premature. Several groups of researchers have now found that when they injected monkeys with SIV modified by deleting three

CATHY BLAIVAS *AIDS Healthcare Foundation*

HEALTHY VOLUNTEERS ARE LINING UP for a live AIDS vaccine, including physician Charles F. Farthing of the AIDS Healthcare Foundation in Los Angeles.

different sections of the virus's genetic material (and so named SIV delta 3), some of the animals subsequently developed simian AIDS from the vaccine itself. This occurred even though the genetic deletions markedly slow the replication of the delta 3 virus as compared with normal SIV. And a delta 4 form of HIV itself, which has four deletions and replicates at a very slow rate compared with normal HIV, failed to protect two inoculated chimpanzees from infection with natural HIV later. (Chimps can acquire HIV, but they rarely get sick.)

The main force behind U.S. clinical trials of a genetically modified HIV as a vaccine is Ronald C. Desrosiers of Harvard Medical School, the discoverer of SIV. Seven years ago Desrosiers found that monkeys infected with SIV from which he had deleted a gene called *nef* did not become ill and were protected against natural, wild-type SIV when subsequently challenged with the virus. And evidence with human patients supports the idea that HIV itself, when missing a functional *nef* gene, can infect people but fails to cause AIDS over a decade or more. Desrosiers and John L. Sullivan of the University of Massachusetts School of Medicine have, for example, studied a U.S. patient with a natural deletion in his HIV *nef* gene who has been infected for 15 years but has yet to advance to AIDS; a group of eight Australian patients who were infected with HIV that had a different *nef* deletion also have not become sick. (There is doubt about one deceased patient, who may have had AIDS.)

AARON DIAMOND AIDS RESEARCH CENTER

RHESUS MACAQUE IS A TEST SUBJECT for AIDS vaccine development.

Given the need for an inexpensive AIDS preventive, "I don't see how you can come to any other conclusion" except to plan for clinical trials, Desrosiers says. Although his experiments (conducted with Larry O. Arthur of the Frederick Cancer Research and Development Center in Maryland) showed that an HIV delta 4 vaccine did not stop chimps from getting infected with HIV, unpublished data indicate that the levels of wild-type virus in the animals subsequently were lower than normally found, Desrosiers claims. And other researchers, including Erling Rud of Health Canada, have shown that a deleted virus can defer subsequent SIV disease.

Encouraged by these findings, Desrosiers is collaborating with Sullivan and with Therion Biologics in Cambridge, Mass., to plan clinical trials in HIV-negative patients of a vaccine candidate consisting of HIV delta 4 (though not the same virus the chimps received). Desrosiers and Sullivan believe that with the multiple gene deletions, the virus will replicate so slowly it will never cause illness. Sullivan explains that the first vaccinees, who might be enrolled in early 2000, would probably be terminal cancer patients. Healthy volunteers might come later, suggests Dennis L. Panicali of Therion.

Therion has initiated discussions about manufacturing plans for the vaccine with the Food and Drug Administration. Manufacturing a genetically modified HIV as a medical product presents exceptional challenges. HIV is normally grown in human cancer cells, but the FDA has never before approved a medical product grown in such cells for fear the products might somehow cause cancer. Panicali says his company is now considering an alternative for the trials: a DNA-molecular clone of HIV, which can be made without cancer cells. John Mills of the Mcfarlane Burnet Center for Medical Research in Australia plans to initiate within 18 months clinical trials of a molecular clone of naturally *nef*-deleted HIV.

Desrosiers's leading critic is Ruth M. Ruprecht of the Dana-Farber Cancer Institute in Boston. She agrees with Desrosiers that SIV delta 3 can protect against SIV in some monkeys. But she reported in 1995 that this deleted virus uniformly causes simian AIDS in newborn monkeys, which have weak immune systems. Furthermore, she and some other research groups have since found that a few percent of adult animals inoculated with SIV delta 3 developed the disease. Some other animals vaccinated with deleted virus have died.

Ruprecht argues that accumulating results with delta 3 forms of SIV, most still not published, show that "slowing the replication doesn't abrogate pathogenicity" but merely delays it. And there are other worries. Martin P. Cranage of the Center for Applied Microbiology and Research in England found that SIV with a natural *nef* deletion, injected into monkeys, can mysteriously repair itself within the animals. Mark G. Lewis of the Henry M. Jackson Foundation in Rockville, Md., has evidence that *nef*-deleted SIV offers some protection against a virus resembling that used to make the vaccine but not against a different form of SIV.

If Ruprecht is right, vaccination with a delta 4 virus of the type being considered for clinical trials would eventually cause AIDS. Moreover, Ruprecht disputes Desrosiers's figures on the effectiveness of SIV delta 3 as a vaccine. According to her, Desrosiers's data show only a 50 percent rate of preventing disease when conservatively analyzed. "This is a poor basis for going into human trials," she states. Ruprecht argues that nonlive vaccines show results just as encouraging—and that they are likely to be much safer.

Desrosiers is unwavering. He insists researchers should be able to develop an effective live-virus vaccine by starting from one that replicates very slowly and making successively more vigorous strains. Desrosiers says his unpublished experiments with SIV delta 4 show none of the "problems" found by Ruprecht and others with SIV delta 3. Moreover, the SIV delta 4 gave "reasonably good" protection to monkeys from vaginally administered SIV, Desrosiers states, although not a larger injected dose.

Desrosiers is not without support. Marta L. Marthas of the California Primate Research Center has isolated a form of SIV that replicates in monkeys at a harmless, low level for over a decade. Furthermore, this virus can delay subsequent disease after the animals are exposed to pathogenic SIV. Margaret I. Johnston of the International AIDS Vaccine Initiative says her organization is supporting Desrosiers to design a large, deleted-SIV experiment that might provide good safety information. Such testing would cost millions, she acknowledges. But whatever animal studies may show, Johnston notes, the first person to receive a live AIDS vaccine will be making "a leap of faith." *—Tim Beardsley in Washington, D.C.*

EXTRATERRESTRIAL LIFE

ENDANGERED

Other explanations now appear more likely than Martian bacteria

Eighteen months after David S. McKay and his colleagues at the National Aeronautics and Space Administration Johnson Space Center raised eyebrows with their claim that a potato-shaped meteorite, dubbed ALH84001, contained microscopic fossils of ancient life from Mars, the team has made few converts. "There was a very quick division into a few groups that believed it and many more that didn't," recalls Allan H. Treiman of the Lunar and Planetary Institute in Houston. Since then, Treiman says, "I haven't seen anybody change their mind."

While McKay's team has spent much of the intervening months searching for bacteria on Earth that at least proves that the creatures they hypothesize are not impossible, its critics have published dozens of new observations they believe make that theory increasingly improbable, compared with nonbiological explanations for the meteorite's puzzling features.

One such conundrum is the proximity of iron sulfides, tiny crystals of magnetite (a form of iron oxide) and carbonate rosettes in which Martian bugs supposedly thrived. The carbonate is partially dissolved around the minerals—strange, because sulfides and magnetite form together only at high pH, whereas carbonate dissolves at low pH. But there are bacteria on Earth, McKay's team points out, that excrete both sulfides and long chains of magnetite crystals; perhaps similar microbes lived in weak acid that dissolved the carbonate, they suggest.

An analysis conducted last year by Harry Y. McSween of the University of Tennessee at Knoxville and his colleagues, however, found that the sulfides in ALH84001 are too rich in sulfur 34, a heavy isotope of the element, to have been produced by microbes like any seen on Earth. Moreover, no one has yet reported finding telltale chains of a dozen or more magnetite particles. And McSween and others have observed magnetite crystals growing directly out of other minerals—a sure sign that at least some of them formed through simple chemical means.

Recently Adrian J. Brearley of the Institute of Meteoritics at the University of New Mexico sketched out what those means may have been. The carbonate rosettes contain magnesium-rich cores surrounded by iron-rich rinds in which magnetite and the other purported signs of life are concentrated. A strong blow to ALH84001 (it is known to have suffered at least two) could have rapidly heated much of the rock to more than 550 degrees Celsius—hot enough to cause the iron-rich carbonate to degenerate into magnetite but not so hot as to disrupt the magnesium-rich cores, which are stable up to much higher temperatures. When the iron condensed into crystals, Brearley theorizes, it would have released carbon dioxide enriched in heavy oxygen isotopes and left magnetite particles trapped inside voids.

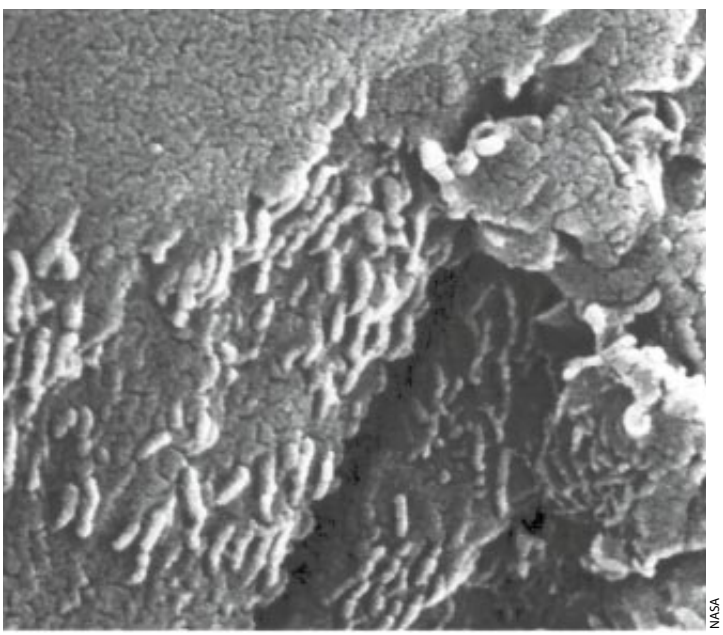
All those consequences have been seen inside ALH84001. "Adrian's idea is quite good," McKay admits. He, Brearley and others are now banging on carbonates in the lab to see whether all the predicted effects do indeed occur.

The biological theory also leaned heavily on the discovery by Richard N. Zare, a co-author of McKay, that the meteorite holds in its rosettes an unusual mix of both very light and very heavy varieties of organic compounds known as polycyclic aromatic hydrocarbons, or PAHs. The PAHs, Zare proposed, could have come from decomposed corpses of Martian germs.

The mix could also have come from inorganic chemical reactions that are known to create a few heavy PAHs from a batch of lighter ones, argued Edward Anders of the University of Chicago in late 1996. Although the process moves slowly at low temperatures, magnetite can act as a catalyst, accelerating the conversion. Zare has conceded that the PAHs could have formed in this way. If they did, it might help explain results reported in March by Thomas Stephan and his colleagues at the University of Münster. Stephan found that PAHs are present all throughout the meteorite and, if anything, are scarcer in the rosettes than elsewhere.

Proof, if it exists, of Martian life thus seems to stand now on one remaining leg: the alleged microfossils themselves. Many of the awe-inspiring herds of egg- and rod-shaped features have turned out under closer examination to be bits of clay or ridges of mineral. McKay grants that "the wormy features that we believe are fossils are not very common." In fact, although many scientists have examined fragments of the meteorite at high magnification, only one other group has released images of structures that McKay believes are microfossils. Nevertheless, he says, "There is no question in our minds that there is evidence for life in ALH84001."

How can they be so



NASA

NOT EVIDENCE OF MARTIAN LIFE, concedes the scientist who found these tiny structures inside ALH84001. Such forms are probably clay or mineral deposits.

sure? Unreleased electron micrographs offer "very strong evidence that will convince any biologist that there was life in that meteorite," McKay says, provocatively, but he refuses to elaborate until the analysis is peer-reviewed. Yet he also confides that the first chemical study of the microfossils, not yet published, shows that the structures are not composed of organic material but rather of iron oxides (such as magnetite) and other minerals. That does not disprove McKay's hypothesis, because ancient microfossils on Earth also lack organic chemicals. But it may aid skeptics' arguments that the "fossils" are merely unusual mineral formations.

Even if new pictures convince everyone that something once lived in ALH-84001, however, there now seems little hope of a scientific consensus that the life was Martian. Two studies published in January revealed that the meteorite is rife with contamination from homegrown organic material. A. J. Timothy Jull of the University of Arizona looked inside the meteorite for carbon 14, a variety that is common on this planet but nowhere else (so far as we know). He found plenty: all but a trace of the organic molecules from his samples clearly comes from Earth. Jull is uncertain whether the tiny remainder that came from Mars is organic or not.

Jeffrey L. Bada of the Scripps Institution of Oceanography in La Jolla, Calif., looked for a different biological signature—amino acids. "PAHs are not good biomarkers: they are everywhere, constituting, by some estimates, up to a few percent of the total carbon in the universe," Bada points out.

Bada's analysis dismayed McKay, even though it revealed that the rock does indeed contain amino acids—for they were the same amino acids, present in nearly the same proportions, as those in the Antarctic ice in which ALH84001 lay for 13,000 years. "We agree with Jull and Bada that there is a fair amount of contamination in this meteorite," McKay allows. "It will make it harder to prove that any life we find is Martian."

Bada, among others, doubts that is even possible. "This meteorite just has too complex a history to tell us whether life ever existed on Mars," he says. "To answer that question, we're going to have to go to the planet and either analyze the rocks there more thoroughly than Viking did or bring samples back."

—W. Wayt Gibbs in San Francisco

BIOLOGY

CLOCK SETTING

Lighting up your knees may reset your circadian rhythms

Organisms from bread molds to bread makers rely on biological clocks that respond to light cues that help them synchronize their activities to the rising and setting of the sun. In humans, this circadian clock controls a variety of physiological processes, including daily rhythms in body temperature, hormone production and sleep itself. Now Scott S. Campbell and Patricia J. Murphy of Cornell University Medical College in White Plains, N.Y., report in *Science* that they can reset the master circadian clock in humans by shining a light not in the subjects' eyes but on the backs of their knees.

"The results are incredibly provocative," says Steve Kay of the Scripps Research Institute in La Jolla, Calif. "And very surprising," he adds, because previous studies in humans suggested that the light signals that entrain the body's

clock travel to the brain via the retina.

Campbell and Murphy set out to test this dogma by shedding light on a part of the body that lies outside the eyes' line of sight. Using fiber-optic light pads designed to treat jaundice in newborns, the researchers bathed the backs of volunteers' knees with a steady light—brighter than office lights but not as bright as sunlight (even on a cloudy day).

Volunteers received light treatments in three-hour intervals at different times of the day and night, whereas control subjects wore the light pads but received no light. (Both groups heard the machines switch on and off.) Campbell and Murphy then monitored the subjects' body clocks by taking their temperatures and tracking their melatonin levels. The researchers found that light delivered to the knees during the night—particularly around 5 A.M., when the body temperature in most healthy adults hits its minimum—could reset the circadian clock, either delaying or advancing the body's physiological rhythms.

"The data look right," says Thomas A. Wehr of the National Institute of Mental Health, but he adds, "I have some reservations about the study design and the statistical analyses," which done differently might not have produced as robust a result. Still, Wehr thinks it is "important to challenge conventional wisdom. I applaud them for that."

INSTITUTE FOR CIRCADIAN PHYSIOLOGY

***BEHIND-THE-KNEE LIGHT PADS** were used to manipulate the biological clocks of volunteers.*

How might this extraocular entrainment work? Although it is too early to know, Campbell raises a hypothesis touted by Dan A. Oren of Yale University. Oren proposes that hemoglobin in the blood acts as a photoreceptor, absorbing light and generating a chemical message that is carried by the circulation back to the brain's master clock, the suprachiasmatic nucleus (SCN).

Other investigators are more dubious about Oren's so-called humoral hypothesis. "Hemoglobin is not a photoactive pigment," says Aziz Sancar of the University of North Carolina at Chapel Hill. "It absorbs light like a black hole, and, photochemically, nothing happens." Instead Sancar suggests that Campbell and Murphy look to cryptochromes—photoreceptor proteins that are present in tissues throughout the body. "We have good evidence that cryptochromes are the photoreceptors that control the circadian clock in humans," he says. "They could induce a local photoresponse behind the knee, behind the ear or wherever you want."

With photoreceptors in every tissue, could humans be covered in clocks? Kay and his colleagues have shown that *Drosophila* have clocks all over their bodies. "If fruit flies have clocks on their

IN BRIEF

Hazy Findings

When cars emit nitrogen oxides and volatile organic compounds in the summer, sunlight frequently mixes the two gases into a low-lying ozone smog that can choke people and kill plants. But apparently this photoreaction does not happen as often as scientists thought. Daniel J. Jacob and his colleagues at Harvard University recently examined ground-level ozone trends between 1980 and 1995 in three major U.S. cities: New York, Los Angeles and Chicago. They found that although the number of miles vehicles had traveled during the same period rose 60 percent, ozone concentrations showed a significant drop.

D. KIRKLAND *Sygma*

Cook Out . . . Way Out

Strange dishes are coming from Cornell University kitchens of late. Scientists there are busy concocting recipes that can be easily prepared in space. To do so, they are limiting themselves to only 15 to 30 crops for ingredients. (After all, you cannot serve freeze-dried ice cream on a space station indefinitely.) Wheat and potatoes are the main staples, complemented with rice, soy, peanuts, salad crops and herbs. So far Cornell cooks have whipped up such culinary delights as carrot "drumsticks," tempeh sloppy joes and tofu cheesecake.

Hairless Heirs

Geneticists at Columbia University reported the first human gene associated with hair growth (January 30 issue of *Science*). The group, headed by Angela M. Christiano, searched out this bit of DNA, dubbed *hairless,* by comparing a gene found in hairless mice with human chromosomes from individuals with a rare form of balding, called alopecia universalis. *Hairless* appears to trip a series of events that stimulates hair growth. Christiano and crew hope that a better understanding of the effects of *hairless* may help them find treatments for a range of balding conditions, including male-pattern baldness and stress-induced hair loss.

lips and legs and noses," Campbell reasons, "so could we." But there's a catch, Kay notes. The peripheral clocks in flies function locally to control feeding, olfaction or flight. Each clock works independently, responding directly to cues from the sun. But to coordinate complex physiological rhythms, such as body temperature or sleep in a human, clocks behind the knees, or elsewhere, have to send a synchronizing signal back to the master clock in the brain. How? Kay's money is on melatonin—or something like it. Perhaps light destroys melatonin or another blood-borne hormone that relays messages to the SCN, he hypothesizes; the drop-off would serve as the signal.

JEFFREY PLAUTZ AND STEVE KAY *Scripps Research Institute*

CIRCADIAN CLOCKS ***all over the fruit fly show up as blue bioluminescent spots.***

Sancar's and Kay's suggestions are consistent with the data, observes Campbell, who is the first to declare that his results must be replicated. If the data hold, the study implies that circadian clocks can be reset overnight, which could help people experiencing jet lag, insomnia or seasonal depression. "If we could treat people while they sleep, that would be great," Kay concludes, adding, "We can argue about the mechanism later."

—Karen Hopkin in Washington, D.C.

ANTI GRAVITY

Comic Relief

Medical conventions are the last place one might expect to find clowns, other than speakers extolling the virtues of managed care. But on January 31, at the opening of the annual conference of the American Association for Therapeutic Humor (AATH), the clowns in attendance actually sported big, red noses.

They wore their red badges of courage proudly because these clowns work in hospitals, bringing some levity to the lives of sick kids, mostly, but also some adults. These genuine jesters were joined at the Washington, D.C., meeting by a few M.D.s, a smattering of psychologists, a bunch of social workers and a load of nurses to spread the word that while laughter might not be the best medicine, it was in fact pretty good medicine.

Barry Bittman, a neurologist who just happens to have the perfect name for a Vegas marquee, was the opening act, discussing a number of studies that showed what appear to be immune system enhancement through comedy. The doctors of tomorrow served as the studies' subjects because, Bittman said, "medical students are like lab rats—if you feed them, they'll do anything." A control group of students sat in a quiet room, while the test group watched a one-hour Gallagher video. (For the uninitiated, Gallagher is a comedian best known for ending his shows by smashing watermelons with a gigantic mallet, an instrument he calls "the sledge-o-matic." The Algonquin Round Table it ain't, but keeping a straight face through a Gallagher show is nonetheless a challenge.)

Blood tests showed that the laughing group boosted their levels of a number of molecules important in immunity, such as various immunoglobulins and natural killer cells, which find and destroy tumor cells and viruses. "When you're laughing, smiling, telling jokes, there really is biology going on," Bittman said. Despite his high opinion of humor's therapeutic potential, Bittman was also quick to note humor's place beside, but not in place of, conventional therapies. "I think humor is a valuable tool," he observed, "but you don't cure people with humor alone."

Edward Dunkelblau, a psychologist and the president of the AATH, also made serious points about funny stuff: "Even if no real changes could be seen in studies, improvement in mood and in relationships would seem to be a good reason to incorpo-

SEISMOLOGY

ON SHAKY GROUND

Greek researcher claims to predict earthquakes from electrical measurements

For more than a decade, Panayiotis Varotsos, a solid-state physicist at the University of Athens, has attempted to predict earthquakes in Greece. His technique (dubbed VAN, after the last names of its three originators: Varotsos, Kessar Alexopoulos and Konstantine Nomicos) involves planting electrodes in the ground and extracting precursory electrical signals. By doing so, this researcher says, he can anticipate temblors weeks ahead. Although other scientists are also attempting to find links between low-frequency electromagnetic pulsations and subsequent earthquakes, only Varotsos has been bold enough to issue predictions on this basis. In January he and his colleagues explained some of the theory behind their method in the *Journal of Applied Physics* and were credited with predicting most major earthquakes in Greece in the pages of *Physics Today*. Such exposure lends credence to their approach, which relies on the earth's ability to transmit small electrical signals from stressed rocks over long distances. But does their prediction scheme truly have merit?

In fact, the performance of VAN is almost impossible to score. Some scientists who examined the question in detail in 1996 concluded that the forecasts had no predictive power. Others, such as Stephen K. Park, a geophysicist at the University of California at Riverside, who is trying to monitor electrical precursors to earthquakes in his home state, concluded that the Greek predictions were doing better than chance. Others said the warnings were so vague no objective test was even possible.

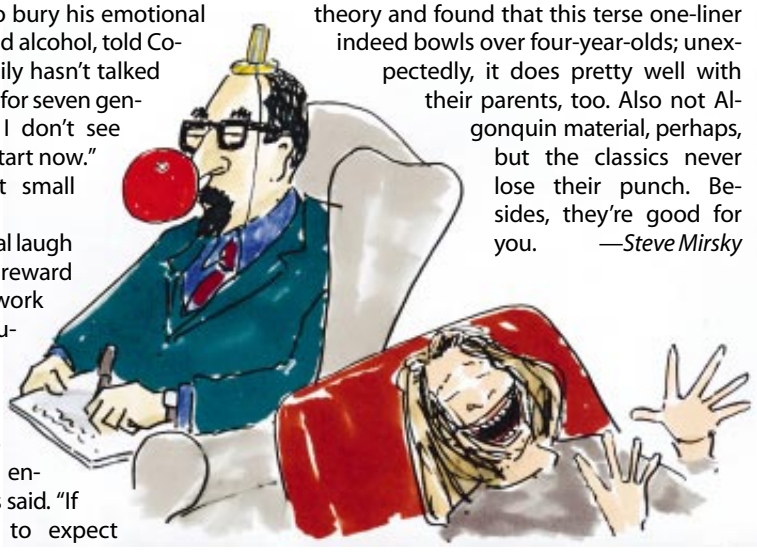
The largest earthquake that Varotsos claims to have successfully predicted illuminates the many vexing questions involved. In April 1995, the month before the quake struck (on May 13, near the Greek town of Kozáni), Varotsos sent three faxes to scientific institutes

rate humor into conventional treatments."

Stuart A. Copans, a psychiatrist who treats children and adolescents, pointed out that humor, carefully used, can create a crucial connection. "It can help establish the relationship," he elaborated, "especially with adolescents, who come into therapy kicking and screaming, as a result of parental or court insistence." A laugh is an emotional reaction, and for some kids, feeling anything is a good first step toward dealing with larger issues. A 16-year-old Vermonter, conditioned to bury his emotional life in drugs and alcohol, told Copans, "My family hasn't talked about feelings for seven generations, and I don't see why I should start now." But with that small joke, he was.

An occasional laugh can also be a reward for the hard work of therapy. "Humor signals that the relationship, though serious, can be enjoyed," Copans said. "If you're going to expect people to deal with painful experiences, you must also offer some pleasurable interaction." Inside jokes represent shared experiences that also help to maintain the therapist-patient relationship.

To employ humor effectively, the therapist must be acutely aware of the patient's own stage of humor development and connect at that level. "Anyone can be a humorist with a four-year-old," Copans asserted. "Just say 'poopie.' " Shortly after the conference, this reporter tested the Copans theory and found that this terse one-liner indeed bowls over four-year-olds; unexpectedly, it does pretty well with their parents, too. Also not Algonquin material, perhaps, but the classics never lose their punch. Besides, they're good for you. —*Steve Mirsky*



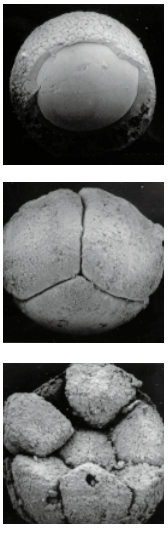
MICHAEL CRAWFORD

Science of the Union

In his annual address this past January, President Bill Clinton made an unprecedented number of comments about science. Among other things, the president proposed $6 billion in tax cuts and spending to encourage the further development of environment-friendly technologies; he proposed a 21st-century research fund—the largest funding increase ever for the National Institutes of Health, the National Science Foundation and the National Cancer Institute; and he urged Congress to ban cloning and to increase its support for building the "next-generation Internet."

Precambrian Preserves

It has never been entirely clear just how long ago multicellular organisms got going on our planet—in no small part because few fossils had been found from before the Cambrian period, which began some 540 million years ago. Now, however, a team of scientists from Harvard University and Beijing University has unearthed remarkably varied, intact plant specimens and animal embryos from the Precambrian Doushantuo formation in southern China. This collection of fossils—which are all about 570 million years old, give or take 20 million years—includes seaweeds preserved in three-dimensional detail; fertilized animal eggs (*photographs*) and embryos; and other developed, surprisingly complex creatures.



SHUHAI XIAO, YUN ZHANG AND ANDREW H. KNOLL

Declassified Data

The Arctic Submarine Laboratory, on behalf of the chief of naval operations, recently declassified a wealth of information collected by submarines that have tracked a swath of Arctic Ocean since 1986. The subs measured the thickness of sea ice for the sake of navigation and defense. But these data should also help scientists better predict how global climate changes may affect Arctic ice. The main block is the size of the U.S.—and more than half of this lump melts and refreezes every year. All the while, intensive studies of this ice continue as part of the Surface Heat Budget of the Arctic Ocean (SHEBA) project.

More "In Brief" on page 24

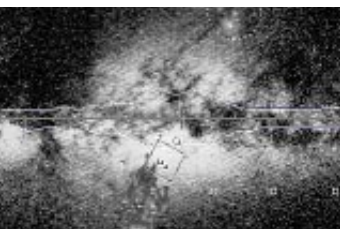
In Brief, *continued from page 23*

Making Transplants Take

Organ transplants do extend lives—but they do not always restore health. So that transplant recipients do not reject a new organ, they must take medications to suppress their immune system. And these drugs render patients more susceptible to infections and other maladies. But a new gene therapy tested in mice could eliminate such risks. Kimberly M. Olthoff and her co-workers at the University of Pennsylvania treated donor livers with a virus altered to contain the gene encoding CTLA41g. This protein, produced in the liver after transplantation, blocked a signal needed to recruit destructive immune cells. As a result, the animal's immunity continued to function yet spared the new organ and developed tolerance.

Extragalactic Interloper

A tiny galaxy named Sagittarius is invading our space, says Rosemary F. G. Wyse and her colleagues at Johns Hopkins University. They noticed that some stars inside the Milky Way's core seemed suspicious because they did not move in step with the rest. As it turned out, these stars belonged to Sagittarius, which has about one thousandth the mass of the Milky Way. Apparently Sagittarius has orbited through the Milky Way at least 10 times—which suggests that it contains a lot of "dark" matter. If it did not, the Milky Way's gravitational forces would have surely pulled it apart by now.



RICHARD SWORD *Institute of Astronomy, University of Cambridge*

Reading, Typing and 'Rithmetic?

It is tempting to think that in this digital age, having messy handwriting is no big deal. But a new study found that by practicing penmanship, children developed stronger composition skills. Researchers Virginia W. Berninger and Robert D. Abbott of the University of Washington screened more than 700 first-graders in the Seattle area and assigned 144 kids to remedial work. The children who learned to write letters the most automatically showed the greatest improvements. The researchers suggest that producing characters automatically might free up mental resources for other activities. *—Kristin Leutwyler*

L. PAPADOPOULOS *Sygma*

GREEK EARTHQUAKES,
such as this June 1995 event, are the focus of a controversial prediction scheme.

abroad noting signals recorded near Ioánnina and predicting that a quake would occur. But the epicenter proved to be well north and east of this monitoring station, away from either of two anticipated locations and well outside the general region that he and his coworkers had at the time said this station was capable of monitoring. So in this sense, the prediction failed.

"This is purely a misunderstanding," Varotsos remarks. He points out that the focal zone of the earthquake had previously been aseismic, so he had no way to tell that this locale was also a candidate area. His explanation is reasonable, yet it reveals a key flaw in logic. If the scope of a forecast can change after the fact, then the validity of the method cannot be rigorously tested.

The Kozáni earthquake was also the wrong size. Varotsos's April warnings said that the magnitude would be either about 5.0 or about 5.5 to 6.0, depending on location. Because the May event ranked 6.6, Varotsos considers his prediction a success. (He generally claims an accuracy of plus or minus 0.7.)

In a lengthy critique, Robert J. Geller, a seismologist at the University of Tokyo and one of Varotsos's chief faultfinders, observes that the range of precision usually proffered (1.4 of these particular magnitude units) corresponds to a factor of about 1,000 in earthquake energy. For the April 1995 VAN predictions, the allowable magnitude span would be even greater (from 4.3 to 6.7 units), corresponding to a factor of about 250,000 in earthquake energy.

A 6.7 quake could cause considerable damage, but 4.3-level shaking would be only marginally perceptible. So even if Greek authorities deemed the 1995 forecast to be 100 percent reliable, they could not have reasonably evacuated a large chunk of western Greece for what might have been a pip-squeak quake in some remote spot. In fact, the prediction warned of nothing out of the ordinary. By Geller's count, Greece experienced 139 quakes in that magnitude bracket over the previous year.

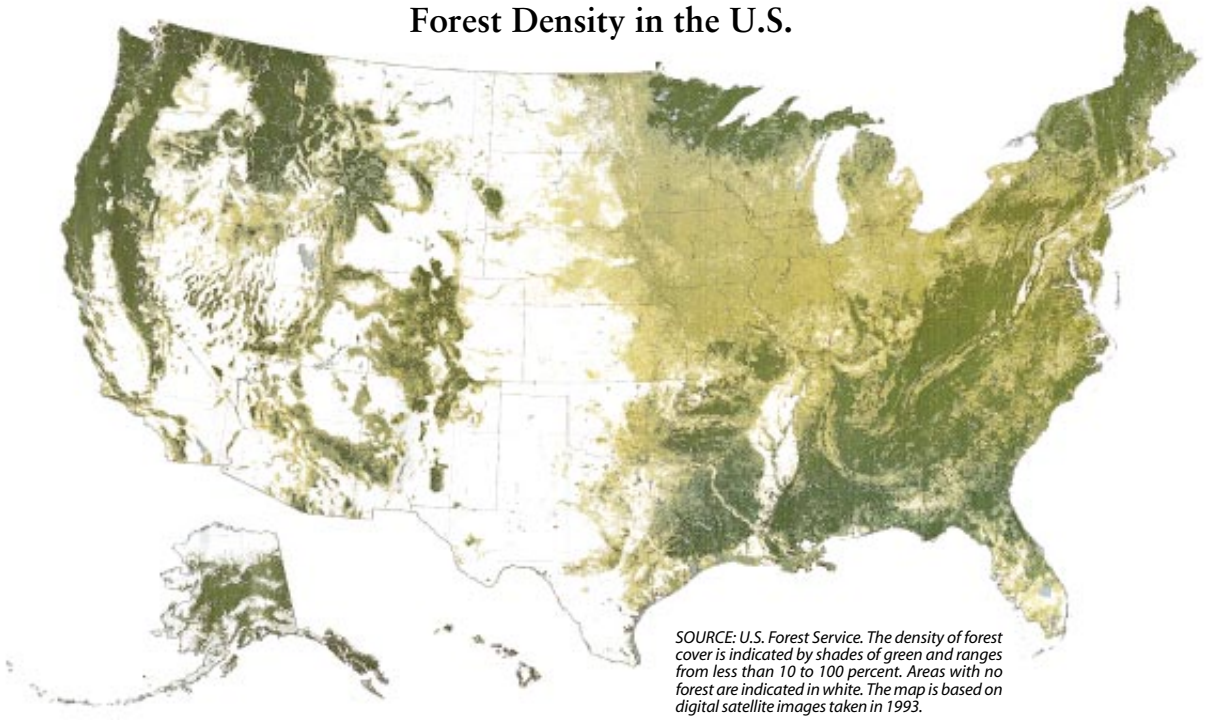
Others have voiced concerns about the signals themselves. Sylvie Gruszow, then a graduate student at the Institut de Physique du Globe de Paris (IPGP), was in Greece in 1995, hoping to duplicate the VAN measurements. Her instruments also picked up the erratic electrical activity at the time. But she and her colleagues later showed that the 1995 signal resembled one recorded at the same spot by the VAN group in 1988. (Varotsos had linked this earlier signal to an earthquake some 200 kilometers to the south.)

Both waveforms were strangely regular and had curious 13-minute gaps in the midst of their oscillations, and both lasted 70 minutes overall. Gruszow and her colleagues concluded that "the similarities in shapes and durations of the 1988 and 1995 signals seem too remarkable for the hypothesis of primary sources located in two distinct tectonic areas, hundreds of kilometers apart… to be plausible." They posited that both signals came from nearby industry, a conclusion Varotsos hotly contests.

Indeed, Varotsos is dogged in defending his measurements, methodology and public warnings. But his combativeness and unorthodox style irk many scientists. Pascal Bernard, a geophysicist at the IPGP says, "He's a physicist, but he's not acting as a researcher." Geller is more acerbic, characterizing Varotsos's work as a "funky combination of science and witchcraft." Even Park, a mild supporter, notes: "I wouldn't be issuing predictions at this point." *—David Schneider*

BY THE NUMBERS

Forest Density in the U.S.



SOURCE: U.S. Forest Service. The density of forest cover is indicated by shades of green and ranges from less than 10 to 100 percent. Areas with no forest are indicated in white. The map is based on digital satellite images taken in 1993.

As far back as the Civil War, Americans were concerned that the forests were being destroyed by logging and the conversion of woodland to farms. There was talk of an impending "national famine of wood," and indeed the facts must have seemed discouraging at a time when wood was the chief source of energy. In the late 19th century there was little prospect of a major expansion of prime cropland needed to feed a population that was increasing by more than 20 percent per decade. But the ecological crisis that loomed never came. Forest acreage stopped declining about 1920 because there was little need for additional farms. In fact, forests in many parts of the Northeast and the South have actually expanded since 1900, as agriculture shifted to the Midwest. The need for new farm acreage diminished partly because the use of crops to feed draft animals declined steeply with the introduction of tractors and other motorized equipment. And the productivity of farms rose as a result of genetically improved strains, increased use of fertilizers and better irrigation.

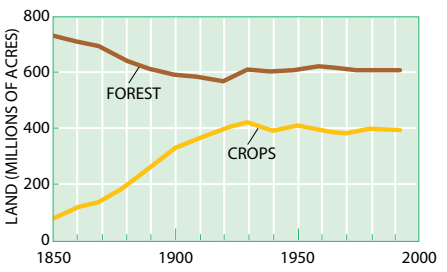
Forests also recovered as coal and oil replaced fuelwood, and conservation measures begun in the era of President Theodore Roosevelt and his chief of the forest service, Gifford Pinchot, started to take effect. Pollution by pulp and paper mills was cut drastically, and tree planting increased. Although population has grown by 2.5 times in the past 80 years, forests have been able to satisfy the rising demand for lumber, paper and other wood products.

But this rosy picture must be tempered by the prospect that forests in the 21st century may not be able to meet the needs of a population that is projected to grow by more than 120 million in the next 50 years. Timber mortality—deaths of trees from natural causes—is rising for reasons not completely understood but that may include chemical pollution, insect pests and drought. The result has been a stagnation of timber productivity in many sections of the country. Although air and water pollution in forests are declining, there are new concerns about the effect of chlorinated compounds and other pollutants associated with paper production.

A related concern is the decline in biodiversity in American forests: more than half of all endangered species are associated with forest ecosystems. Global warming, which most scientists believe has already begun, threatens trees, whose growth and reproduction can be affected by a change as small as one degree Celsius occurring over several years. This prospect seems particularly threatening in the light of new information suggesting that global warming will not occur gradually over the next century but will happen suddenly, perhaps over a period as short as a decade.

If American forests are to be sustainable, per capita consumption of wood and paper must drop, substitutes such as hemp and plastics must play a bigger role, and new technology, such as electronic media, will have to replace most paper.

Before European colonization, the forest covered 46 percent of the land and was far more diverse than today. It now covers about 32 percent, and virtually none of the original trees (old-growth forests) remain. The major areas of shrinkage in the past 400 years have apparently been in the Midwest and the lower Mississippi Valley, which were extensively converted to farmland, and southern Florida, where many trees were harvested for timber. The semicircular area of largely unforested land stretching from Alabama and curving through Mississippi is a region with clay soil unsuitable for trees.



—Rodger Doyle (rdoyle2@aol.com)

RODGER DOYLE

PROFILE

An Ethnologist in Cyberspace

Sociologist Sherry Turkle explores the emotional and intellectual connections to virtual pets, chat rooms and other products of the computer age

Beep. "At a certain point you want to kill it," says Sherry Turkle, pressing the tiny buttons of her daughter's virtual pet. *Beep*. Like many mothers the world over, Turkle is sometimes enslaved to a demanding electronic toy while her six-year-old is away at school. *Beep,* bleats the little plastic object. More buttons pushed. Turkle feeds it. Cleans up after it. Tends to it. *Beep*. But the dinosaurlike critter inhabiting the gray screen wants more of everything. "Because it is young, it needs attention every minute," Turkle sighs. "That is part of the deal."

Sitting at the kitchen counter, surrounded by her daughter's handmade books—which have bright-colored paper covers, a page or two of text or illustration and titles such as "Soccer Is for Boys: Fiction"—Turkle sketches the brief history of electronic toys. The professor of sociology at the Massachusetts Institute of Technology describes how digital devices used to be targeted solely at boys and how, in many ways, these video games taught them to be comfortable with computers. Now, as Tamagotchis, the most famous brand of virtual pet, become the rage for girls, the lessons are shifting. "The transition is from objects-to-think-with to objects-to-nurture," Turkle explains. "The new hook for these kids, and not just for kids, is nurturance instead of control and mastery."

Turkle—who has been described as the Margaret Mead of cyberspace—is concerned about the implications of this transition. "You know intellectually that it is not another creature, but the emotion of not being able to let the Tamagotchi down is on a different register," notes Turkle, who has been studying these toys and their caretakers for a year or so. "The point is not just to be involved with technology; the point is technology for what? What is it doing to us?"

These questions are ones Turkle has been asking since she arrived at M.I.T. in 1975. For more than 20 years, she has delved into the psychology of our interactions and relationships with computers, paying particular attention to children. She has explored how people foist projections and needs—intellectual and emotional—onto computers and, more recently, the on-line world. "I am trying in one way or another to get people to look at the subjective side of technology," Turkle says. "My focus is on the individual experience, on the construction of identity and the way technology is used in the construction of identity."

Because she studies individuals and groups of users—hackers, hobbyists, artificial-intelligence researchers and teenagers, for example—Turkle's findings cannot always be summed up in a neat sound bite. "I can't have a conversation with someone without giving them a dissertation topic," Turkle says, laughing. "It is kind of a professional deformation. Like Cindy Crawford probably can't have a conversation without lipstick." As a result, Turkle's work offers some enriching gray, fine-grained detail to the often black-and-white generalizations about computer use.

In her most recent book, *Life on the Screen: Identity in the Age of the Internet,* Turkle describes how people visit chat rooms and other kinds of multiuser domains to explore facets of their personalities—and how they integrate what they learn into "RL," or "Real Life." (Turkle herself prefers the acronym "ROL," or "Rest of Life.") She found, for instance, that some women who assume male names on-line can talk more easily and are listened to more readily. Whereas men posing as female characters are occasionally harassed sexually or upbraided for talking too much.

LOUIS FABIAN *Bachrach*

***THE MARGARET MEAD OF CYBERSPACE** is how some describe Sherry Turkle.*

Far from being a place littered with cyberaddicts and people trying to avoid responsibility, Turkle has found the Internet to be a world where people can often subtly expand, in a healthy way, their repertoire of interactions—just as they did when the telephone appeared, she notes. At the same time, Turkle is worried about the trend of taking things on the computer purely at "interface value"—that is, not understanding or caring to understand why or how they work. And she is concerned about the consequences of allocating so much of our emotional being to, among other things, psychology programs, software agents and the ubiquitous Tamagotchis.

Turkle says her own childhood was relatively technology free. She grew up in

Brooklyn and attended public school. In 1965 she won a scholarship to Radcliffe College. When her mother died a few years later, Turkle decided to drop out of school and—based entirely on a much loved course on French civilization that she had taken at Harvard University—head to Paris.

Armed only with a letter from the cultural attaché, Turkle immersed herself in classes at the Institute for Political Studies. When the student protest in May 1968 catalyzed strikes and led France into political upheaval, Turkle found herself enthralled. Although the country seemed to return to normal a few months later, Turkle saw that a profound intellectual shift was under way in France—and that psychoanalysis was at the heart of it. She began to examine how ideas of mind—in this case, Freudian beliefs that had previously been reviled—were permeating general culture and finding new resonance. These observations led, many years later, to her first book, *Psychoanalytic Politics: Jacques Lacan and Freud's French Revolution* (1978).

Turkle returned to the U.S., finished up at Radcliffe and then spent a year at the University of Chicago, where she studied with anthropologist Victor Turner. Turner is famous for his work on transitional, or liminal, moments—times of passage when traditional social structures may be suspended, evaluated and often reconstituted. In 1971 Turkle returned to Cambridge, pursued a joint doctorate in sociology and personality psychology at Harvard and, finally, settled in at M.I.T.

It was there these many intellectual currents—psychoanalytic politics, studies of French structuralist and poststructuralist thinkers and reflections on liminality—all came together. "Right away when I got there, I began to see ways in which ideas about the computer as a model of mind were getting into people's individual ways of thinking about themselves," she recalls. The computer seemed a perfect liminal object: it was both alive and not alive, both mind and not mind. "Some people said, 'What's a nice girl like you who knows about French poststructuralism doing in a place like this?' But it was and is still the theme for me," she laughs.

Turkle began to explore the computer as Rorschach blot. In 1984 her next book, *The Second Self: Computers and the Human Spirit,* opened up the world of computing to the lay public. In it Turkle discussed, among other topics, how boys and girls often had very different attitudes to programming. Two fourth-graders whom she interviewed embodied this difference. The boy envisioned his program in its entirety, then broke it down into parts and tackled one piece at a time. Turkle labeled this approach "hard mastery." The girl, however, was less reductionist and went back and forth with her program: she would do one thing, step back, evaluate, then proceed—a process Turkle described as "bricolage," a term borrowed from anthropologist Claude Lévi-Strauss.


R. MAIMAN *Sygma*

XAVIER ROSSI *Gamma Liaison Network*

APPEAL OF VIRTUAL PETS
embodies a shift from mastery to nurturance in computer toys, according to Turkle.

This idea of bricolage—roughly defined as tinkering—has recently taken on new meaning, Turkle maintains. Because the graphical-user interface (embodied by the Macintosh and Windows operating systems) has become the dominant paradigm, most computers users, male and female alike, use bricolage: they cannot see the engine under the hood of the car. "Everything is on the surface. You don't read the rule book; you do it by tinkering," Turkle explains. "The danger is that this sort of bricolage becomes a model for all understanding."

Which is something she is beginning to see in children. In a recent article, Turkle gave the example of Tim, a 13-year-old who was playing the game SimLife while she interviewed him. As she became frustrated because she could not understand the rules of the game, Tim tried to comfort her: "Don't let it bother you if you don't understand. I just say to myself that I probably won't be able to understand the whole game anytime soon. So I just play."

Turkle maintains that rather than focusing on red herrings, such as Internet addiction, parents and educators should figure out how to impart critical reading skills to children. When we read, she argues, we think "who, what, when, where and why" about the text; we question it critically. But in a culture of simulation, she says, we are much more passive.

The job ahead, Turkle continues, is to put the computer in its rightful place, emotionally and intellectually—something she sees many children, including her own daughter, doing quite readily. Rebecca, for instance, loves to read books, but she also loves the liberation of writing on the computer because it is faster than writing by hand. She plays checkers on the computer and has learned analytical skills, but she recognizes that drawing is better when done in ROL. And while Rebecca is very much in the real world, she has "also learned the seduction of a world without emotional aspects," her mother observes.

Everyone needs to integrate both realms, Turkle says, and part of the key to this synthesis seems to lie with children: "This generation of kids, in confronting digital objects and virtual space, are completely comfortable with—call it cycling through, call it bricolage, call it tinkering, call it a radical heterogeneity of theory. Call it what you wish. But it is an acceptance of fluidity that is striking."

Whereas many of their parents are sitting at desks and counters everywhere, struggling with the diurnal cycles of Tamagotchis. "What are we becoming if we are emotionally relating to these objects that are evoking these responses that are meant to be our responses to our children?" Turkle asks, pointing at the dinozoid, which is silent and sated if only for the moment. It is a question she seems destined to answer.

—Marguerite Holloway

PHARMACEUTICALS

NOT WHAT THE DOCTOR ORDERED

Attempts begin to halt the practice of donating expired and unlabeled drugs to needy countries

Richard Laing studies the international drug trade. But instead of monitoring the latest cocaine shipment from Colombia, he is watching to see who is sending antibiotics to Africa. Laing, a professor of International Public Health at Boston University, is one of many observers concerned about the types of supplies pharmaceutical companies ship to needy countries. Too often these drugs are inappropriate and even dangerous. "The problem is very widespread," Laing says, "and there is lots of money involved—the value of these medications is in the hundreds of millions of dollars."

Although by and large drug donations serve a vital need, every year or so a donation gone awry makes headlines. Antibiotics from Eli Lilly and Company that were not approved for use by either the U.S. Food and Drug Administration or the World Health Organization (WHO) were sent to Rwanda in 1994. In 1993, 11 Lithuanian women went temporarily blind after taking a veterinary medicine, made by Janssen Pharmaceutica, that doctors thought was a treatment for endometriosis—because the drugs were shipped with no instructions. In 1990, when Sudan was suffering from the ravages of war and famine, various companies sent donations of contact lens solution, appetite stimulants, expired antibiotics and drugs to treat high cholesterol.

The most recent episode to make the news involves medical supplies sent to the former Yugoslavia. In December 1997 researchers led by Patrick Berckmans of the European Association for Health and Development in Brussels published a troubling study of drug donations sent to Bosnia and Herzegovina between 1992 and 1996. Their article in the *New England Journal of Medicine* described donations that included "army medical supplies from World War II" as well as "a drug for the treatment of leprosy, a disease not found in the former Yugoslavia." The investigators estimated that by mid-1996 there were "17,000 metric tons of useless and unusable medicines stockpiled in warehouses and clinics in Bosnia and Herzegovina"—a figure the authors say is between 50 and 60 percent of the original donations.

Why all these unsuitable contributions? Some drug companies, by their own admission, view donations as a way of unloading old stock, particularly drugs that are about to reach their expiration date. At a conference on drug donations at the University of Notre Dame in April 1997, one industry spokesperson termed the practice "inventory purging." The financial incentive is strong: Berckmans's group estimated that all told, pharmaceutical companies saved $25.5 million by sending the drugs overseas rather than destroying them at home. In addition, Berckmans writes, "Donors may also benefit from substantial tax deductions because their donations are considered 'humanitarian gifts.'"

In an effort to prevent future fiascoes, WHO has stepped in with some advice for both donors and recipients. In May 1996 WHO, in conjunction with eight major international emergency aid organizations, released the document "Guidelines for Drug Donations." Hans Hogerzeil, medical officer with WHO's Action Program on Essential Drugs, explains the motivation behind the publication: "We wanted to define what a good donation is, and we wanted to raise awareness of this issue—to show that it is not always the case that any drug is better than no drug."

According to Hogerzeil, the recommendations draw on several principles. First, donations should be made in response to a specific request for a particular drug. Second, there should be no double standards. "If you can't use a drug in your own country, if it is illegal to sell it there [because it has expired], you can't give it to other people," Hogerzeil says. Finally, the lines of communication must be more open between donors and recipients—donations should not be made unannounced, and instructions on how to use drugs (as well as the labeling on the packages) must be provided and written in a language doctors and nurses in the recipient country will understand.

Critics of the guidelines—mainly from the pharmaceutical industry—worry that with such strict rules, drug companies, which provide most of the supplies donated from the U.S., will simply stop giving. But some companies have developed programs that should enable them to donate much needed medical supplies and still meet the WHO mandate. Johnson & Johnson has a "Produce to Give" project, in which drugs are manufactured specifically for the purpose of being donated. Merck & Co. runs a similar program; it has been producing fresh supplies of the drug Mectizan for 11 years and sends them free of charge to countries in Latin America and Africa to fight river blindness. SmithKline Beecham announced in January that it will manufacture and donate supplies of Albendazol, a treatment for elephantiasis, a disease that now affects more than 120 million people in 73 countries around the world. Besides serving as good public relations, the programs enable the firms to maintain an international presence with drugs that often are not in demand elsewhere.

Whether the efforts of WHO and the pharmaceutical companies themselves will stop future instances of inappropriate contributions remains to be seen. A

INTERNATIONAL COMMITTEE OF THE RED CROSS

INTERNATIONAL AID ORGANIZATIONS,* *including the Red Crescent—shown here distributing drugs in Pakistan—have worked with WHO to develop guidelines for donating medicines to needy countries.

study to assess the effect of the WHO guidelines is currently under way; Michael Reich of the Harvard School of Public Health heads the committee, which includes representatives from pharmaceutical companies and charities. The results of the study won't be available until later this month, but Reich gives a cautious assessment of the ramifications of the WHO policies: "[They] have increased the awareness among all the players about the complexity of the donations process."

There is one more complication that WHO has begun to tackle: What to do with all those tons of unwanted drugs and other supplies now sitting in warehouses? According to Laing, countries already strapped for resources cannot easily dispose of unwanted drugs—which in such large quantities qualify as hazardous waste. He elaborates: "To burn them, you need [an incineration facility capable of generating] very high temperatures. To bury them, you need concrete. These countries would much rather be using the concrete to build houses." —*Sasha Nemecek*

CHEMICAL ENGINEERING

TAKING ON THE ENERGIZER BUNNY

Researchers develop fuel cells for portable electronics

Batteries are a notorious weak link for many portable devices, such as laptop computers and cellular phones. They are expensive, heavy and cumbersome, often requiring recharging at the most inopportune times. Recent advances in fuel-cell technology might bring relief. Several research groups are developing "micro–fuel cells" that could, for example, result in mobile phones running continuously for weeks on standby power.

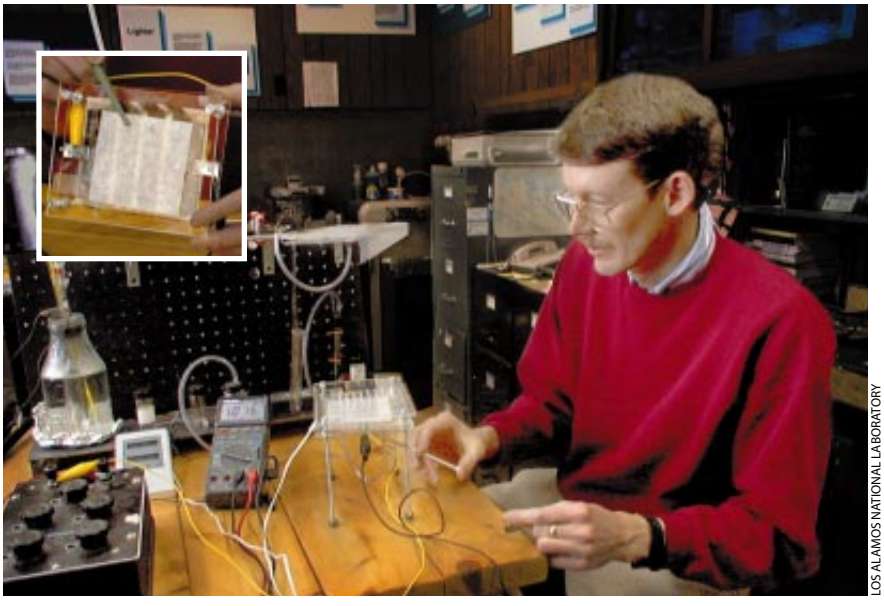
Fuel cells are simple devices, basically consisting of a nonmetallic conductor called an electrolyte sandwiched between two electrodes. Hydrogen from a fuel, such as methanol, flows through the electrolyte to mix with an oxidizer, such as oxygen from air, and the chemical reaction produces an electric current between the two electrodes. The cells can be replenished easily—and quickly—by adding more fuel. Fuel cells also run cleanly, their main by-product being water from the combination of hydrogen and oxygen, whereas batteries, which eventually wear out from repeated recharging, present a disposal problem.

While various laboratories have been busy developing large, powerful fuel cells to replace automotive combustion engines, other work has concentrated on miniaturization. Robert G. Hockaday, a researcher on leave from Los Alamos National Laboratory, where he worked in diagnostic physics, has patented a micro–fuel cell that he predicts will be able to provide power for up to 50 times longer than traditional nickel-cadmium batteries—all for a comparably sized and priced package but at half the weight. With this technology, Hockaday envisions cell phones running continuously for 40 days on standby while consuming less than two ounces of methanol.

The invention is more a triumph of engineering than a wonder of science. Hockaday has taken modern techniques for fabricating electronic circuitry and applied them to the time-honored technology of fuel cells. The key was in the packaging. Whereas most fuel-cell researchers start with the design of the electrolyte and electrodes, Hockaday realized that he could best achieve miniaturization and mass production by using a thin film of plastic as the basic container for microscopic fuel cells. The plastic membrane, only 25 microns thick, is bombarded with nuclear particles and then chemically etched to form fine pores through which a liquid electrolyte is later poured. The metal electrode plates, a catalyst material and a conductive grid to connect the individual cells can then be layered and etched on the plastic structure by using proved chipmaking techniques such as vacuum deposition. "I'm basically building fuel cells like circuit boards," Hockaday says.

To complete his research, Hockaday is receiving $1 million from Manhattan Scientifics, a New York City–based holding company. He expects to have a prototype ready for production in a year.

Hockaday's invention is not the only game in town. Christopher K. Dyer of Bell Communications Research (Bellcore) has brought forth an innovative design that draws the hydrogen and oxygen from the same source. (In most fuel cells, as with Hockaday's, the two substances need to be kept separate, which complicates the internal plumbing of the devices.) Meanwhile DTI Energy in Los Angeles is working on commercializing its fuel-cell technology from the Jet Propulsion Laboratory in Pasadena, Calif., and the University of Southern California. DTI claims its device can use methanol directly instead of having the hydrogen extracted beforehand from the alcohol. Although the different groups boast competing approaches, Bellcore's Dyer asserts they share a common enemy: "We really should replace batteries because they're awful things." —*Alden M. Hayashi*



LOS ALAMOS NATIONAL LABORATORY

MICRO–FUEL CELL INVENTOR ROBERT G. HOCKADAY worked in his basement to develop fuel-cell technology **(inset)** ***that could keep cellular phones running for more than a month on standby power.***

AGRICULTURAL ENGINEERING

FERTILIZING THE SEA

A firm wants to add nutrients to the ocean to create fisheries and soak up carbon dioxide

"Give me a half-tanker of iron, and I'll give you an ice age," said the late oceanographer John H. Martin, referring to the concept of stimulating the growth of phytoplankton by adding iron to ocean water. According to this scheme, which has been called the "Geritol solution" to global warming, the newly spawned microscopic plants would draw carbon dioxide from the atmosphere to support photosynthesis and carry carbon to the deep sea after they died.

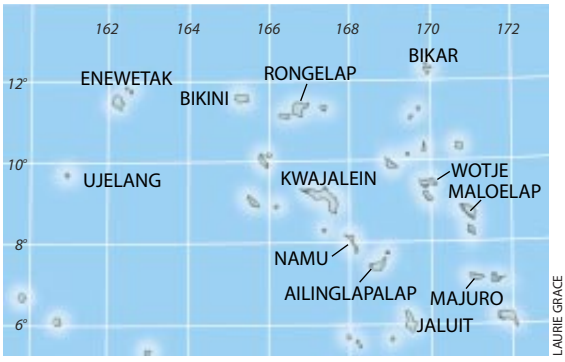
While putting it less brashly, Michael Markels wants to apply the same principles, not only to alleviate the buildup of greenhouse gases but also to establish fisheries in otherwise nutrient-poor waters. Markels, a chemical engineer who founded the McLean, Va.–based company Ocean Farming, Inc. (OFI), literally wants deserts to bloom at sea. "The oceans, for the most part, are a great barren wasteland: 60 percent of the plant life comes from just 2 percent of the surface," he says. "Fertilization is required to make the barren parts more productive."

Markels was inspired by the "IronEx" experiments designed by Martin—former director of the Moss Landing Marine Laboratories near Monterey Bay, Calif., who died in 1993—and carried out near the Galápagos Islands in 1993 and 1995. In both outings, researchers successfully created phytoplankton blooms in fertilized patches of ocean, and in the second experiment, they measured a 60 percent drop in the flow of carbon dioxide from the ocean to the atmosphere. But these effects were short-lived, lasting less than a week after the last infusion of iron.

It is possible to do better, Markels says, by using the right mix of iron, phosphorus and trace elements. The materials would be encapsulated in buoyant, chemically protective containers that keep the nutrients in the "photic zone" longer and release them over time. Through continuous fertilization, he hopes to simulate conditions off the coast of Peru, where nutrient-laden water is brought to the surface by upwelling.

OFI has secured an option from the Marshall Islands for private property rights to all or some of the 800,000 square miles in the "exclusive economic zone" surrounding the archipelago—the first agreement that has ever been made to privatize a portion of the ocean for fish production and carbon dioxide sequestering. Under the agreement, OFI will pay the Marshall Islands government a minimum of $3 million a year for rights to the entire region and a reduced fee for a smaller area. Markels estimates that with a 100,000-square-mile area, "we could sequester in the deep ocean one fourth to one third the amount of carbon dioxide that the U.S. puts into the atmosphere."

OFI is conducting experiments in the Gulf of Mexico during the first half of this year to determine the best means of fertilization and the optimal mix of nutrients. Oceanographic studies around the Marshall Islands will be carried out next to establish baseline concentrations for key chemicals. With sufficient funding, commercial operations could begin as early as 2000, whereby a ship would steadily deposit fertilizer throughout that nation's territorial waters.



***MARSHALL ISLANDS** could be the site for commercial ocean fertilization.*

Scientists familiar with the venture have voiced numerous concerns. Caution is in order, says Sallie W. Chisholm, a Massachusetts Institute of Technology oceanographer who participated in the IronEx studies, because "the gap between science and private enterprise is just too big." To illustrate that point, she notes that the upwelling systems off Peru have been evolving for hundreds of millions of years. "You can't expect to duplicate that just by pouring nutrients into the water," she argues.

David A. Caron of the Woods Hole Oceanographic Institution maintains that there is no way to predict which phytoplankton species will be stimulated by fertilization or what kinds of fish might feed on them. "The last thing you'd want to do is produce 100,000 square miles of toxic bloom. That would be a mess, not a fishery," he says.

Moreover, it would take a huge fertilization effort to make a sizable dent in the global carbon dioxide problem, Caron says, adding, "Who knows what the side effects would be? We're talking about intentional eutrophication"—an oxygen-depleting process resulting from organic decay that has led to deleterious environmental consequences in lakes and coastal zones throughout the world.

If adverse impacts become evident, Markels says, operations would cease immediately. "We only have to stop fertilizing, and all traces of the nutrients are gone in about 20 days," he contends.

But some problems may not be apparent without an extensive, and expensive, biological sampling effort. Caron thinks an adequate monitoring program would take three to 10 years, which may not be economically feasible. "It's not cost-effective for them to do that, especially since they don't have to do it," Chisholm says. Some side effects, moreover, may be irreversible: "Once you kill the reefs in that area, which you probably would do, it's not clear they would ever come back," she adds.

Markels realizes the potential for problems, which he hopes to avoid, but also sees the potential for significant benefits to humanity. "If we don't do anything that might possibly cause harm, we'd never do anything at all. We might never have transformed the land—increasing agricultural output by a factor of 2,000—with all the advances that came with it," he asserts.

Those who view ocean fertilization as an unproved option for boosting food production and averting global warming are not recommending that nothing be done. "But before we resort to radical manipulations of this planet, we ought to make greater efforts to reduce carbon dioxide emissions," asserts Andrea C. Ryan, an environmental policy researcher at M.I.T. "And even if we do consider 'geoengineering' options, ocean fertilization still may not be at the top of the list."

—Steve Nadis in Cambridge, Mass.

TELECOMMUNICATIONS

A NEW FAT PIPE

A powerful consortium pushes a new path to the Internet

In the high-stakes struggle to make the Internet more mainstream, one monumental challenge has loomed from the very beginning. That problem is replacing the thin "soda straws" through which data get to most home users with big "fat pipes."

Until a few months ago, the only fat pipes that seemed to have a reasonable chance of succeeding were cable television lines, converted to convey data through cable modems. Recently, however, three computer giants—Compaq Computer, Intel and Microsoft—threw their considerable weight behind the only real competitor to cable modems. The fat-pipes sweepstakes has become a bona fide race.

This past January the computer colossi announced that they were joining with the large regional telephone companies in the U.S. to form a consortium dedicated to hastening the availability of hardware and software for a technology known as asymmetric digital subscriber line (ADSL). At data rates that are expected to range from about 400 kilobits per second for home users to 1.5 megabits per second for commercial clients, ADSL will be slower than cable-based data services, which offer rates up to 10 megabits per second. But ADSL is a considerable improvement over today's telephone modem, which has data rates below about 50 kilobits per second.

ADSL, too, works over a telephone line but differs in a critical aspect. A conventional modem converts data to an audible signal that is sent on the line's voice band, between zero and 4,000 hertz. An ADSL modem, on the other hand, translates the data to signals in a much higher frequency band, in the hundreds of kilohertz. Thus, a single ADSL connection can be used to cruise the Internet while carrying on a phone conversation. More important, the high frequency permits far higher data rates in comparison with the voice band.

This neat technical picture omits a number of major problems, however. Because the signal degrades as it travels over the copper wires, the length of telephone line over which an ADSL connection can be established is limited. Specifically, the line known as the local loop, which connects a home with a telephone company's central office, cannot exceed a length of three to eight kilometers, depending on the quality of the line and the desired data rate. In addition, the line must consist of copper wires all the way to the home. Rough estimates are that these limitations exclude 40 percent of U.S. homes.

Moreover, if the service becomes as popular as some projections suggest, local telephone central offices could become rather crowded. Each ADSL connection requires a modem at both ends. These modems currently cost several hundred dollars, and the need to install thousands of them in a central office could present a storage problem. The problem would be mitigated, presumably in the near future, when it becomes possible to put an entire ADSL modem on one integrated circuit. Another challenge to be surmounted involves devices called loading coils, which have been installed on lines to improve the voice signal. Unfortunately, they also block the ADSL signal. "It's not going to be easy to turn ADSL into a competitive product," comments Jay A. Rolls, director of multimedia technology for cable giant Cox Communications.

One of the biggest problems of all, Rolls adds, may be economic. Many telephone companies now make handsome profits leasing T1 lines, which cost anywhere from $350 to $1,000 a month or more and offer data rates of 1.544 megabits per second. With ADSL, however, a company will be able to get comparable capacity with one or two high-end lines—and at a cost well below $200 per month.

When that happens, why would anyone want a T1 line? For one, T1 lines do not have the length limitations of ADSL, notes Greg Gum, who is in charge of the country's largest ADSL trial, at the regional telephone company U S West. In addition, Gum says, many business users need capacity far in excess of even T1 rates, and such capacity would be impractical to implement with ADSL. Finally, that "A" in ADSL, standing for asymmetric, reflects the fact that a user can receive data at high rates but can send only at much lower ones. "I think it's a bit strong to say, 'There goes the T1 market,'" says Joseph Bartlett, who studies the Internet for the Yankee Group, a market analysis firm.

The new ADSL consortium is hoping to have widespread deployment of the technology sometime in 1999. In the meantime, however, essentially all the regional telephone companies have trials that are either ongoing or planned for the near future. The most advanced is U S West's, which is called MegaBit and was unveiled in the Phoenix area last September. Home users are paying $40 a month for a 192-kilobit-per-second connection (to be increased to 256 kilobits per second in the near future, Gum notes), plus $19.95 for Internet service, $199.95 for the installation and about $200 for the modem. The prices are somewhat higher and the data rates significantly lower than those for the competing cable-modem Internet service, offered in the same area by Cox Communications. U S West is also offering higher-speed ADSL services aimed at businesses; a 704-kilobit-per-second connection (to be upgraded to 768 kilobits per second) costs $125, plus fees for Internet service, installation and the modem. —*Glenn Zorpette*

Internet Data Services for the Home

Technology	Data rate (kilobits per second)	Cost per month; other fees	Comments
Telephone modem	Up to about 50	Approximately $15 plus $19.95 for Internet service; $125 for modem	Additional line needed for voice
Asymmetric digital subscriber line	Up to 256 in current trials	$40 plus $19.95 for Internet service; $199.95 for installation and $200 for modem	As many as 40 percent of homes will not be able to use the service for technical reasons
Cable modem	Up to 10,000	$29.95 (includes Internet service); $149.95 for installation (includes Ethernet card for PC) and $399 for modem	Data rate is affected by number of users in one area; security may be more difficult to implement

JOHNNY JOHNSON

CYBER VIEW

The Unabomber and the Bland Decade

Today is a black day for anyone associated with alt.fan.unabomber," wrote one member of an Internet newsgroup's mailing list on January 22. That's when Theodore Kaczynski finally agreed to plead guilty to all federal charges for the bombings, which killed three people and seriously injured two others. "[We] will lose the chance of seeing Kaczynski attempt to sell his anti-technology views to a jury," the posting continued.

The writer, like many others, spoke with regret. On the Net, Kaczynski's political ideas have received a fairly respectful airing. His 35,000-word manifesto, entitled "Industrial Society and Its Future," has been widely quoted, its philosophy—the author calls for a revolution against the industrial system, arguing that it has been a "disaster for the human race"—debated with some seriousness. There were the inevitable jokes: "A 17-year reign of terror?" one correspondent wrote of the Unabomber's time at large. "Maybe the real terror is having to read his sophomoric essay." But in general Kaczynski's writing drew considerable interest and discussion, particularly among anarchists, antitechnologists, radical environmentalists and others inclined toward his notion that "the time is ripe for the presentation of anti-industrial ideas."

A handful of others, too, beyond the Net found Kaczynski's writing if not intriguing, at least coherent. "There is nothing in the manifesto that looks at all like the work of a madman," commented political scientist James Q. Wilson of the University of California at Los Angeles in an op-ed in the *New York Times*. "The language is clear, precise and calm. The argument is subtle and carefully developed, lacking anything even faintly resembling the wild claims or irrational speculation that a lunatic might produce.... Apart from his call for an (unspecific) revolution, his paper resembles something that a very good graduate student might have written.... If it is the work of a madman, then the writings of many political philosophers—Jean-Jacques Rousseau, Tom Paine, Karl Marx—are scarcely more sane," noted Wilson, whose books on the law and morality include *Moral Judgment* and *The Moral Sense*.

Wilson's view, though, is an oddity. In the news, Kaczynski's writing was routinely described as "disjointed," "incoherent," "rambling" or "a screed," forming the basis for the popular image of Kaczynski as a madman.

"Mad"—it's the one word in the coverage that sums up the Unabomber, his universal epitaph. Ramzi Yousef and Timothy McVeigh, his companion bombers in the news, received quite different labels. When Yousef, sentenced to life imprisonment for his role in masterminding the World Trade Center bombing, proclaimed in court that he

SCOTT MANCHESTER *Sygma*

TED KACZYNSKI at Berkeley in 1968

was proud of his work, few called him mad. Evil, yes, but mad—not quite. And certainly not "misguided"—the word most commonly applied to McVeigh, the primary Oklahoma City bomber.

The pervasive labeling of Kaczynski and his writings as mad probably arose in part from stock notions the public has of scientists. "Dirty, wild-eyed and disheveled—a caricature of the mad scientist," said an ABC television reporter, along with most everyone else. Of course, Kaczynski is a "lapsed" scientist, the world's most notorious Luddite. ("Science marches on blindly," he wrote in his manifesto, "without regard to the real welfare of the human race or to any other standard, obedient only to the psychological needs of the scientists and of the government officials and corporation executives who provide the funds for research.") Apostate or not, though, in popular discourse he became the successor to Vincent Price in a fright wig or to Dr. Strangelove careening in his wheelchair across the War Room: another techno-head bringing evil on us all.

But part of the reflexive stereotyping probably sprang from a different public distrust—one directed at the politicized 1960s and its wave of protesters. When Kaczynski—ex-Harvard, ex-Sixties, ex-mathematician—was moved out of his Montana cabin and into Judge Garland Burrell's courtroom in Sacramento, he became in some ways an unairbrushed, unwelcome sign of the protesting past, as startlingly anachronistic as the Japanese soldiers who hid out after World War II rather than surrender.

Thirty years ago Kaczynski would probably have been construed as political first, mad last. His manifesto—so similar in tone to dozens written then—makes an argument for violence ("to get our message before the public with some chance of making a lasting impression, we've had to kill people"). Although most of the Sixties generation advocated peace, some committed themselves to violence as a political act. The Internet—with its varied cast of characters and its penchant for political discussion—is in some ways very reminiscent of that turbulent era when manifestos were a dime a dozen, were widely debated and were, in some cases, the basis for violence.

Political debate is largely out of fashion. According to a recent trio of articles in the *New York Times Magazine,* it is private lives and stock portfolios that matter in this, what the magazine calls the Bland Decade. And if ordinary political discussion is marginal to most people, its more radical forms—and certainly Kaczynski's manifesto is political philosophy at its most extreme—have virtually vanished from the landscape.

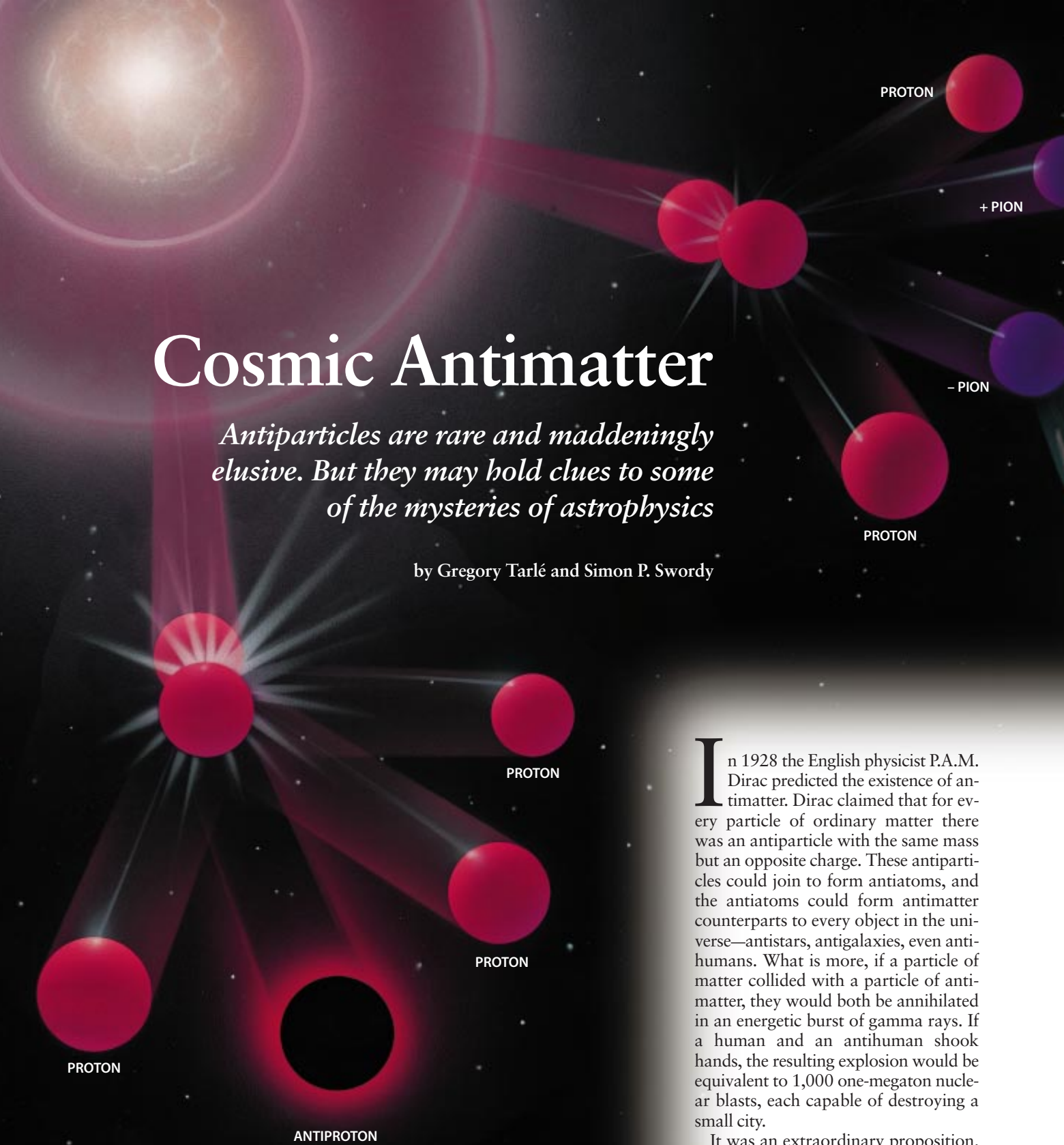
It's over, his murderous campaign against technology and the people he associated with it. Unless prosecutors in New Jersey or California file murder charges, which is thought unlikely, he will not appear again in court after his sentencing in California on May 15. The plea he accepted is unconditional—it permits no lesser sentence than life in prison and no possibility of release. He may still live on in the Internet, though, the ghost of protests past kept afloat courtesy of the very technology he so utterly opposed.

—Anne Eisenberg in New York City

Cosmic Antimatter

Antiparticles are rare and maddeningly elusive. But they may hold clues to some of the mysteries of astrophysics

by Gregory Tarlé and Simon P. Swordy



ALFRED T. KAMAJIAN

VIOLENT COLLISIONS of protons accelerated by a supernova shock front create much of the antimatter that scientists observe. Some collisions produce a shower of positrons, electrons and other particles (*top*), whereas the most powerful impacts generate antiprotons (*bottom*).

In 1928 the English physicist P.A.M. Dirac predicted the existence of antimatter. Dirac claimed that for every particle of ordinary matter there was an antiparticle with the same mass but an opposite charge. These antiparticles could join to form antiatoms, and the antiatoms could form antimatter counterparts to every object in the universe—antistars, antigalaxies, even antihumans. What is more, if a particle of matter collided with a particle of antimatter, they would both be annihilated in an energetic burst of gamma rays. If a human and an antihuman shook hands, the resulting explosion would be equivalent to 1,000 one-megaton nuclear blasts, each capable of destroying a small city.

It was an extraordinary proposition. The theory was confirmed just four years later, when Carl D. Anderson, a physicist at the California Institute of Technology, detected the first antiparticle. While using a cloud chamber to study cosmic rays—high-energy particles that bombard the earth from space—Anderson observed a vapor trail made by a particle with the same mass as an elec-

tron but an opposite (that is, positive) charge. Dubbed the positron, it was the antimatter counterpart of the electron. Antiprotons proved harder to find, but in 1955 physicists at Lawrence Berkeley Laboratory used a particle accelerator to create them. In 1995 scientists at CERN, the European laboratory for particle physics near Geneva, synthesized atoms of antihydrogen—for a brief instant—by merging positrons and antiprotons in a particle accelerator.

In recent years scientists have built sophisticated detectors to search for antimatter in cosmic rays. Because cosmic rays are destroyed by collisions with the nuclei of air molecules, researchers have lofted their detectors into the least dense reaches of the atmosphere. We are involved in one of those experiments, the High Energy Antimatter Telescope (HEAT), which rides on high-altitude balloons to detect positrons in cosmic rays. Other balloon-borne detectors can observe antiprotons. More ambitious antimatter searches on the drawing board include ones involving extended balloon flights and detectors orbiting in space. The results of these experiments could tell much about the origins of antimatter. They may also indicate whether antistars and antigalaxies really exist.

Astrophysicists believe most of the antiparticles observed in the upper atmosphere were created by violent collisions of subatomic particles in interstellar space. The process starts when the magnetic fields in the shock wave from a supernova explosion accelerate an interstellar proton or heavier atomic nucleus to enormous speeds. If this nucleus—now a high-energy cosmic ray—collides with another interstellar particle, part of the energy of the cosmic ray can be converted to a particle-antiparticle pair.

A Bucket of Cosmic Rays

Some collisions produce pairs of pions, unstable particles that quickly decay into positrons, electrons, neutrinos and antineutrinos. The most energetic collisions, involving particles moving at nearly the speed of light, produce proton-antiproton pairs. This process is the reverse of matter-antimatter annihilation: energy turns into matter instead of matter turning into energy.

Yet the number of antiparticles produced by interstellar collisions is relatively small. In the cosmic rays observed by the HEAT instrument, particles far outnumber antiparticles. To understand the difficulty of detecting antimatter, imagine a bucket filled with steel screws. A hundred of the screws have normal right-handed threads (representing the negatively charged electrons in cosmic rays), and 10 screws have left-handed threads (representing the positively charged positrons). Cosmic rays also contain protons, which are positively charged like positrons but far more massive. These protons could be represented by adding 10,000 heavier left-handed screws to the imaginary bucket. Now each left-handed screw must be weighed to see if it is a proton screw or a positron screw. And the weighing must be done very accurately. If only one in 1,000 proton screws is mistaken for a positron screw, the apparent number of positron screws will double.

The HEAT instrument has an error rate that is below one in 100,000. The device uses a superconducting magnet and an assembly of detectors to identify positrons. After cosmic rays speed through a collecting aperture, the superconducting magnet deflects the negatively charged electrons in one direction and the positively charged protons and positrons in the other. The detectors measure the charge and direction of each incoming particle, as well as the amount of deflection it experiences in the magnetic field. This last measurement helps to distinguish between protons and positrons; a proton, being heavier, will travel in a straighter path than will a positron with the same velocity.

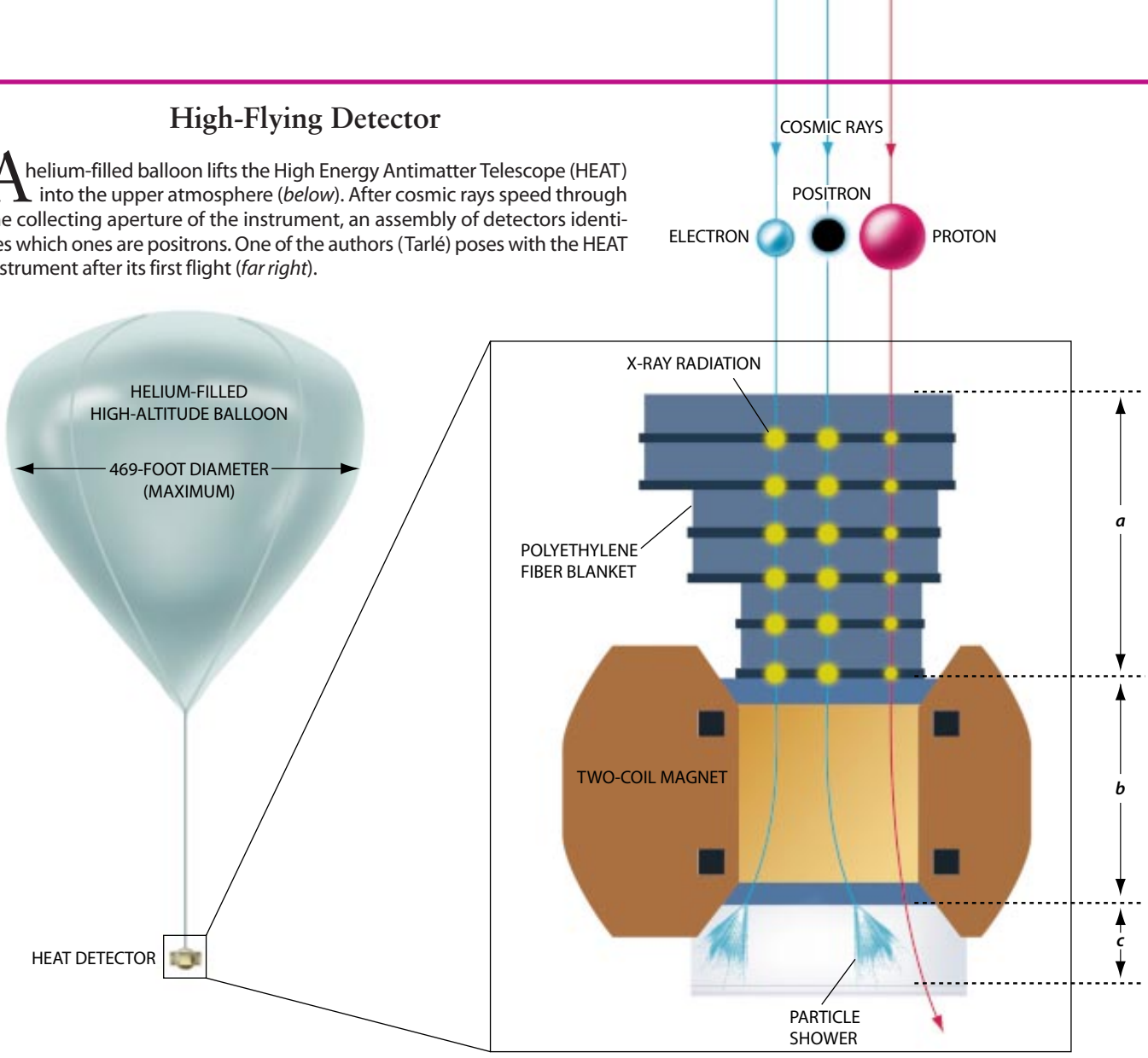
The National Aeronautics and Space Administration's scientific balloon facility launched the HEAT device for the first time in 1994 from a site in New Mexico. Although the device weighs about 2,300 kilograms (5,000 pounds), a giant helium-filled balloon raised it to an altitude of 37,000 meters (120,000 feet)—above 99.5 percent of the atmosphere. HEAT conducted measurements of cosmic rays for 32 hours, then parachuted to a soft landing in the Texas Panhandle. NASA launched HEAT again in 1995 from a site in Manitoba, Canada. The second flight allowed the device to observe lower-energy positrons, which can penetrate the magnetic field of the earth only near the north and south magnetic poles.

The results from these two flights were intriguing. The number of low-energy positrons recorded by HEAT was very close to the number expected to be produced by interstellar collisions. Yet the device found more positrons than anticipated in the high-energy range. The observed excess is not particularly large and could be the result of subtle errors. If the surplus is real, however, it suggests that an unappreciated source of high-energy positrons exists in the cosmos. One candidate is the putative weakly interacting massive particle, or WIMP.

This hypothetical particle offers a possible solution to the bedeviling "dark matter" problem. In order to explain the observed rates of galactic rotation, astrophysicists believe that each galaxy is embedded in a huge halo of dark matter that cannot be observed by ordinary means. The hypothetical WIMP would be a good candidate for the dark matter because it does not give off light or any other form of electromagnetic radiation. If WIMPs exist at the predicted density, collisions among them would produce a significant number of high-energy positrons. This process could account for the excess observed by the HEAT device. But before we and the other investigators involved can make that claim, future measurements from HEAT or other detectors must confirm our observations with greater precision.

High-Flying Detector

A helium-filled balloon lifts the High Energy Antimatter Telescope (HEAT) into the upper atmosphere (*below*). After cosmic rays speed through the collecting aperture of the instrument, an assembly of detectors identifies which ones are positrons. One of the authors (Tarlé) poses with the HEAT instrument after its first flight (*far right*).



ALFRED T. KAMAJIAN

While we have been hunting for positrons in cosmic rays, other scientists have been chasing an even more elusive quarry—the antiproton. Antiprotons are rarer than positrons because they are nearly 2,000 times heavier. Consequently, a much greater amount of energy is needed to create them. Interstellar protons must collide at speeds above 99 percent of the speed of light to produce a proton-antiproton pair.

Antimatter detectors such as the Isotope Matter Antimatter Experiment (called IMAX for short) and the Balloon-borne Experiment with Superconducting Solenoidal Spectrometer (dubbed BESS) have found a maximum abundance of only one antiproton for every 10,000 protons in the rain of cosmic rays. The rarity of these antiparticles forces the scientists searching for antiprotons to take special care to avoid false readings. Their detectors must have an error rate below one in a million to be sufficiently sensitive.

In Search of Antiworlds

The first extensive search for larger fragments of cosmic antimatter was the one initiated by the physicist Luis W. Alvarez in the 1960s. Alvarez began looking for heavy antiparticles, such as the nuclei of antihelium or anticarbon or antioxygen, in cosmic rays. Unlike positrons and antiprotons, these heavy antiparticles are too massive to have resulted from interstellar particle collisions. So the discovery of an antihelium nucleus would prove that some antimatter survived the big bang. And the detection of an anticarbon or antioxygen nucleus would reveal the existence of antistars, because carbon and all heavier elements are created only in stars.

Most astrophysicists are skeptical of the existence of antistars. Although light from an antistar would look the same as light from an ordinary star, the antistar would inevitably collide with particles of ordinary matter streaming toward it from interstellar space. The ensuing matter-antimatter annihilation would then produce a huge flux of gamma rays. Orbital detectors have observed low-energy gamma rays indicating the annihilation of an immense plume of positrons apparently extending from the center of our galaxy. Still, scientists do not believe these positrons are being produced by an antistar, which would appear as an intense, localized source of much more energetic gamma rays. The fact that no detector has observed such a source suggests that there are no antistars in the galaxy and, by similar reasoning, no

GEORGIA DENOLFO

Section *a* shows the transition radiation detector, a series of six polyethylene fiber blankets. Positrons and electrons generate x-rays as they pass through the blankets, while protons of the same energy produce a much weaker signal.

Section *b* shows the magnetic spectrometer, which uses a superconducting magnet to deflect the cosmic rays. Electrons veer in one direction, while protons and positrons swerve the opposite way. Protons and positrons can be distinguished because a positron will curve more than a proton having the same velocity.

Section *c* shows the electromagnetic calorimeter, a stack of plastic slabs and thin layers of lead. When electrons and positrons hit the lead layers, they produce particle showers, which generate flashes of light in the plastic slabs. Most protons pass right through.

antigalaxies in the local galactic cluster.

What about farther away? Perhaps the universe contains isolated antigalaxies, separated by vast distances from galaxies of ordinary matter. In the past decade, astronomers have made extensive surveys of the distribution of galaxies as far away as a billion light-years. The surveys show no isolated regions that could conceivably be made of antimatter. Instead they show a web of galactic clusters surrounding great empty spaces, like a tremendous foamy bubble bath. If large parts of the universe were made of antimatter, the regions where matter and antimatter overlapped would have produced enormous amounts of gamma rays in the early history of the universe. Astronomers have not detected such a powerful background glow. Antigalaxies, if they exist at all, must lie beyond the range of our best telescopes—or at least several billion light-years away.

What is more, modern cosmology provides a reason why the universe can be composed almost entirely of ordinary matter. According to the most widely accepted theories, the big bang produced a small excess of matter over antimatter in the first instant of creation. This phenomenon occurred because of a slight asymmetry in the laws of physics, known as the CP violation, which has been observed in the laboratory. For every 30 billion particles of antimatter created during the big bang, 30 billion and one particles of matter also emerged. About a millionth of a second after the big bang, the particles began annihilating the antiparticles until only the excess ordinary matter was left. This small surplus—still a vast number of particles—became the universe as we know it.

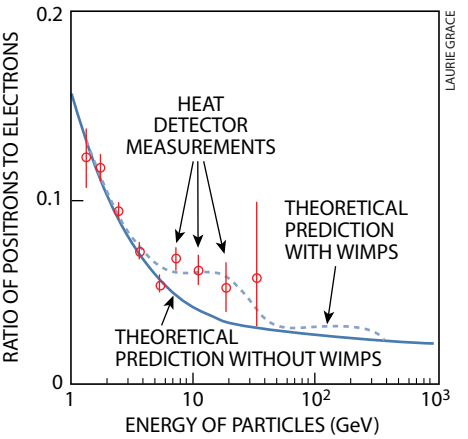
Although this theory seems persuasive, some scientists have continued searching for heavy antiparticles. They remain convinced that large regions of antimatter exist and that heavy antimatter nuclei moving nearly as fast as the speed of light could cross the huge expanse separating them from our galaxy. In the 1960s and 1970s Alvarez and other scientists deployed detectors that analyzed tens of thousands of cosmic-ray hits to determine whether any were made by heavy antiparticles. More recent experiments have sampled millions of cosmic rays. Despite all these efforts, no antiparticle heavier than an antiproton has ever appeared.

It is conceivable that distant antigalaxies are emitting heavy antiparticles, but the magnetic fields in intergalactic space prevent them from reaching the earth. Recent measurements of synchrotron radiation passing through galactic clusters have shown that the magnetic field within such clusters is about one millionth as strong as on the surface of the earth. Because such fields probably intensified 1,000-fold during the formation of the clusters, astrophysicists infer that the field between widely separated galaxies is only a billionth the strength of the field on the earth.

Although such a field would be too weak to nudge a compass needle, over time it would have a significant effect on an antiparticle traveling the enormous distances of intergalactic space. The path of the antiparticle would be bent into a helix, only a few light-years in diameter, around one of the magnetic-field lines. Astrophysicists do not agree on the orientation of magnetic fields in intergalactic space; some believe the fields are coherent, like the field around an ordinary bar magnet. Others claim the field lines are hopelessly tangled. If that is true, antiparticles could not travel far in one direction. They would bounce randomly amid the snarl of field lines. One can liken this movement to a drunken man trying to walk from a bar to his house 10 kilometers away. A sober man would walk in a straight line and reach his home in a few hours. But the drunkard takes steps in random directions and so makes little progress. He would be unlikely to reach his house even in a year.

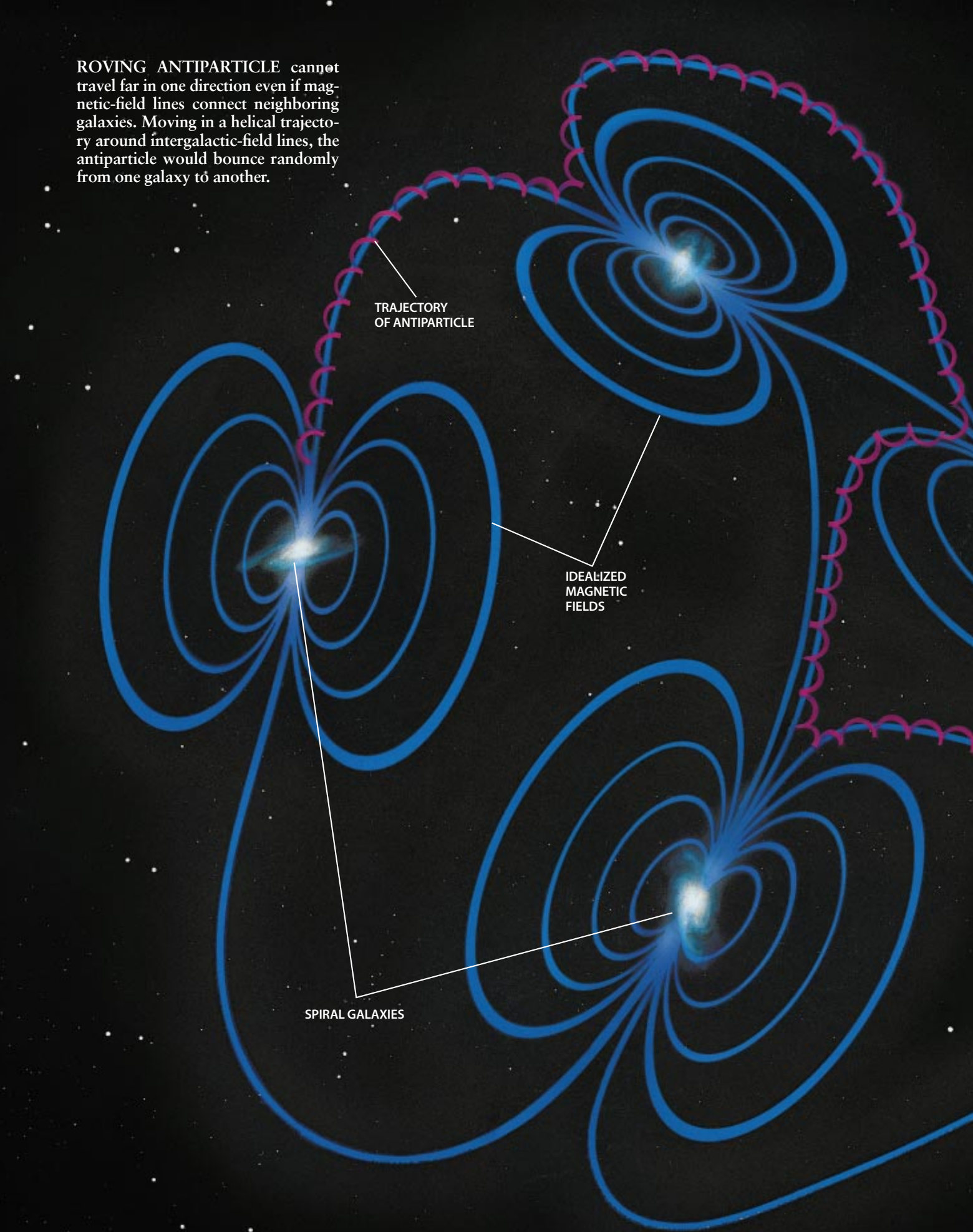
If, on the other hand, the intergalactic magnetic field is coherent, the field lines could conceivably stretch from one galaxy to another. Under these conditions, antiparticles would be funneled between neighboring galaxies along cosmic highways that are millions of light-years long. The antiparticles still would not travel in a straight line; they would hop from one galaxy to another. It is as though our drunken wanderer is guided from one street corner to the next but still makes little progress because he moves randomly at the intersections. The antiparticles could travel only a few hundred million light-years from their starting point, even if they were given the entire age of the universe to make the trip. That distance is far shorter than the billions of light-years to the nearest possible antigalaxy.

Even if, by some miracle of persistence, an antiparticle approaches our galaxy, it still may not reach the earth. Because the magnetic field inside the galaxy is far stronger than the field outside, it

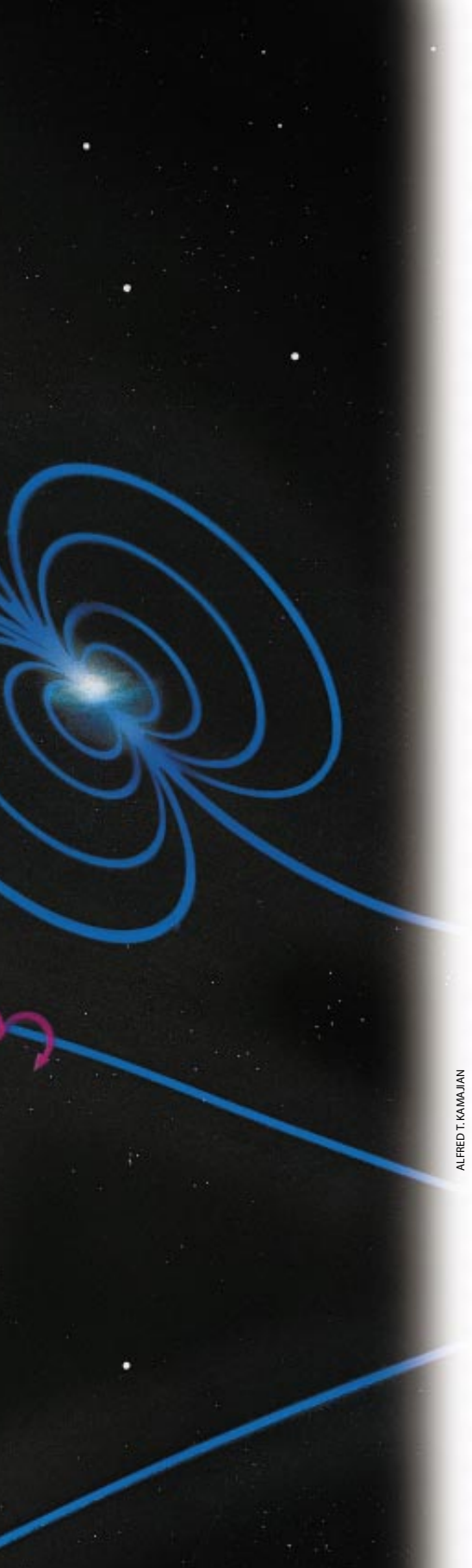


LAURIE GRACE

SMALL EXCESS in the number of high-energy positrons observed by the HEAT device may suggest another possible source of antimatter—the hypothetical weakly interacting massive particle, or WIMP.



ROVING ANTIPARTICLE cannot travel far in one direction even if magnetic-field lines connect neighboring galaxies. Moving in a helical trajectory around intergalactic-field lines, the antiparticle would bounce randomly from one galaxy to another.



ALFRED T. KAMAJIAN

Cosmic Antimatter

will deflect the vast majority of antiparticles heading inward. The drunken man has finally made it to his house—and now he cannot find the key to the door.

Future Flights

It seems highly unlikely that heavy antiparticles will ever be found in our own galaxy. Nevertheless, the search continues. The U.S. Department of Energy is sponsoring a project to put an antimatter detector into orbit. The device, called the Alpha Magnetic Spectrometer (AMS), is primarily aimed at searching for heavy antimatter nuclei. NASA plans to test the AMS on the space shuttle later this year. If all goes as planned, the AMS will fly on the International Space Station for three years beginning in early 2002.

With such a long exposure time, the AMS would, in principle, have 100 times the sensitivity of previous antimatter detectors. The real challenge will be to ensure a commensurate level of accuracy in distinguishing between particles and antiparticles. To identify one heavy antiparticle from a background of 100 million particles, the detector must correctly determine the deflection of each particle in a magnetic field. The most precise balloon-borne instruments make 15 or more measurements to determine the deflection of speeding particles. The AMS will make only six.

Another device intended to observe cosmic antimatter from orbit, PAMELA, is scheduled to be launched from the Russian space center in Baikonur in 2000. PAMELA will search for positrons and antiprotons as well as heavy antinuclei using a system that is more sophisticated than the one built into the AMS. PAMELA will collect fewer cosmic rays, however, because of its small size, so it may not be able to conduct a thorough search for heavy antiparticles.

More balloon-borne searches for cosmic antimatter are on the horizon. For example, we are building a new version of the HEAT detector designed to look for high-energy antiprotons. We hope to improve our measurements by increasing the amount of time the detector remains aloft. NASA has launched high-altitude balloons in Antarctica that can fly for 10 to 20 days, traveling in a circle around the South Pole. And the NASA Wallops Island suborbital team is developing new lightweight fabrics for balloons that may allow flights of up to 100 days. Flight tests of balloons constructed from these materials should occur in the next few months.

The search for antimatter in the cosmos has undergone many twists and turns. The earliest experiments were motivated by a desire for symmetry, an eagerness to prove that there are equal amounts of matter and antimatter in the universe. The results, though, have shown a widespread asymmetry. Antimatter detectors have found very few positrons and antiprotons in the cosmic rays and no heavy antiparticles whatsoever. Antistars and antigalaxies might still lurk somewhere in the universe, billions of light-years from our own galaxy. Yet heavy antiparticles from such distant regions would be unlikely to reach the earth, and hunting for them may be a futile task. Nevertheless, the search for positrons and antiprotons may help reveal the nature of dark matter, one of the great mysteries of astrophysics. SA

The Authors

GREGORY TARLÉ and SIMON P. SWORDY have both been conducting cosmic-ray research for more than 20 years. Tarlé, a professor of physics at the University of Michigan, earned his doctorate from the University of California, Berkeley, in 1978. He is also active in experiments to search for magnetic monopoles, cosmic neutrinos and neutrino oscillations. Swordy, a professor at the University of Chicago, received his Ph.D. from the University of Bristol in 1979. He was a member of the team of investigators for the Cosmic Ray Nuclei Experiment, which flew on the space shuttle in 1985.

Further Reading

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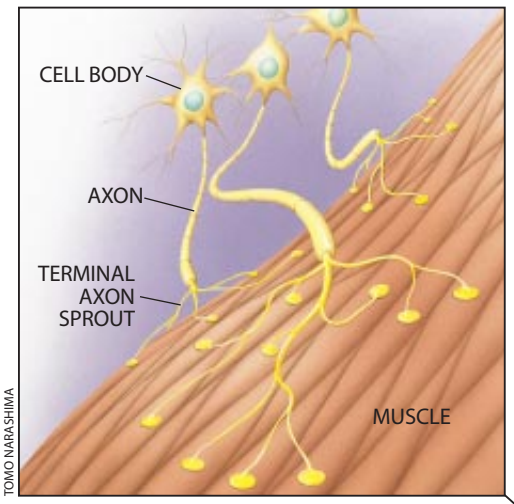
Information on the AMS experiment can be found at http://hpl3sn05.cern.ch:8080/ams01.html on the World Wide Web.

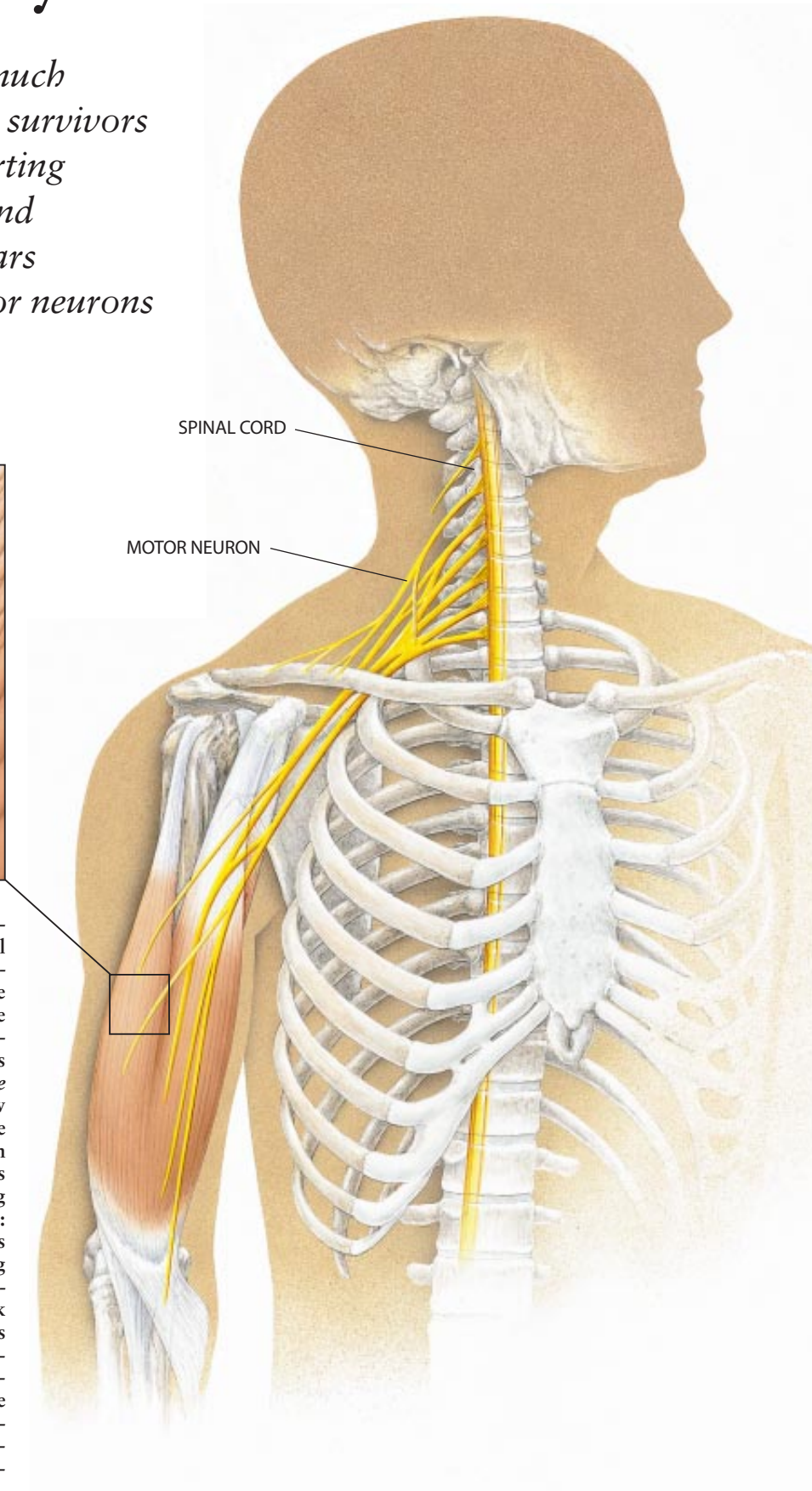
Post-Polio Syndrome

Decades after recovering much of their muscular strength, survivors of paralytic polio are reporting unexpected fatigue, pain and weakness. The cause appears to be degeneration of motor neurons

by Lauro S. Halstead



TOMO NARASHIMA



MOTOR NEURONS (*yellow, at right*) that control voluntary muscle movement have their cell bodies in the spinal cord and long axons that extend to groups of muscles, for instance, in the arm. Sprouts near the end of each axon innervate individual muscle cells (*above*). Some motor neurons infected by poliovirus survive, but others die, leaving paralyzed muscle cells (*a, opposite page*). Recovered motor neurons develop new terminal axon sprouts (*green*) that reinnervate orphaned muscle cells (*b*). A single motor neuron may grow sprouts to innervate five to 10 times more muscle cells than it did originally, creating a giant motor unit. The adaptation is not static: in a process called remodeling, the motor unit is constantly both losing old sprouts and growing new ones (*c*). After many years of functional stability, these enlarged motor units begin to break down, causing new muscle weakness. Two types of degeneration have been proposed. A progressive lesion is produced when normal regeneration of the axon sprouts no longer keeps pace with dying or malfunctioning sprouts (*d*). A fluctuating lesion occurs when there is a faulty synthesis or release of the neurotransmitter acetylcholine [*see illustration on page 44*].

In the first half of the 20th century, the scourge of paralytic poliomyelitis seemed unstoppable. A major polio epidemic hit the New York area in 1916, and in the following decades the epidemics grew in size and became more deadly. The epidemic of 1952, for instance, affected more than 50,000 Americans and had a mortality rate of about 12 percent. It is difficult to realize today the extent of the fear and panic that gripped the public. Polio haunted everyone: families stayed at home; swimming pools were closed; public events were canceled.

Children in particular were at risk. With the introduction of Jonas E. Salk's injected killed-virus polio vaccine in 1955 and Albert B. Sabin's oral live-virus vaccine six years later, the epidemics were brought to an end. By the mid-1960s the number of new polio cases dropped to an average of 20 a year. Polio had been vanquished. Or so it seemed.

For the average American, polio no longer meant a disease but a vaccine. Medically, polio came to be regarded as a static, nonprogressive neurological disorder. It was believed that after rehabilitation and reeducation most survivors could reach a plateau of neurological and functional stability that would last more or less indefinitely—and that is where our understanding of polio as a chronic disease remained until fairly recently.

Then, in the late 1970s, reports began to surface that people who had recovered from paralytic polio decades earlier were developing unexpected health problems such as excessive fatigue, pain in muscles and joints and, most alarming of all, new muscle weakness. Because there was little in modern medical literature about delayed neurological changes in polio survivors, the initial response by many physicians was that the problems were not real. For a time they were dealing with a cluster of symptoms that had no name—and without a name there was, in essence, no disease. Having a name—even if imprecise and misleading as to causation—at least confers an element of credibility.

By sheer weight of numbers, persons experiencing the late effects of polio finally started attracting the attention of the medical community, and in the early 1980s the term post-polio syndrome was coined. Today the syndrome is defined as a neurological disorder that produces a cluster of symptoms in individuals who had recovered from paralytic polio many years earlier. These symptoms typically appear from 30 to 40 years after the acute illness. The major problems are progressive muscle weakness, debilitating fatigue, loss of function and pain, especially in muscles and joints. Less common are muscle atrophy, breathing problems, swallowing difficulties and cold intolerance. Of all these health problems, however, the critical symptom of post-polio syndrome is new progressive weakness.

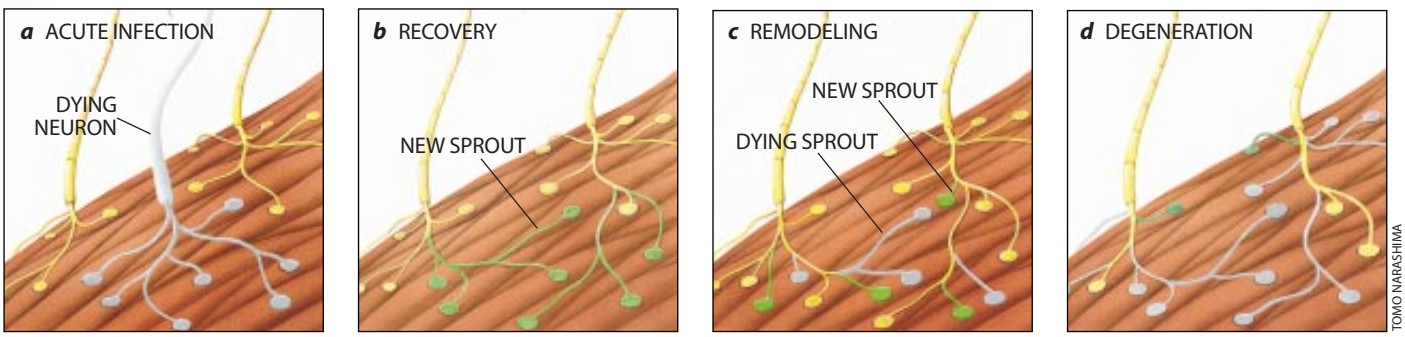
Patients most at risk for post-polio syndrome are those who had suffered a severe attack of paralytic polio, although some patients who seemingly had a mild attack have also developed the syndrome. The onset of these new problems often is insidious, but in many cases they appear to be precipitated by specific events such as a minor accident, a fall, a period of bed rest or surgery. Patients characteristically say that a similar event several years earlier would not have caused such a large decline in health and function.

My own experience seems to be typical of both recovery from paralytic polio and the new development of post-polio syndrome. I contracted polio during the epidemic of 1954 while traveling in Europe after my freshman year in college. I was 18 years old. My six-month journey of recovery took me from iron lung to wheelchair to foot brace and then to no assistive device at all. At times, improvement in strength seemed to happen overnight. Although my right arm remained paralyzed, the rest of my body regained most of the strength and endurance I had before my illness. As a result, I thought of myself as cured. I returned to college, learned to write with my left hand and even played intramural squash. On the morning of the third anniversary of the onset of my polio, I reached the summit of Mount Fuji in Japan after a climb of over 12,000 feet. As I watched the sun rise, I thought, "Polio is behind me. I have finally conquered it."

With the conquest of Mount Fuji fresh in my mind, I began to look for other mountains to climb. After college, I entered medical school. Internship and residency initiated yet another cycle of physically demanding years. In short, I got on with my life while polio receded ever further in my memory. Several years ago I began developing new weakness in my legs. As the weakness progressed over a period of months, I went from being a full-time walker who jogged up six flights of stairs for exercise to having to use a motorized scooter full-time at work.

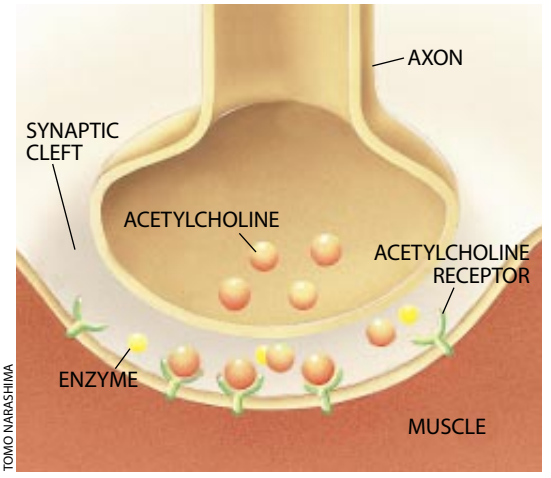
Historical Background

Post-polio syndrome, it turns out, is not a new disorder after all. It was described in the French medical literature in 1875, and then, as often happens in medicine, it was forgotten. Over the next 100 years, approximately 35 reports on post-polio weakness were published in the medical literature. By 1984 a growing awareness of the delayed effects of polio prompted me and other researchers to organize an international conference at the Warm Springs Institute for Rehabilitation—the great polio treatment mecca in southern Georgia established by Franklin Delano Roosevelt, who was paralyzed by polio in



1921 at the age of 39. Roosevelt felt that swimming in the warm waters of a natural spring at a health resort strengthened his muscles, and in 1926 he purchased a hotel there and turned it into a nonprofit foundation.

A second international meeting on post-polio syndrome was held at the Warm Springs Institute in 1986, and in the following years there was a dramatic increase in basic and clinical research into the long-term effects of polio. In 1994 the New York Academy of Sciences and the National Institutes of Health cosponsored another international meeting that culminated in the publication of a special issue of the *Annals of the New York Academy of Sciences:* "The Post-Polio Syndrome: Advances in the Pathogenesis and Treatment." That conference signaled the acceptance of post-polio syndrome as a legitimate clinical entity.



NORMAL ACTIVITY of acetylcholine leads to muscle contraction. When acetylcholine is released from an axon into the synaptic cleft, it binds to receptors on the muscle cell, causing it to contract. An enzyme splits the remaining acetylcholine in the synaptic cleft into choline and acetate, which are reabsorbed by the axon and resynthesized into new acetylcholine. Chronic disruption of this cycle may result in progressive muscle weakness.

Surprisingly, accurate figures about the number of Americans who have had paralytic polio are not available and probably never will be. There is no national registry of persons who were diagnosed with the disease, and there is no way, after all these years, to compile accurate figures from state and local health departments. The best estimate is based on information from the federal government's National Center for Health Statistics, which collects data on health and disability issues every year from a random sample of U.S. households. Based on data from the 1987 survey, the National Center for Health Statistics calculated there were more than 640,000 survivors of paralytic polio, which would mean there are more survivors of paralytic polio than there are persons with multiple sclerosis, amyotrophic lateral sclerosis or even spinal-cord injury.

Since 1987 an unknown number of polio survivors have died, but immigrants, refugees and illegal aliens have added an unknown number to the U.S. population of polio survivors. No one knows how many survivors of paralytic polio have post-polio syndrome. Some studies indicate the figure could be as high as 40 percent. If this estimate is accurate, then the total number of persons in this country currently suffering from post-polio syndrome could reach 250,000.

Knowledge of how the poliovirus infects the body can be helpful in understanding the possible causes of post-polio syndrome. It is a small RNA virus that can enter the body when contaminated water or food are ingested, and even when contaminated hands touch the mouth. The vast majority of persons who become infected either have no symptoms or experience a self-limited illness characterized by fever and gastrointestinal upset for several days. The poliovirus, which replicates in the lymphoid tissue of the throat and small intestine, either passes harmlessly from the gut or travels in the blood to all parts of the body. In a small minority of infected persons—usually 1 to 2 percent—the virus invades the central nervous system and produces an unpredictable amount of paralysis.

Mechanism of Infection

A distinctive characteristic of acute polio infection is the predilection of the poliovirus for the nerve cells that control muscles. These nerve cells, or motor neurons, consist of a cell body located in the anterior horn of the spinal cord and a long tentacle, or axon, that extends to the muscles. Near the end of each axon, tiny sprouts branch out to individual muscle cells. At the nerve-muscle interface, or synapse, the sprouts from the axon release acetylcholine, a neurotransmitter that causes the muscle fibers to contract. A motor neuron and the group of muscle cells that it activates are called a motor unit.

With uncanny precision, the poliovirus invades the motor neurons, leaving intact adjacent nerve cells that control the functions of sensation, bowel, bladder and sex. How this exquisitely targeted behavior occurs was a mystery until recently, when researchers identified poliovirus receptors at the nerve-muscle interface. These receptors apparently allow the poliovirus to enter an axon and then to migrate to the nerve cell body in the anterior horn of the spinal cord. The poliovirus typically infects more than 95 percent of the motor neurons in the spinal cord and many other cells in the brain. The infected cells either overcome the virus or die.

The extent of paralysis is unpredictable. Motor neurons that survive develop new terminal axon sprouts in response to an unknown stimulus. These new sprouts reinnervate, or reconnect, with the muscle fibers left orphaned by the death of their original motor neurons. In a sense, the growth of additional axon sprouts is the body's effort to keep as many orphaned muscle cells as possible alive and working. A single motor neuron that initially stimulated 1,000 muscle cells might eventually innervate 5,000 to 10,000 cells, creating a giant motor unit. These vastly enlarged motor units make it possible for fewer motor neurons to do the work of many.

Another adaptation that leads to increased strength is the enlargement of muscle cells when they are regularly exercised. These two compensatory adaptations—increase in muscle size and axon sprouting—are so effective that up to 50 percent of the original number of motor neurons can be lost without the muscle losing clinically normal strength. These adaptations are neither static nor permanent, however. To the contrary, after recovery from acute polio there is an ongoing process of remodeling of the motor units that consists of both denervation (losing old sprouts) and reinnervation (gaining new ones). It is this process of remodeling or constant repair that allows the motor units to achieve a steady state of muscle strength. When this steady state is disrupted, new muscle weakness occurs.

There is a growing consensus among researchers that post-polio syndrome

involves a slow degeneration of the terminal axon sprouts that innervate the muscle cells. David O. Wiechers and Susan L. Hubbell, then affiliated with Ohio State University, proposed this explanation in the early 1980s after diagnostic tests indicated that the functioning of motor neurons in polio survivors progressively worsens as the number of years from their recovery increases. More recently, Daria A. Trojan and Neil R. Cashman of the Montreal Neurological Institute and Hospital, after examining the results of muscle biopsy and electromyographic (EMG) studies in their laboratory and by researchers elsewhere, postulated that there are two types of disintegration of the motor neurons: a progressive lesion and a fluctuating one.

The progressive lesion, in their view, occurs when the normal regeneration of the sprouts from the axon to the muscles is interrupted and malfunctioning sprouts are not replaced. This interruption of the repair process produces irreversible, progressive muscle weakness. The fluctuating lesion, on the other hand, is thought to be caused by defective synthesis or release of the neurotransmitter acetylcholine. Cashman, Trojan and others have demonstrated that muscle weakness and fatigue can be reversed in some patients with post-polio syndrome by the drug pyridostigmine, which enhances the effectiveness of acetylcholine in triggering muscle contractions. Other researchers are testing another class of agents known as nerve growth factors, which stimulate both nerve and muscle cell growth.

Possible Causes

Degeneration of the axon sprouts can explain the new muscle weakness and fatigue, but what causes the degeneration in the first place remains a mystery. The most plausible hypothesis proposes that the muscle weakness is simply the result of overuse of individual motor neurons over time. This explanation assumes that after recovery from polio the surviving giant motor neurons must labor more than normal neurons just to maintain daily activities. After many years of continued overuse, these enlarged motor neurons eventually suffer from a kind of metabolic exhaustion that leads to an inability to regenerate new axon sprouts to replace degenerating ones. There is no direct way to measure metabolic fatigue in motor neurons, but evidence to support this hypothesis can be inferred from abnormalities on muscle biopsies, electrodiagnostic tests and clinical response to exercise.

In addition, some researchers report that some motor neurons in the anterior horn of the spinal cord of polio survivors appear to be smaller than normal. It is believed that these smaller motor nerve cells were somehow damaged at the time of the acute polio infection and that they are vulnerable to premature failure. Normally, significant attrition of motor neurons does not occur until a person reaches the age of 60 years or more. Because polio survivors have a greatly reduced number of motor neurons, the loss of even a few functioning motor units could result in a disproportionate loss of muscle function.

Attrition of motor neurons because of aging alone, however, may not be a significant factor in post-polio syndrome. Several studies have failed to find a positive relation between the onset of new weakness and chronological age. To the contrary, these studies suggest it is the length of the interval between onset of polio and the appearance of new symptoms that is a determining variable.

Persistence of the poliovirus in the body—or, more precisely, viral particles that have lain dormant for many years and then are reactivated by some unknown mechanism—may also play a role. Researchers at a number of centers have reported poliovirus-like RNA fragments in the spinal fluid and spinal-cord tissue of some patients with post-polio syndrome but not in polio survivors who do not have the syndrome. These small RNA fragments, however, do not appear to have any infectious potential. Whether these findings are simply incidental or indicate a possible viral role is not known.

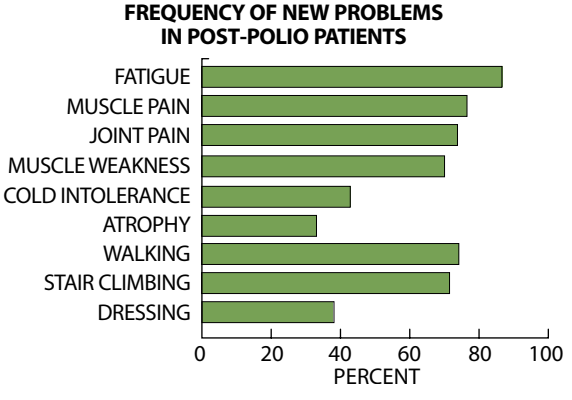
Other causes of post-polio syndrome, such as an immune-mediated response, hormone deficiencies and environmental toxins, have also been proposed. Although some of these hypotheses, and others, seem plausible—and none has been completely excluded—at the present time there is not enough evidence to justify strong support for them.

No definitive tests exist for post-polio syndrome. Diagnostic tests of the blood, muscle biopsies and EMG recordings of muscle activity often show essentially the same abnormalities in polio survivors with post-polio syndrome as in those without it. Therefore, diagnosis relies primarily on systematically ruling out other causes of a patient's symptoms.

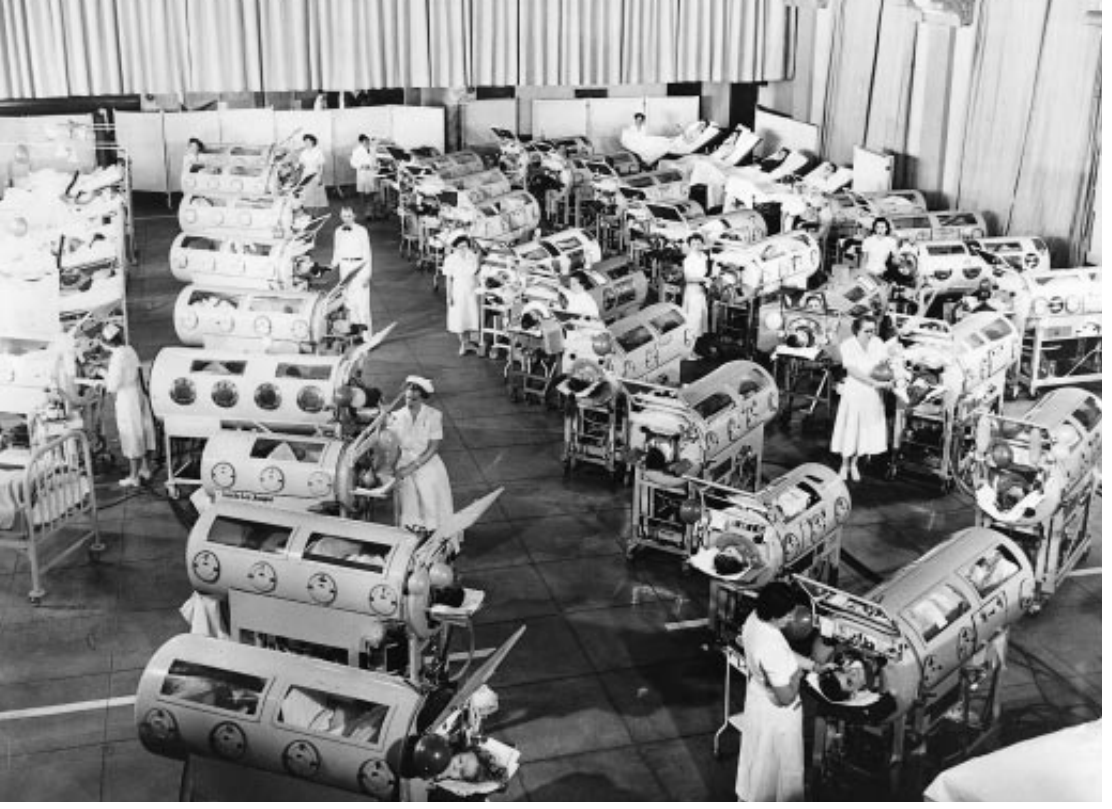
Diagnosis and Treatment

A set of criteria for diagnosing post-polio syndrome has been developed by the Post-Polio Task Force, a group of researchers, clinicians and polio survivors. The onset of new muscular weakness after many years of stable functioning is perhaps the most characteristic symptom. Yet many of the symptoms of post-polio syndrome are so general that ruling out all possible causes is often impractical. For instance, new weakness may result simply from the lack of use of the muscles. Muscle weakness from disuse can mimic post-polio syndrome and complicate it. Regardless of the underlying cause, once the weakness begins it may initiate a cascade of other complaints that makes the original symptom impossible to identify.

As with many other chronic conditions, the essence of good medical care is to relieve symptoms, improve muscular function and enhance the patient's sense of well-being. This management strategy is frequently referred to as bracing and pacing. Effective intervention can be as simple as prescribing a cane or a wheelchair or as complicated as putting someone in an iron lung or providing some other form of assisted ventilation. For both physical and psychological reasons, patients are encouraged to



MOST COMMON new health problems reported by post-polio patients in several clinical studies are fatigue, muscle pain, joint pain and weakness. Functional problems include walking and stair climbing.



IRON LUNGS and rocking beds were clustered together to make it possible for nurses and doctors to monitor a large number of polio patients in rehabilitation centers, such as this one in Rancho Los Amigos, Calif. The concept of clustering patients who require special care is one of the legacies of polio, and that legacy can be found today in the intensive care unit that is an essential part of every modern hospital.

MARCH OF DIMES BIRTH DEFECTS FOUNDATION

remain as active as possible. The new lifestyle, however, should incorporate regular rest breaks. An exercise program is desirable for virtually all patients. For some, this may be nothing more strenuous than gentle stretching or various types of yoga. For others, it may be considerably more vigorous and even include aerobic workouts.

With certain types of exercise in carefully monitored settings, some patients have been able to regain and maintain muscle strength. Although there are no magic bullets, medications can occasionally be helpful: for example, low doses of a tricyclic antidepressant may relieve muscle pain in some patients, and pyridostigmine may reduce fatigue and improve muscle strength.

As a general rule, the progression of symptoms is fairly slow and the overall prognosis is good, unless there are severe breathing or swallowing difficulties. Yet when reserves of strength and stamina are low, a minor change in the stability of the motor neurons can result in a disproportionately large loss of muscular function, which often is psychologically devastating.

Personal Legacies of Polio

Most polio survivors tell a story of struggle and triumph: the sudden, random onset of paralysis, the gradual restoration of strength seemingly as a result of individual willpower and, finally, for many, resumption of an active, productive life, which leads them to believe they have put polio behind them.

The story, for most, is made possible by denying their disability and the reality of what was lost and the life that might have been. Perhaps the most famous example of disability denial is provided by our 32nd president, Franklin D. Roosevelt. Although he regained normal use of his arms fairly quickly after his polio illness, he spent many years in a heroic, but largely unsuccessful, effort to relearn to walk. Even after he became president, Roosevelt went to extraordinary lengths to disguise the extent of his disability. In the waning months of his life, he experienced increasing muscular weakness that appears to be compatible with post-polio syndrome.

Virtually every polio survivor I have met has displayed self-deception or denial. Until recently, most of us tended to avoid other polio survivors and polio help groups. We knew we weren't physically normal, but if we thought about it at all, we considered ourselves as inconvenienced, not disabled. By retraining the muscles that remained, we felt we could do just about anything, even become president, like Roosevelt.

Later in life, when polio survivors begin to experience the new weakness of post-polio syndrome, the denial usually is still intact, which makes understanding and accepting the new changes all the more difficult. As they begin to accept the fact that they are disabled, they may be overcome by feelings of anger, bitterness and despair. Fortunately, a post-polio support movement has sprung up, and there are now more than 300 support groups throughout the country. In my own case, it took me several years after developing post-polio syndrome before I joined a support group and began talking with other polio survivors about my new weakness and pain. Only then did I start to grieve for the body I lost 35 years earlier.

Many post-polio survivors exhibit an extraordinary commitment to exercise, a legacy from their recovery from polio. When a physical therapist prescribed 10 repetitions twice a day to strengthen a certain muscle, patients typically would do 20 or more repetitions three times a day. For many, exercise became a daily obsession, for others, almost a religious devotion. Thus, survivors of polio developed a special relation to their bodies unknown to able-bodied persons. They experienced a new mastery over their muscles and movements, an element of control that had not existed before polio. It was a visceral lesson that carried over into other aspects of their lives and probably accounts for why so many polio survivors have excelled at school and at work.

Individuals who have recovered from paralytic polio have, on average, more years of formal education than the general population, and they take on marriage and family responsibilities at approximately the same rate as persons who are not disabled. Also, the rate of employment of polio survivors is reported to be about four times the rate of other disabled persons.

Over the past few decades much of the leadership for the disability move-

ment has come from polio survivors. Their efforts have led to the founding of the Independent Living movement and to the passage of legislation such as the Architectural Barriers Act and the Americans with Disabilities Act.

What is not widely known is that many of these leaders were among the most disabled: walking with braces and crutches, riding motorized wheelchairs and attached to portable ventilators. In his novel about the plague, Albert Camus wrote, "It helps men to rise above themselves." He could have been describing polio.

Social Legacies

Polio has had a far-reaching effect on medicine. The successful development of a safe vaccine after years of effort was a triumph of enormous proportions. It involved the eager participation of millions of ordinary Americans, initially through door-to-door fund-raising and later in volunteering their children to participate in the 1954 field test of the Salk vaccine. The massive research effort to develop a polio vaccine led to many discoveries that have since revolutionized the fields of virology and immunology.

The polio epidemics accelerated the development of rehabilitation medicine. In contrast to traditional medicine with its focus on the curing and repairing of diseased organs, rehabilitation medicine emphasizes the rebuilding of body functions and the teaching of the skills necessary for independent living. The principles developed to treat polio patients decades ago are essentially the ones used today to rehabilitate persons with head and spinal injuries, strokes and degenerative disorders.

The intensive care unit that is now an integral part of every modern hospital is another legacy from the era of polio epidemics. When large numbers of polio patients requiring iron-lung ventilators started to overwhelm the staff in rehabilitation centers, the iron lungs were clustered together so they could be readily monitored by only a handful of nurses. In addition, regional respiratory centers were created to treat the most severely affected polio patients. Some of these centers have survived and continue to provide care for persons with spinal-cord injuries.

The money that originally funded these respiratory centers was raised by the National Foundation for Infantile Paralysis, which later became known as the March of Dimes. It was Eddie Cantor, the famous singer and entertainer, who suggested that Americans could be asked to mail dimes to support the fight against polio. For a while, the fight against polio brought out many of the best qualities of American society: neighbors carried food to families quarantined at home, teen clubs raised money to help hospitalized classmates, and women's groups adopted local polio wards for the year.

UPI/CORBIS-BETTMANN

FRANKLIN D. ROOSEVELT, after being stricken by paralytic polio in 1921, believed that swimming in naturally heated water at Warm Springs, Ga., strengthened his muscles. He went to great lengths to hide his disability from the public.

Then the vaccines were developed, and not only did polio disappear in America but the war against polio seemed to be forgotten—along with the survivors. Once held up as examples of heroic human fortitude, thousands of polio survivors who continued to need medical and financial help were largely ignored by the public. As veterans of other wars would continue to discover, the public does not like to be reminded of the wounded and the dead after the war is over. Also, as with other conflicts, the polio war left more wounded and uncounted survivors than are generally recognized.

Even the miracle vaccines have their problems. Most scientists agree that the Sabin oral vaccine is superior to Salk's injected one; however, the oral polio vaccine is not free of risk. In fact, it causes the very disease it is designed to prevent in 10 to 15 people every year because of either a mutation in the virus or an immune deficiency in the recipient that allows the weakened virus to take hold and produce paralysis. The federal government has changed its vaccination policy and is now recommending two initial immunizations with the injected killed-virus vaccine followed some time later by two doses of oral live-virus vaccine. In theory, this combination provides the advantages of both vaccines and, we hope, will end forever this nation's rendezvous with polio. SA

The Author

LAURO S. HALSTEAD is director of the spinal-cord injury and the post-polio programs at the National Rehabilitation Hospital in Washington, D.C., and clinical professor of medicine at the Georgetown School of Medicine. He received his M.D. from the University of Rochester in 1963 and a master of public health degree from Harvard University in 1970. Halstead taught rehabilitation medicine and epidemiology at Rochester and Baylor College of Medicine for more than 20 years. His research interests include the late effects of polio, metabolic and endocrine changes in persons with spinal-cord injury, enhancing fertility in men with spinal-cord injuries and developing outcome measures for rehabilitation patients.

Further Reading

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The Earliest Views

Re-creating the experiments of pioneering microscopists reveals what they actually saw with their simple, single-lens instruments

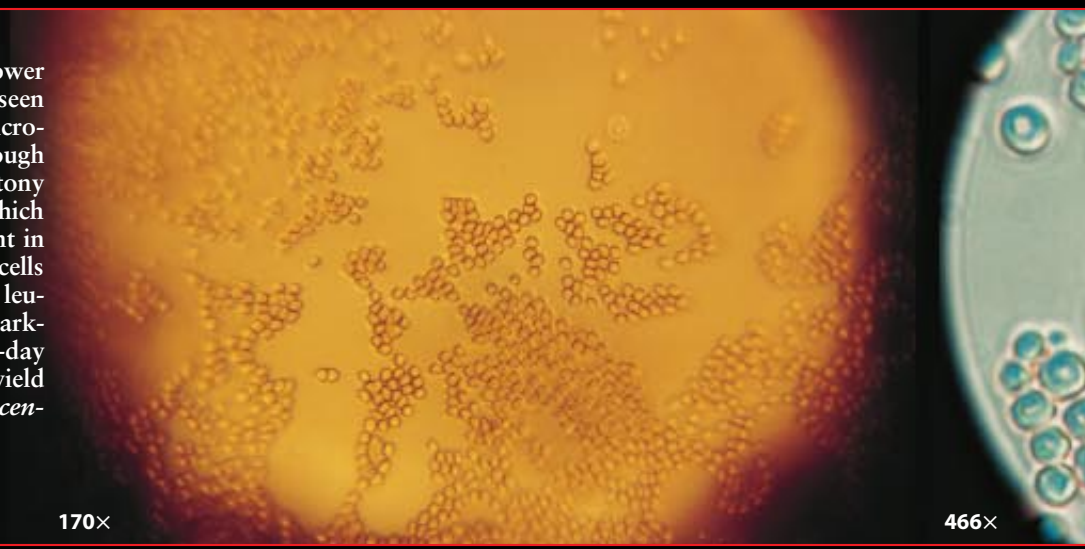
by Brian J. Ford

In 1674 Antony van Leeuwenhoek peered through one of his homemade microscopes and discovered a new and entrancing universe. The Dutch amateur scientist was staring at slime he had collected from the surface of a lake when he suddenly saw unknown organisms: "I saw so many little animalcules and the motion of them in the water was so swift, and so various, upwards, downwards and round about, that it was wonderful to see."

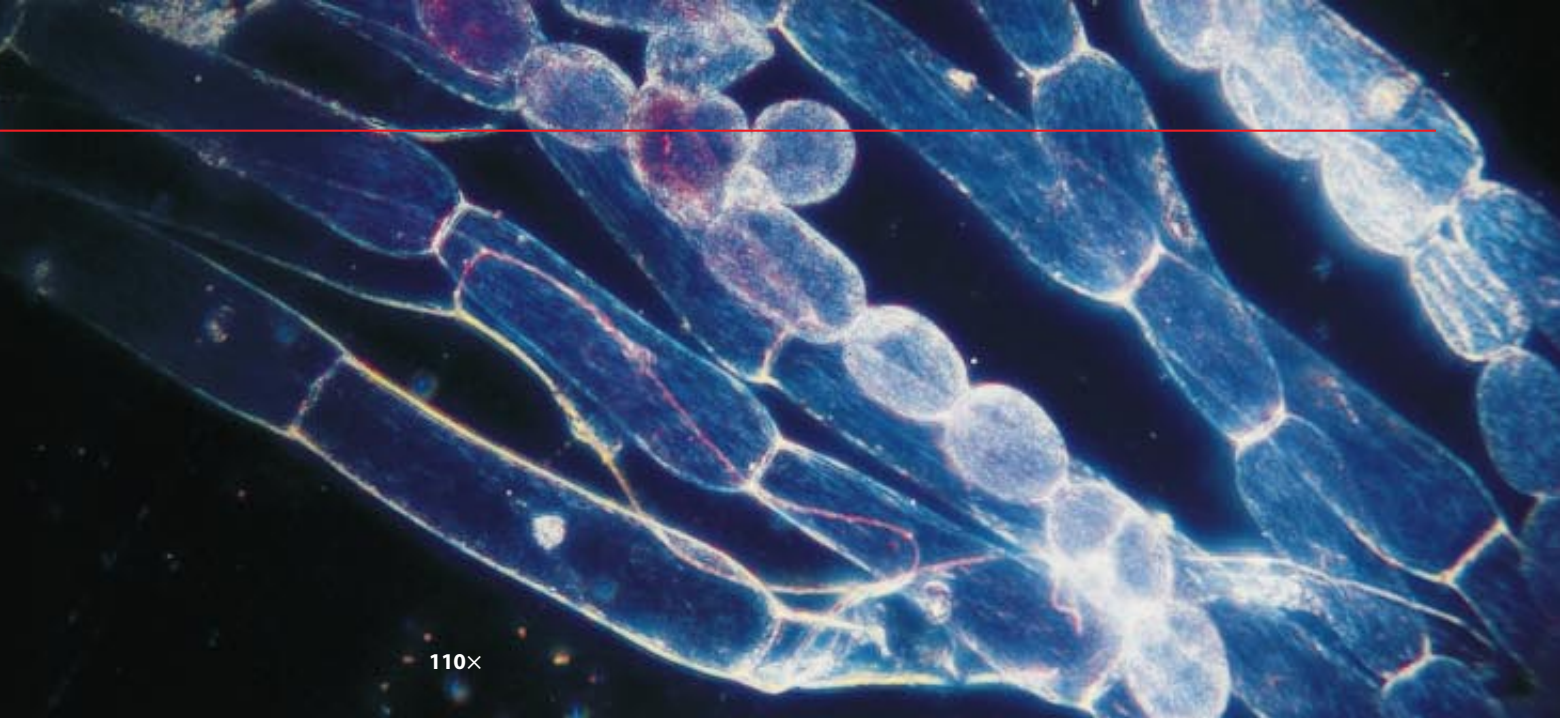
Leeuwenhoek, who lived from 1632 to 1723, had inadvertently launched the field of microbiology. Working in an era before the science of optics really flourished, Leeuwenhoek himself constructed more than 500 microscopes. Using these basic instruments, he recorded—in addition to the "animalcules," or microbes—many cellular structures as well as the existence of red blood cells and spermatozoa. He also described bacteria, protozoa, rotifers, plant cells and fungi.

Nevertheless, many of Leeuwenhoek's contemporaries dismissed him as a dilettante, a man of fertile imagination. His insights never caught on. Indeed, it was not until the mid-1800s—the time of Louis Pasteur—that the idea of microorganisms was widely accepted. Even today some scientists insist that Leeuwenhoek could not have seen what he claimed to observe through his simple, single-lens instruments. Modern-day studies have used a Leeuwenhoek microscope to argue that these magnification devices cannot resolve the fine details he described; in one such experiment, red blood cells seemed mere blurs.

Detractors have leveled similar accusations at Robert Brown. In 1827 the young Scottish surgeon documented something that today bears his name: Brownian movement. He saw inside cells the ceaseless motion of tiny particles. A few years later Brown saw another previously unrecorded



LUMINOUS CELLS from the flower *Tradescantia virginiana* can be seen through one of Robert Brown's microscopes as the sunlight streams through them (*top of opposite page*). Antony van Leeuwenhoek's microscope, which is kept at the University of Utrecht in Holland, clearly reveals red blood cells (*left*)—even the lobed nucleus of a leukocyte can be resolved by this remarkable little instrument. A modern-day single-lens microscope can also yield dramatic images: living yeast cells (*center*) and fungi spores (*far right*).

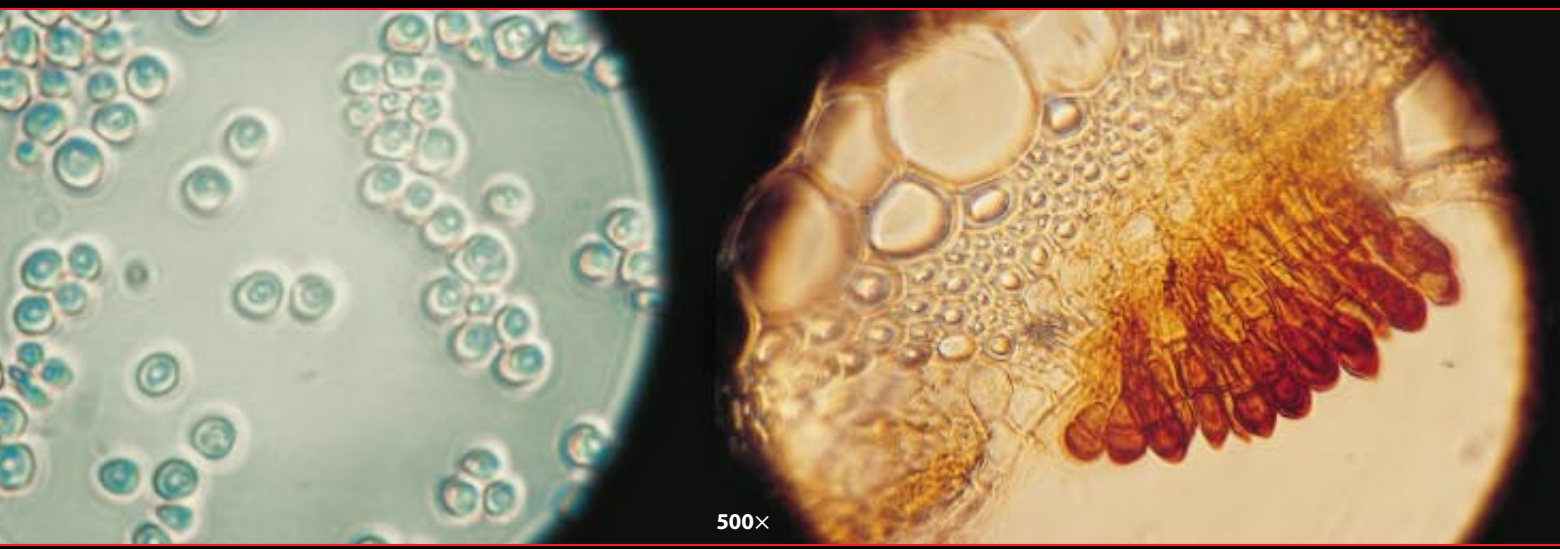


phenomenon through his single-lens microscope. He had traveled to Australia in search of exotic plants and had become fascinated by orchids he collected on the way. As he examined plant cell after plant cell, he became aware of a repeated structure: "In each cell of the epidermis ... a single circular areola, generally more opaque than the membrane of the cell, is observable." Brown soon determined that this feature was common to the cells of many organisms. He later dubbed the structure what we call it still: "the cell nucleus."

As was Leeuwenhoek, Brown was often underrated. Some contemporary textbooks even say that he observed only the motion of pollen grains, not the far tinier movement within cells. Further, one recent assessment of Brown's microscope concluded that the instrument might have been a useful aid for dissection, but it could not have resolved structures as small as a nucleus.

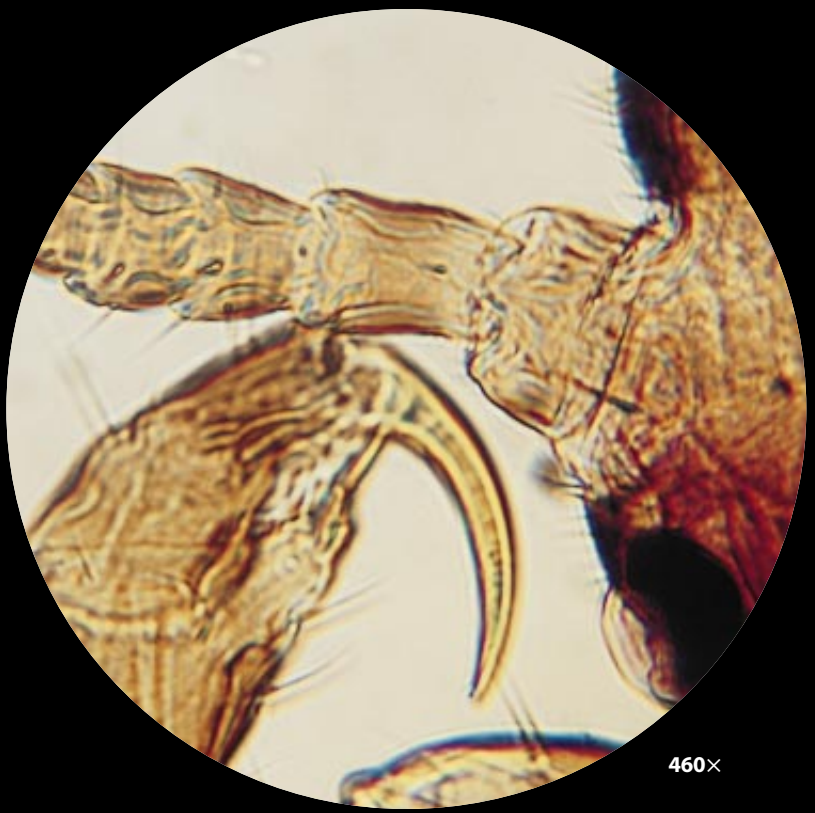
By using these scientists' original microscopes—and by making single lenses myself—I, too, have re-created many of their original experiments. It is difficult work because there are no detailed accounts of the methods these two biologists used and because much care must be taken to adjust the microscopes and adhere faithfully to the experiments. Yet I have found that, contrary to the claims of many, a simple microscope can reveal living bacteria, cell nuclei and Brownian movement. Using Brown's microscope, I can even resolve mitochondria, which are hundreds of times smaller than the cell nucleus. Leeuwenhoek and Brown were honest scribes.

The images presented here have not been enhanced. They show how exciting and beautiful these early views were. And they reveal how the simplest of instruments—in this case, straightforward single-lens microscopes from the 1600s and the 1800s—can alter our perspective forever.

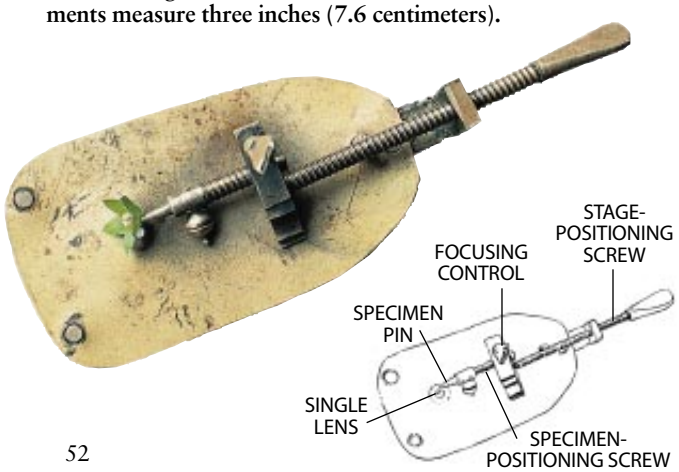


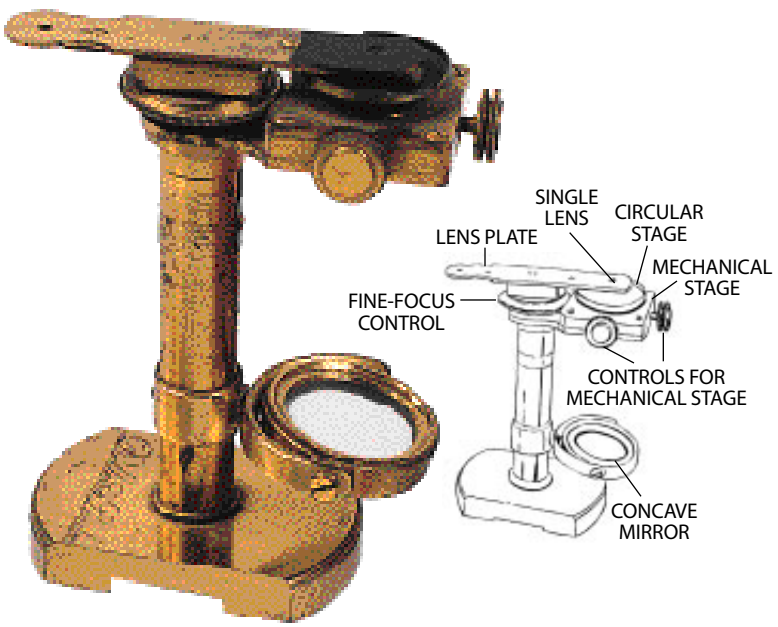
SPINY SPORES from a truffle (*Tuber melanosporum*) serve as a good test for the Leeuwenhoek microscope. The tiny spores are the size of a typical living cell, the spines the size of bacteria. Yet despite its simplicity, the 300-year-old microscope can capture both clearly.

HEAD OF A LOUSE is beautifully seen through a lens recently ground by the late Horace Dull of Luton, England, in an effort to determine the original power and clarity of a 17th-century microscope. The antenna and the dark brown eyes of this insect—which was annoyingly familiar to early biologists—are quite distinct. Single lenses, such as this one, keep chromatic aberration to a minimum.



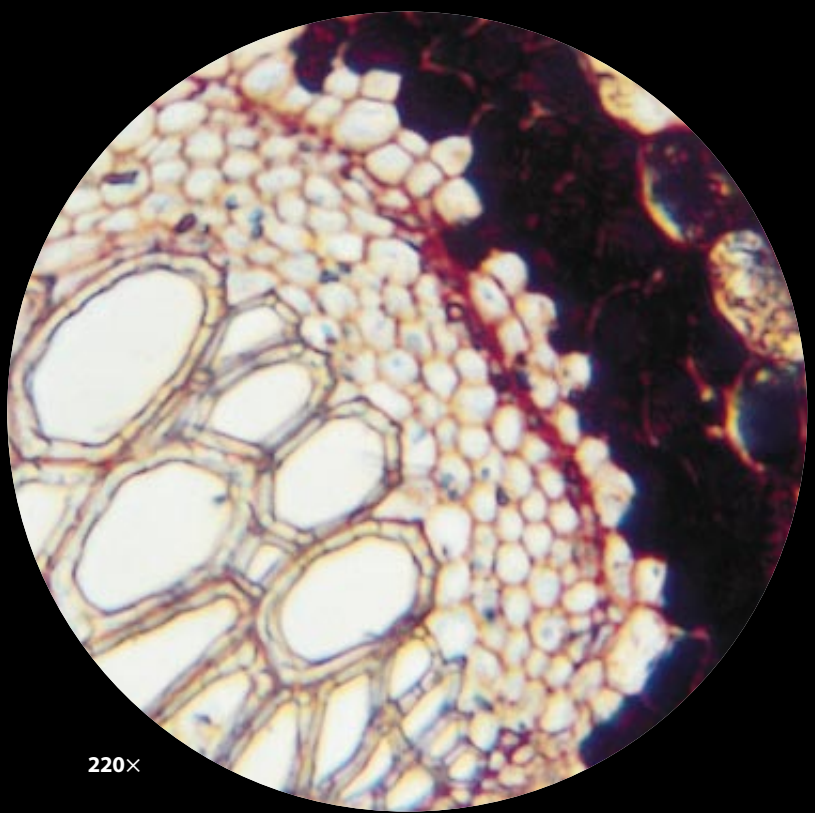
FIRST SIMPLE MICROSCOPES from the 1670s were of the Leeuwenhoek type (*below*). This instrument is handmade from brass. Twin screws were used to position the specimen and to bring it into focus. The single magnifying lens, little bigger than a pinhead, even reveals bacteria. The design reached its pinnacle 150 years later (*right*) in the hands of the London instrument firm of Dollond. Robert Brown possessed one of these beautiful instruments. There is a fine-focus control at the top of the body pillar stage; two screws operate a sophisticated mechanical stage. Accessories included an 800× lens. Both instruments measure three inches (7.6 centimeters).





CELL WALLS of the root of the royal fern (*Osmunda regalis*) can be observed through a single-lens microscope from the 1700s. This image, in fact, has a clarity comparable to those made with most modern optical microscopes.

LIVING BACTERIA could indeed be captured by Leeuwenhoek through his single-lens microscope. This view of *Spirillum,* one of the species described by the Dutch pioneer, proves that Leeuwenhoek was a skilled investigator; the bacteria are difficult to see unless the light and the focus are exactly right.

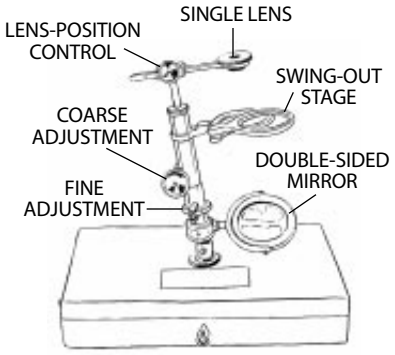


220×

1,200×

BROWN'S MICROSCOPY was mostly done with sturdy little microscopes made by the London firm of Bancks and Son. This well-designed example, which is about six inches (15 centimeters) tall, is part of the collection at Kew Gardens. It has coarse- and fine-focusing controls mounted on the pillar and a double-sided substage mirror. Single lenses could give magnifications ranging from 30 to more than 150.

ILLUSTRATIONS BY RICHARD JONES



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How Females Choose Their Mates

Females often prefer to mate with the most flamboyant males. Their choice may be based on a complex interaction between instinct and imitation

by Lee Alan Dugatkin and Jean-Guy J. Godin

Picture a man who has a way with the ladies, and a character not unlike James Bond may spring to mind. He's clever, classy, fearless and flashy—characteristics that are almost universally appealing to the opposite sex. Throw in the powerful sports car, and you have a nearly irresistible combination.

That females often flock to the most ostentatious males is not a phenomenon unique to humans. In many different species, successful males—those that sire the most offspring—are often larger or more brightly colored or "show off" with more vigorous courtship displays.

Females tend to be the choosier sex when it comes to selecting a mate, partly because males can produce millions of sperm, whereas females' eggs are few and far between. Thus, females may be more selective because they have more invested in each gamete and in the resulting offspring. And because the availability of eggs is a limiting factor in reproductive success, males tend to compete for female attention and not vice versa.

Charles Darwin was the first to propose that competition for mates plays an important role in reproductive success—a process he dubbed sexual selection. In *The Descent of Man, and Selection in Relation to Sex,* published in 1871, Darwin hypothesized that any trait that gives a male mating and fertilization advantages will evolve in a population because males with such traits will produce more offspring than their competitors. Assuming the trait is heritable, offspring expressing the beneficial trait will, in turn, achieve greater reproductive success than their competitors, and so on, through future generations. Further, Darwin proposed that some of these traits may have evolved because they attract the attention of females.

The idea that females are discriminating and can actively choose with whom to mate was controversial from its inception—perhaps because male-male battles can be quite spectacular. Males may fight amongst themselves, occasionally in dramatic battles to the death, to gain mating privileges with females. In comparison, female choice is generally much more subtle.

Finding Mr. Right

Over the past 25 years, a considerable body of scientific evidence in support of female choice has accumulated. Females actively choose their mates in a large variety of species—particularly ones in which males are less aggressive and display individual differences in secondary sexual characteristics, such as ornamental plumage or courtship displays. Nevertheless, how and why females select their partners and how mating preferences have evolved remain hotly debated issues among evolutionary biologists.

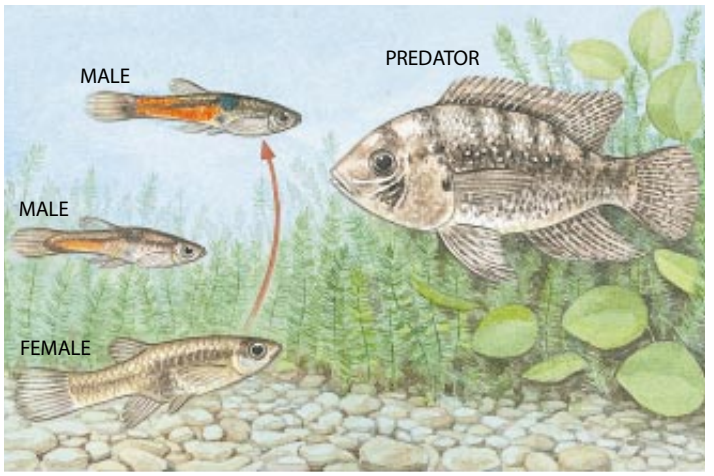
A choosy female faces two general tasks in selecting a mate. First, she must search for and locate a male. This task can be difficult if the population is sparse or if the danger of predators prevents her from spending a good deal of time searching for a suitable mate. Once she has encountered a male, the female must then decide whether to accept or reject him as a mate. The decision often involves some shopping around. In cer-

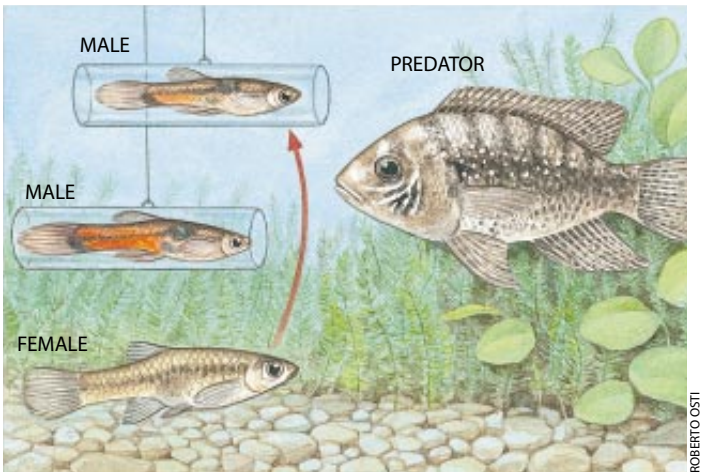
FEMALE TRINIDADIAN GUPPIES do the choosing when it comes to selecting a mate. Generally speaking, female guppies prefer males that are brighter or more orange in color (*upper right*). But even guppies are prone to social pressure. If, for example, an older female appears to fancy a drabber male, a young female may ignore her instincts and choose to copy her elder's mate selection (*lower left*).

tain mating systems, females may encounter a group of available males and can compare them on the spot. For example, in early spring, male sage grouse (*Centrocercus urophasianus*) aggregate "cheek-to-jowl" in temporary communal mating arenas called leks, where they strut their stuff for the females. A female typically observes the displays of a number of males, apparently comparing them before mating with one lucky suitor. She then leaves the lek to nest and raise her brood elsewhere. Of all the potential mates on a lek, a few preferred males receive the bulk of the female attention.

But males are not always conveniently displayed like chocolates in a sampler box. More commonly, females encounter males one at a time. Comparing males in this case is presumably a more challenging cognitive task, as it involves remembering the characteristics of an individual that is no longer in sight. Studies have shown that females can rank the characteristics of sequentially presented males. Theo C. M. Bakker and Manfred Milinski of the University of Bern in Switzerland found that female three-spined sticklebacks (*Gaster-*

ROBERTO OSTI





ROBERTO OSTI

MALE GUPPIES inspect predators; female guppies inspect the males. When a predator—such as the cichlid pictured here—approaches a school of guppies, a pair of males often swims over to inspect the potential threat. Such bold behavior may be attractive to females, which tend to choose as a mate the suitor that swims closest to the predator (*left*). Although the bravest males are often the most colorful, females will choose a less flashy contender if he appears to be more courageous than his inspection partner (*right*). In the laboratory, custom-made containers allow the authors to position the males.

osteus aculeatus) will tailor their mate choice to the relative attractiveness of the present and previously encountered males. Females were more likely to show interest in a male if his red nuptial coloring was brighter than the previous male's and more likely to reject a suitor whose coloring was less bright than his predecessor's.

Whether a female chooses her mate from among a dozen dancing grouse or between a pair of crimson fish, she generally selects the most conspicuous contender. Empirical evidence indicates that females commonly prefer male traits that most strongly stimulate their senses. (This evidence has recently been reviewed by Malte Andersson of the University of Göteborg in Sweden and by Michael J. Ryan of the University of Texas at Austin and Anne C. Keddy-Hector of Austin Community College.) For example, when given a choice, female green tree frogs (*Hyla cinerea*) are preferentially attracted to males that call the loudest and most frequently; female guppies (*Poecilia reticulata*) to the most brightly colored males; and female mallards (*Anas platyrhynchos*) to males that court them most frequently. Because of such preferences, males have typically evolved exaggerated secondary sexual traits to attract the opposite sex.

Why Be Choosy?

Even though evidence indicates that females can actively choose their mates, the question of why females discriminate, rather than mate at random, remains largely unresolved. How did female choice originate and evolve? What are its benefits and costs to individual females?

In some cases, females may favor mating with a male that is loud or brightly colored simply because he is easy to locate. Reducing the amount of time it takes to find a mate may reduce a female's risk of being killed by a predator. But for many species, mate choice is probably more complex. For many birds and mammals, natural selection appears to favor females who choose mates that provide them with some direct benefit that will increase their fecundity, their survival or the survival of their offspring. Such benefits might include food, a safe haven or even the prospect of fewer parasites.

In a long-term study of the barn swallow (*Hirundo rustica*), Anders P. Møller of the CNRS in Paris observed that females prefer to mate with males possessing elongated tail feathers. As it turns out, the long-tailed males are infected with fewer bloodsucking mites than their short-tailed counterparts. Because these parasites can jump from bird to bird, females that mate with long-tailed males benefit by avoiding infection and by producing greater numbers of healthier chicks than females that mate with shorter-tailed males. Unfortunately, because selecting a mate that offers direct benefits seems so obvious, few studies have tested this evolutionary model in a rigorous way.

When males provide no obvious resources, such as food or protection, females may choose to mate with the males that appear to have the best genes. How do they know which males have good genes? And why don't males just cheat by faking the traits associated with such genes? In 1975 Amotz Zahavi of the University of Tel Aviv in Israel suggested that females assess only those traits that are honest indicators of male fitness—a hypothesis known as the handicap principle. Honest indicators, which are "costly" to produce and maintain, should be associated with the most vigorous males.

While studying antipredator behavior in the Trinidadian guppy, we recently obtained some evidence that is consistent with the handicap principle. When a predatory fish nears a school of guppies, males, often in pairs, cautiously approach the potential threat to "inspect" it. Such risky behavior has been observed in many species, and behavioral ecologists have suggested that bold males may swim close to a predator to advertise their vigor to nearby females. In fact, laboratory studies have shown that when no females are present, no male guppy plays the hero by approaching the predator more often than his counterpart.

We hypothesized that boldness exhibited during predator inspection might be attractive to females because it should be a reliable indicator of fitness. Less vigorous guppies who tried to "fake" competence in predator inspection would likely be eaten. By using small, custom-built containers that allowed us to position males at different distances from a predator fish, we found that females indeed preferred the most intrepid males. Such courage appears to correlate with color: the males that swim

closest to the predator are usually the most colorful. Thus, in the wild, females may have evolved a preference for the flashier males because color is a proxy for boldness and fitness.

Once females have expressed a preference for a certain trait, a process called runaway selection can occur. The model, first brought to the attention of evolutionary biologists by Ronald Fisher in 1958, suggests that a male trait and the female preference for that trait coevolve. For example, females that prefer to mate with large males should produce large sons as well as daughters that show a preference for large males. Under certain conditions, this process can escalate, producing increasingly exaggerated male traits and stronger female preference for those traits.

A number of behavioral ecologists have found some evidence for runaway coevolution of orange body coloration in male guppies and of female preference for this male trait. But a more convincing example of runaway selection has recently been presented by Gerald S. Wilkinson and Paul Reillo of the University of Maryland in their study of the stalk-eyed fly (*Cyrtodiopsis dalmanni*). In this species, females generally prefer to mate with males possessing widely spaced eyes. By selectively breeding the flies for 13 generations, Wilkinson and Reillo generated one line of flies in which the males had large eyestalks and another line of shorter-stalked males. They found that females in each line preferred the male trait selected for in that line—that is, females from the large-stalk line preferred males with the longest stalks, and females from the short-stalk line preferred shorter-stalked males. Female preference thus coevolved with the selected male trait.

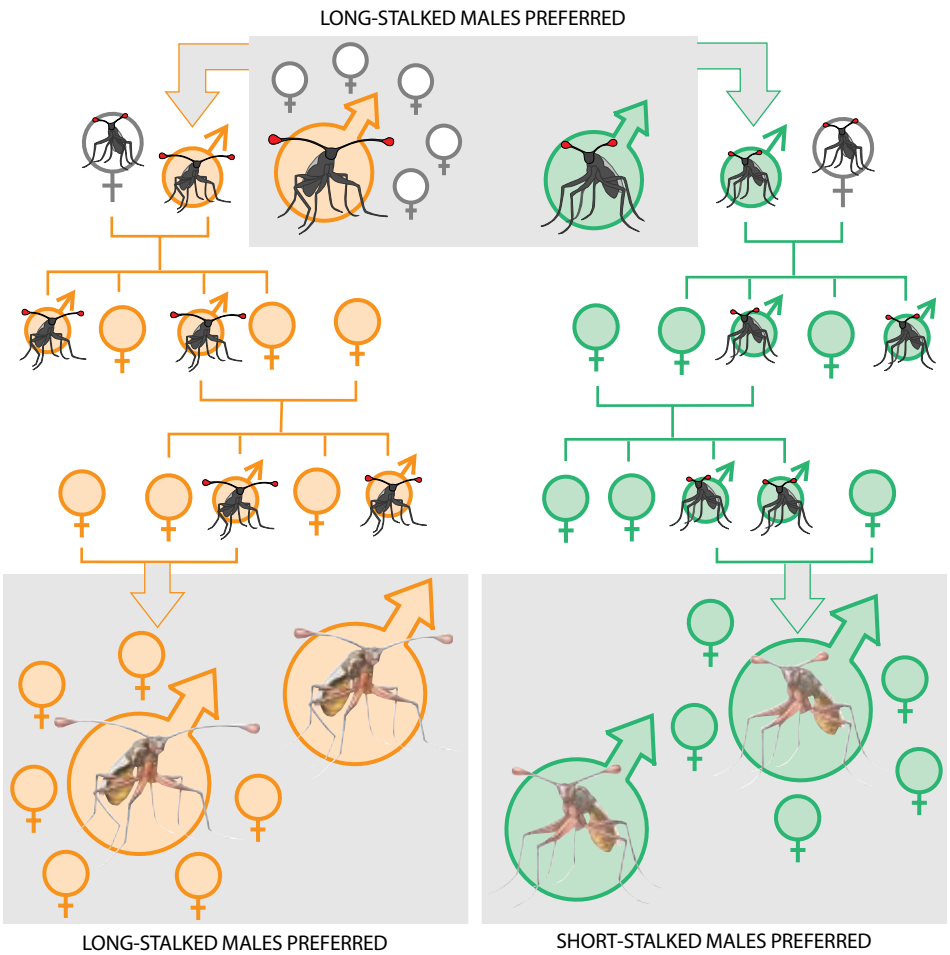
How do preferences about mate choice originate? In some cases, females may have a preexisting sensory bias for a certain trait, not because it represents anything but because it attracts attention—a hypothesis championed most prominently by Ryan and by John Endler of James Cook University in Australia. For example, female swordtails (*Xiphophorus helleri*) prefer males with long "swords" on their tail fins. And although males of a related species—the platyfish *Xiphophorus maculatus*—lack swords completely, Alexandra L. Basolo of the University of Nebraska found that when she attached artificial, plastic swords onto these naturally swordless males, female platyfish showed an immediate, strong and consistent preference for the males with the counterfeit swords. In other words, platyfish females harbored a preexisting bias for long swords, even though swords reveal nothing about the fitness of platyfish males.

These evolutionary models may be operating separately or in conjunction; it is difficult to untangle them experimentally. Female guppies, for instance, may be partial to orange males because bright coloring is a proxy for boldness or for good health (males with the brightest pigments are probably eating well). But the preference could have originated because females are more attuned to colors of a particular wavelength and then further evolved through a runaway mechanism.

All these models assume that female preference is genetically determined. Recent studies indicate, however, that social factors, such as imitation, also influence mate choice.

Copycat Birds and Fish

Some guys get all the girls. On a crowded grouse lek, for example, the top male may receive 80 percent of the mating opportunities. Is he simply irresistible? Or do females take one another's choices into account when selecting a mate? In the early 1990s a group of Scandinavian researchers, led



DRAWINGS BY ROBERTO OSTI; DIAGRAM BY JENNIFER C. CHRISTIANSEN

RUNAWAY SELECTION may shape mate preferences in stalk-eyed flies. Females of the species normally choose to mate with males that sport the longest stalks (*top center*). But when researchers used selective breeding techniques to generate two lines of flies—one in which males have long stalks (*left*), the other in which males' stalks are short (*right*)—they found that female preferences evolved along with male stalk length. Females from the long-stalk line were partial to males with longer stalks (*bottom left*), and females from the short-stalk line preferred shorter-stalked males (*bottom right*).

by Jacob Höglund and Arne Lundberg of Uppsala University and Rauno Alatalo of Jyväskylä University, initiated a detailed study of mate-choice copying in the black grouse (*Tetrao tetrix*). Using stuffed dummies to represent interested females, the researchers showed that female grouse mated preferentially with the male that appeared to have other females in his territory.

Why copy? Perhaps imitation teaches females what to look for in a male. In an extensive series of experiments on mate-choice copying in guppies, we determined that young females are more likely to copy the mate choice of older, more experienced females than vice versa. Further, copying may save time. Relying on the judgment of others may allow a female to assess a potential mate quickly and efficiently, leaving her more time to forage for food or hide from predators.

For species in which females copy, a fascinating question emerges: How much of female mate choice is based on instinct and how much on imitation? To tease apart the relative contributions of genetic and social factors involved in mate choice in guppies from the Paria River in Trinidad, one of us (Dugatkin) carried out a behavioral "titration" experiment. First, a female guppy was allowed to choose between two males that differed in the amount of orange that covered their bodies. As expected, females virtually always chose the more orange of a pair of males. Then a copying opportunity was staged, in which the test female was allowed to observe another female apparently choosing the less orange male as her putative mate.

Which male did she then choose for herself? Remember that the female's genetic predisposition is "pulling" her toward the more orange male, but social cues and the potential to copy are tugging her toward the drabber male. In the end, her choice depended on how much the males differed in coloration. When the paired males differed by small (12 percent) or moderate (25 percent) amounts of orange, the female consistently chose the less orange of the two. In this case, the female succumbed to peer pressure, her tendency to copy overriding her genetic preference for orange males. If, however, the males dif-

SEXUAL SELECTION comes in many styles. During mating season, male mule deer challenge their rivals to battle for the right to claim the available females. Male kangaroos also fight for their mates. But in species in which female choice is the main mode of sexual selection, males have evolved bold traits designed to attract the attention of females. Male peacocks show off by being spectacularly colored and meticulously groomed. Human males employ strategies that are somewhat less obvious.

ERWIN AND PEGGY BAUER *Bruce Coleman, Inc.*

DAVID C. FRITTS *Animals Animals*

M. AUSTERMAN *Animals Animals*

LARA JO REGAN *Gamma Liaison Network*

fered by a large amount (40 percent) of orange, the female ignored the seemingly bad advice and chose the more orange male, her genetic predisposition masking any copying effects.

It appears as if there exists in guppies a color threshold, below which social cues steer female mate choice and above which genetic factors predominate. Dugatkin is performing further experiments to assess whether copying behavior in guppies is itself heritable. Although imitation appears to be based on social cues, perhaps genes govern the likelihood that a female guppy will engage in copying behavior.

Sadie Hawkins Day

Although people are more complex than guppies and grouse, some of the same mate-choice rules may apply to human dating games. According to popular wisdom, it is human females who are the choosier sex when it comes to selecting a mate. As a species, humans meet the criteria for female choice: men, for the most part, will avoid fighting to the death for the hand of a young maiden. And females can distinguish between various males on the basis of differences in their characteristics: some men are brasher, some are brighter and some have bigger bank accounts.

Women may even engage in mate-choice copying. After all, imitation is important in many types of human learning. To determine whether copying plays a role in how women rate a man's attractiveness, Dugatkin is currently collaborating with social psychologists Michael Cunningham and Duane Lundy of the University of Louisville. Although their results are preliminary, they find that women are more likely to express an interest in going out with a man if they are told that other women also find him attractive.

Of course, evolutionary theory will never be able to explain fully singles bars, personal ads or cyber-romance. Even for animals, it appears that the benefits and costs of being choosy when selecting a mate differ for different species, in different environments and sometimes at different times of day. In any case, if animals as simple as guppies can consider the opinions of their peers when choosing a mate, imagine how complex the cues must be that guide humans in their search for the perfect mate. SA

What Females Want

MALE TRAIT	FEMALE PREFERENCE	SPECIES
Call (song)	Greater intensity Greater frequency Longer duration Greater complexity Larger repertoire	Meadow katydid American toad Green tree frog Tungara frog Song sparrow
Courtship display	Greater frequency	Sage grouse
Body size	Larger size	Convict-cichlid fish
Tail	Longer tail Greater tail height Greater number of "eyespots"	Barn swallow Crested newt Peacock
Comb	Larger comb	Red jungle fowl
Bower	More decorated bowers	Satin bowerbird
Breast stripe	Larger stripe size	Great titmouse
Body color	Greater brightness Greater area of orange	House finch Guppy

JENNIFER C. CHRISTIANSEN

The Authors

LEE ALAN DUGATKIN and JEAN-GUY J. GODIN first joined forces in Trinidad, where they became fascinated by the mating behavior of guppies. An evolutionary biologist, Dugatkin has been an assistant professor of biology at the University of Louisville since 1995. He received his Ph.D. in biology from the State University of New York at Binghamton in 1991. His research interests include the evolution of cooperation and altruism and the interaction of genetic and social factors in shaping behavior. Godin, a behavioral ecologist, is professor of biology at Mount Allison University in New Brunswick, Canada, where he has been on the faculty since 1981. He received his doctorate in zoology from the University of British Columbia and has been a visiting fellow at the University of Oxford. His research focuses on the behavioral ecology of antipredator, foraging and mating decisions in animals.

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Laser Scissors and Tweezers

Researchers are using lasers to grasp single cells and tinier components in vises of light while delicately altering the held structures. These lasers offer new ways to investigate and manipulate cells

by Michael W. Berns

The intense, pure beams of light known as lasers are now standard components of such commonplace objects as compact-disc players and printers. The everyday presence of lasers does not mean, however, that they have been reduced to performing only pedestrian tasks. Imagine focusing a beam specifically onto an organelle, a structure within a living cell. Consider further that the beam can actually grasp that minuscule entity and hold it in place. Now imagine that while this "microbeam" acts as tweezers, a second beam serves as scalpel or scissors to conduct delicate surgery on the organelle.

Even in a world accustomed to lasers, such musings have the ring of science fiction. Nevertheless, much as medical surgeons guide micromachined tweezers and scissors through endoscopes to perform minimally invasive surgery on organs, the cell biologist can now use "laser tweezers" and "laser scissors" to perform minimally invasive manipulations on living cells and their organelles.

Laser scissors came first. Almost three decades ago Donald E. Rounds and I, while at the Pasadena Foundation for Medical Research, suggested lasers might be wielded to probe the structure and function of cells and organelles [see "Cell Surgery by Laser," by Michael W. Berns and Donald E. Rounds; Scientific American, February 1970]. Our early work focused on defining the parameters of our lasers (such as wavelengths of light and durations of exposure) and on determining which organelles could be successfully manipulated with light beams that could alter intracellular regions as small as 0.25 micron in diameter. (The diameter of an average human hair is about 100 microns.)

During the intervening years, my colleagues and I found that laser scissors could be used to study organelles of the nucleus, such as chromosomes and the mitotic spindle that segregates chromosomes during cell division. Lasers also facilitated studies of cytoplasmic constituents—namely, mitochondria (the energy factories of cells) and such structures as microfilaments, microtubules and centrosomes—involved in maintaining cellular architecture and transporting molecules within cells.

Putting Lasers to Work

Although we do not always know exactly how lasers produce the specific changes they make in cellular components, we can nonetheless generate certain alterations reproducibly and without compromising the target's structure or environment. For example, the traditional biological tools of light and electron microscopy show that laser scissors can produce a particular change in a chromosome, deep within a cell. Early work by our group demonstrated that scissors can inactivate a selected part of a chromosome in dividing cells—specifically, a region containing genes that control construction of a nuclear organelle known as a nucleolus. What is more, the alteration persisted in the cloned progeny of those cells, all of which possessed inactive versions of the genes in that same region.

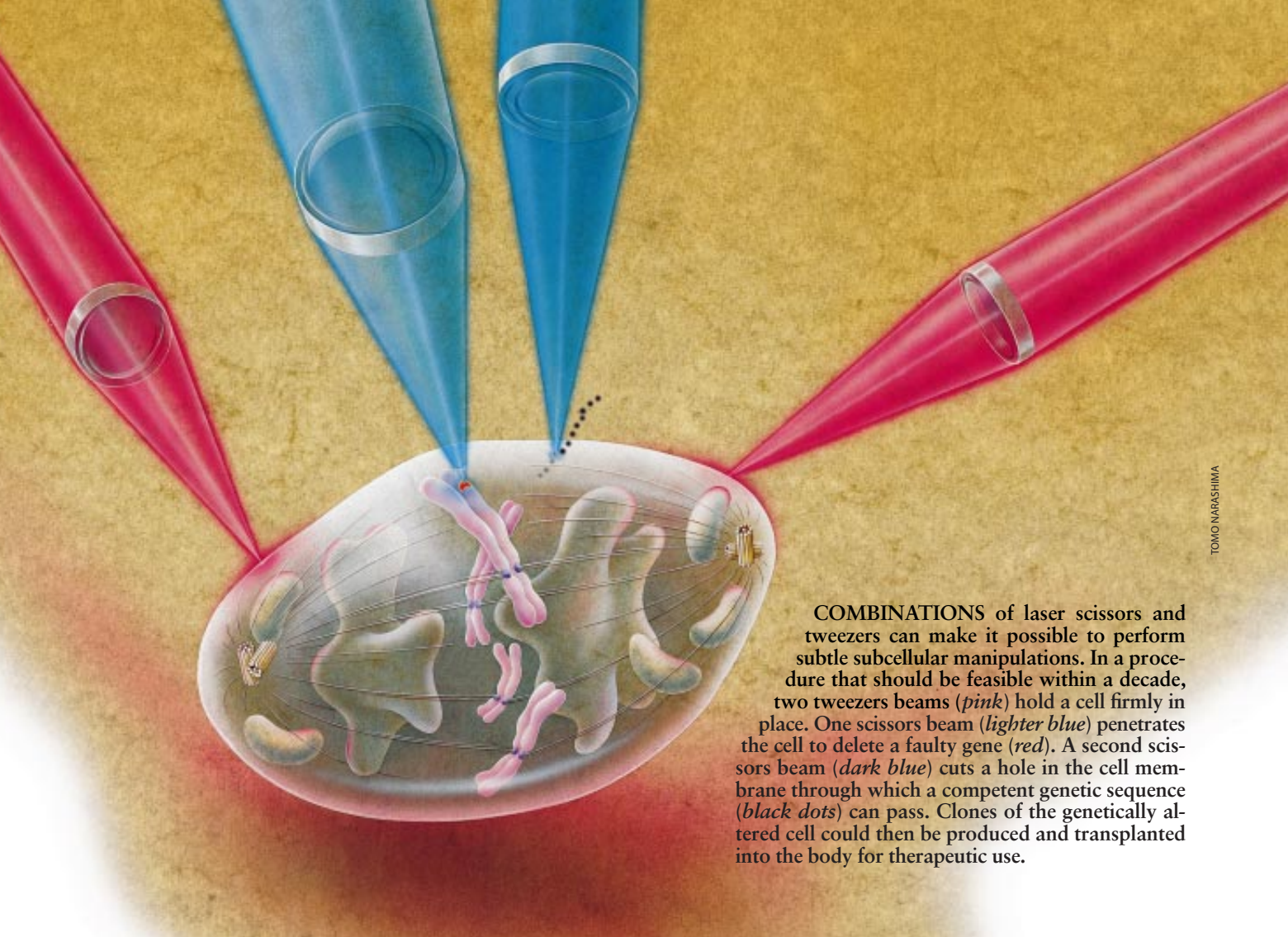
The alteration to the chromosome—a lesion less than a micron in size—appears as a lightened region when the live cell is viewed under a phase-contrast light microscope. Careful transmission electron microscopy, capable of 10,000 to 100,000 magnification, reveals that same region to be a cleanly defined structural alteration, with the chromosomal material on either side of the lesion, as well as the cytoplasm surrounding the chromosome, apparently unaffected. The "lightening" seen in light microscopy is actually the result of a change in refractive index rather than a complete physical removal of material—the laser is changing the chemical and physical properties of the chromosome without totally destroying it.

The cell membrane can likewise be studied, via a gentle perturbation of its fluidity. The membrane can even be incised, the laser cutting a micron-size hole that seals within a fraction of a second. Through this technique, called optoporation (pore production through optical means), molecules can be inserted into a cell when the pores are open without permanently damaging the membrane.

Optoporation may be especially suitable for genetic manipulation of plants, which have rigid cell walls that are relatively impenetrable compared with the supple membranes of animal cells. At the University of California at Irvine, my colleague Hong Liang and I have taken advantage of optoporation to insert genes into single rice cells; these genetically modified cells gave rise to whole plants in which every cell carried and expressed the introduced genes. This work, when considered with the inactivation of nucleolus genes, demonstrates that laser scissors can be employed either to insert or to delete genes.

In Europe, laser-scissors manipulation of gametes (sperm and egg) has been applied recently in the human clinic, as part of a procedure called assisted hatching. The scissors thin or remove a small area of the protective zona pellucida of eggs that have been fertilized in a laboratory dish. The very early embryos are then placed in the womb, where the thinning of the zona appears to abet implantation. Thinning can also be accomplished by more conventional techniques, but the laser method works without toxic chemicals that can damage the embryo.

The most extensive human study to



TOMO NARASHIMA

COMBINATIONS of laser scissors and tweezers can make it possible to perform subtle subcellular manipulations. In a procedure that should be feasible within a decade, two tweezers beams (*pink*) hold a cell firmly in place. One scissors beam (*lighter blue*) penetrates the cell to delete a faulty gene (*red*). A second scissors beam (*dark blue*) cuts a hole in the cell membrane through which a competent genetic sequence (*black dots*) can pass. Clones of the genetically altered cell could then be produced and transplanted into the body for therapeutic use.

date, performed by Severino Antinori's group at the Associated Research Institute for Human Reproduction in Rome, reported a greater than 50 percent increase in pregnancy rates in more than 200 women whose embryos had undergone laser zona thinning compared with women who had not undergone the procedure. The first multicenter trials of laser zona thinning have just gotten under way in the U.S. Similar studies are in progress in Australia and await government approval in Israel.

In collaboration with Nancy L. Allbritton's group at Irvine, my laboratory is using laser scissors in another way as well—to open a single cell so that its chemical components can be analyzed at any given moment. We take advantage of what can sometimes be an unwanted side effect of laser scissors: development of a minuscule cloud of ionized gas called a microplasma that forms when laser light is focused on or above the glass microscope slide on which the cell rests. The expansion and contraction of this microplasma generates mechanical stresses that, in turn, can rupture the cell. (Physicians exploit a similar effect on a macroscale to pulverize kidney stones and some cataracts via a laser-initiated shock wave; see "Laser Surgery," by Michael W. Berns; Scientific American, June 1991.)

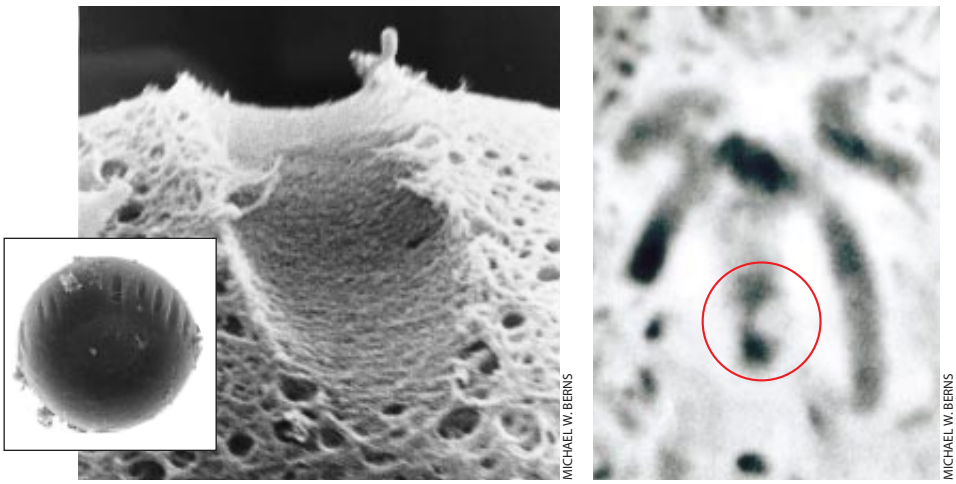
By positioning a tiny glass capillary tube just above the cell, we are able to collect its contents and analyze them, producing a snapshot of the cell's biochemistry at that moment. This technique has the potential for major applications in single-cell analytical chemistry. One goal is to determine the exact identities and concentrations of proteins important in cancer at the single-cell level.

Expanding Understanding of Scissors

In all applications of laser scissors, investigators need to achieve precision and selectivity. Precision refers to the targeting of the laser beam exactly to the correct point; selectivity pertains to the controlled alteration of the target while leaving the surroundings unaffected.

Achieving precision is relatively straightforward, thanks to the high level of optical elements in today's microscopes. Objectives, or lenses, are precisely machined and chromatically corrected throughout the visible spectrum so that all wavelengths focus at nearly the identical point in space; researchers using multiple laser beams of different wavelengths thus can confidently focus those beams to the same point.

With a state-of-the-art, oil-immersion microscope objective at 100 magnification, the physics governing the size of a laser focal spot result in that spot's being slightly smaller than the laser wavelength. A neodymium yttrium aluminum garnet (Nd:YAG) laser operating at a wavelength of 532 nanometers can produce a focused spot of 499 nanometers, or 0.499 micron. Precision, however, can be better even than it first appears. Our laser of choice produces a Gaussian distribution of energy—that



FEATS ACCOMPLISHED by laser scissors include etching of grooves (*left*) in the zona pellucida around a fertilized mouse egg (*inset*) to facilitate implantation. They also include removing a V-shaped wedge from a chromosome (*right*) in a living cell from a kangaroo rat. At its widest, the wedge is about one micron across.

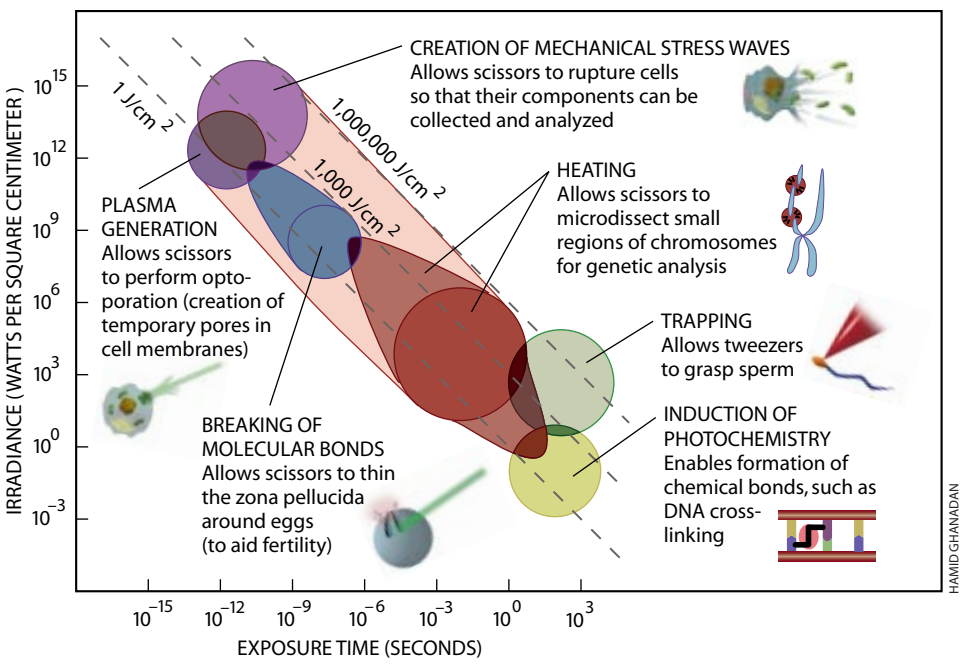
is, the energy forming the focal spot can be characterized by a bell-shaped curve. Because only the peak of the curve may have sufficient energy to alter a particular target organelle, the effective spot can be significantly smaller than the diameter of the measured focal spot.

Selectivity—controlled alteration—can also be achieved as is evident from applications that have been developed so far. Nevertheless, investigators do not yet know how to guarantee selectivity in many new applications (other than by empirically noting what works) because of incomplete understanding of the interactions between laser light and biological targets. Such a circumstance is not unusual in science: people took aspirin for a century before researchers unraveled how it worked at the molecular level. Still, knowing exactly how a drug or a technology operates cannot help but lead to better applications. Therefore, as might be expected, scientists are working intensively to clarify the complex interactions between laser and living cell.

Several factors make defining exact laser effects difficult. Measuring and recording events in submicron regions of a single living cell represents a formidable challenge, as does controlling the energy of the laser beam within such small volumes. Despite these obstacles, we can honestly say we are not completely in the dark. From macroscopic studies, we understand that various physical and chemical processes can potentially come into play when lasers interact with organic tissue. These processes can be triggered by the absorption of single photons or by the nearly simultaneous absorption of multiple photons.

Single photon absorption may simply heat the target; it can also initiate chemical reactions that produce free radicals or other cell-damaging products. And photons of high energy (such as in the ultraviolet) may even break molecular bonds, thus tearing molecules apart, in a process called photoablation. Furthermore, multiple photons can be absorbed so closely in time as to be equivalent to a single, high-energy photon. Such multiphoton absorption can drive chemical reactions or lead to the kind of molecular dissociation seen when single ultraviolet photons are absorbed. Any of these scenarios, or any combination, may operate in a submicron cell target.

In addition to the absorption properties of the target, another key factor that determines the laser's effect is the irradiance of the impinging light (the energy reaching a target's surface in a given time period, measured in watts per square centimeter). With pulsed lasers that expose the target to light in periods ranging from microseconds down to femtoseconds (10^{-15} second), the irradiance can be enormous. Laser effects following absorption in tissue exposed for relatively long periods (hundredths of seconds to minutes) are well known and include heating—which can cause molecular denaturation, coagulation or vaporization—as well as chemical reactions that can create deleterious photoproducts, such as free radicals. We are less



ENERGY DELIVERED to cells (energy dose), which is measured in joules per square centimeter (J/cm^2), depends on the irradiance of the lasers themselves and on how long a cell is exposed to the light. (Diagonal dotted lines represent constant energy doses.) Some of the effects that can be achieved in cells at different combinations of irradiance and time are highlighted. At least some heating (*red*) is common over a wide range of energies. Dark red is where heat is the dominant mechanism.

certain, though, of the effects of the high irradiances in the volumes in which we work intracellularly—a sphere one micron in diameter has a volume of less than a femtoliter.

A major challenge, therefore, is to determine the boundaries at which increases in irradiance will change the effect on the target—for example, discovering the level at which the laser's effect switches from heating of the target to the generation of microplasma-induced shock waves. Irradiance effects and boundaries are still incompletely defined but are certainly affected by the duration of the laser pulse and by the absorbance properties of both the target and its physical environment.

Laser-irradiance boundary studies represent a dynamic area of research, with our group especially concentrating on the submicron realm. The next few years should see great progress in the characterization of laser-target interactions, which will create the opportunity for ever more delicate applications of lasers in subcellular domains.

Despite the unknowns, extremely accurate laser ablation, in which we destroy or inactivate specific regions of targets, can be performed in virtually any cell component that can be visualized through the light microscope. As eagle-eyed baseball great Ted Williams might have put it, "If I can see it, I can hit it."

In the near future we should be able to surpass even that visual limitation. For example, we might employ light-absorbing molecules (LAMs) capable of finding and binding to a sequence of DNA in a gene we wish to manipulate. This sequence could be too small to see, or its location within a chromosome might be unknown. Bathing the entire cell in light of the correct wavelength would energize the LAMs, which in turn would inactivate the bound gene. (The process could also potentially activate that gene or other genes, by transferring energy to initiate a cascade of chemical reactions or by simply inactivating a suppressor gene.) The rest of the cell merely would be bathed in light briefly and be none the worse after the exposure.

Laser scissors, with their short, intense pulses of light, led the way in our attempts to perform microscopic surgery on cells and molecules. More recently, they have been joined by the equivalent of the forceps—laser tweezers.

To the nonphysicist, the use of light to trap and move an object is counterintuitive. That light can heat or burn, measure or calibrate makes sense. But the idea of light creating a force that can hold and move an object may seem as fanciful as a *Star Trek* tractor beam. Still, light has momentum that can be imparted to a target. The resultant Lilliputian forces fall far below our sensory awareness when, for example, the sun's light shines on, and imperceptibly pushes against, us. But these forces can be large enough to influence biological processes at the subcellular level, where the masses of objects are infinitesimal.

What Tweezers Can Do

In the mid-1980s Arthur Ashkin of AT&T Bell Laboratories discovered that a continuous-wave, low-power (under one watt) laser beam could "optically trap" individual bacteria and protozoa. He and his co-workers demonstrated—first with a blue-green argon ion laser and then with the infrared Nd:YAG laser (to which cells are more transparent)—that whole cells and their organelles could be grasped and moved about.

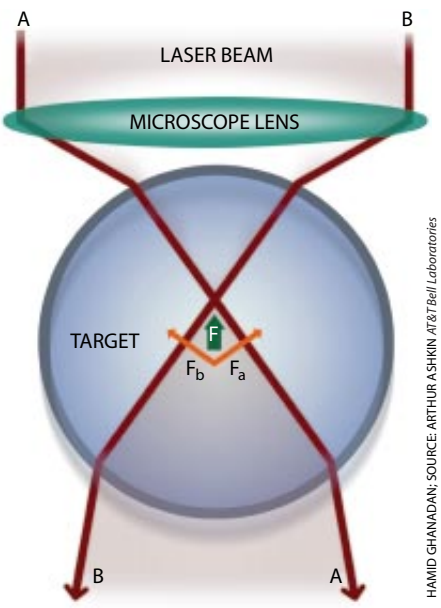
Steven Chu, a 1997 Nobelist in physics, and his colleagues at Stanford University later showed that laser tweezers could also grip molecules. They conjugated transparent polystyrene beads to the ends of coiled, naked DNA and used optical trapping forces to pull the beads and stretch the DNA molecule to its full length [see "Laser Trapping of Neutral Particles," by Steven Chu; Scientific American, February 1992]. Steven M. Block of Princeton University and Michael P. Sheetz of Duke University have employed optical trapping of molecules to study kinesin motors, the proteinaceous cellular structures that drive the whiplike action of a flagellum or a sperm tail and move intracellular particles and organelles.

A small enough object that is relatively transparent to laser light of a particular frequency refracts incident laser beams, bending the light. As a result of this refraction, momentum is transferred from the light to the target. When the geometry of the arrangement of light beams and target is correct, the momentum imparted to the target pulls the target in the direction of the incident laser beam, and the beam can thus hold the target in place [*see illustration below*]. By moving the beam, the laser operator can pull the target from place to place.

The beams of scissors and tweezers differ significantly in duration and intensity. Whereas the scissors employ short pulses of high irradiance, tweezers make use of continuous, low-irradiance beams. The target must be transparent to tweezers so that the beam will pass through the object without significant energy being absorbed and converted to destructive heat or even generating damaging photochemistry.

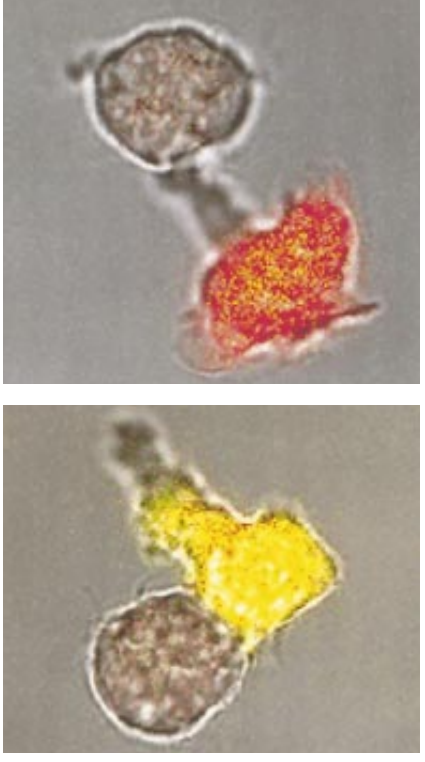
A single beam can grasp a cell or organelle, but that object may still be able to wag; a second beam can lock the target in place, in a vise of light. Laser-tweezers beams typically use light at wavelengths between 0.7 and 1.06 microns and of 25 to 500 milliwatts of power in a focal spot between 0.5 and 1.0 microns in diameter. Such a beam generates forces in the piconewton range, more than sufficient for trapping cells and moving organelles inside and outside of cells.

Laser tweezers make new kinds of experiments possible. My Irvine colleagues Michael Cahalan, Bruce J. Tromberg,



HAMID GHANADAN; SOURCE: ARTHUR ASHKIN *AT&T Bell Laboratories*

LASER AS TRACTOR BEAM can hold an object in its grasp because of basic physical principles, such as the conservation of momentum. The refraction of any pair of symmetric laser light rays within the beam produces forces. A typical set (rays A and B) produces forces F_a and F_b. These result from the response by the target to the change in momentum of the light rays. If the focal point lies before the center of the target, the sum of any pair of such forces is a total force (vertical arrow F) pulling the target toward the beam. A focal point after the center of the target would push the target. Focal points to the left or right of the center would move the target left or right.



XUNBIN WEI *Beckman Laser Institute*

POLARITY OF *T* CELLS is borne out in studies made possible by laser tweezers. *B* cells, which provoke calcium release by *T* cells, were carefully positioned alongside *T* cells using tweezers. Positioning of the *B* cell at one end of a quiescent *T* cell elicited no change; a fluorescent red stain in the *T* cell remained red (*top*). But when the *B* cell touched the other end of the *T* cell, calcium was released, signaled by yellow fluorescence (*bottom*).

Xunbin Wei, Tatiana Krasieva and Paul Negulescu recently employed them to analyze the relation of form to the function of the immune system's *T* cells. Presentation of foreign molecules, or antigens, by the immune system's *B* cells starts a cascade of reactions that includes an increase in calcium ion concentration in the *T* cells. This rise in turn leads to the *T* cell specialization and proliferation so vital in immunity.

T cells have a polarized appearance, defined by shape and the direction in which they crawl. Titanium sapphire laser tweezers trapped *B* cells and placed them at different locations along the *T* cell surface. With the *B* cell placed at the back end of the *T* cell, no response occurred, and the *B* cell detached from the *T* cell within two minutes. But placement of the *B* cell at the leading edge of the same *T* cell quickly elicited a rise in intracellular calcium ion concentration, meaning that the response cascade was in progress [*see illustration above*]. This finding fits nicely with the notion that *T* cells and other white blood cells migrate in specific directions, in part by responding to signals received by receptors on their front ends.

Laser tweezers can trap even highly motile cells. As my Irvine co-workers Yona Tadir, Gregory J. Sonek and William H. Wright (now at SRI International in Menlo Park, Calif.) first demonstrated, tweezers can grasp individual human sperm cells and manipulate them at will. We took advantage of being able to study the swimming forces of sperm, gradually reducing the trapping power to determine the level at which the sperm could escape. Investigation of this "relative escape force" has provided a method to examine the relation between swimming force, velocity and swimming pattern. One exciting discovery—sperm that swim in a zigzag pattern swim with greater force than straight swimmers—may explain clinical observations suggesting that men with a higher proportion of tacking sperm are more fertile than their counterparts who produce straight swimmers.

Another finding from laser-tweezers studies shows that sperm surgically removed directly from the epididymus (where they mature and are stored prior to ejaculation) of men incapable of ejaculation swim with only one third the force of normally functioning sperm. (Full swimming force appears to require the complete maturation that occurs during passage through the epididymus.) This result helps to explain why fertilization is optimized when these patients' sperm are physically injected into eggs, as opposed to simply having them attempt to fertilize eggs in a petri dish, where success may be a consequence of swimming force. Evaluation of relative escape force should therefore be a valuable screening tool to determine if low fertility is caused by poor motility and could also test treatments aimed at improvement of motility. Thus, laser tweezers should find a role both in clinical management of infertility and in sperm motility research.

Application of tweezers in those roles must be achieved delicately, because exposure to tweezers may hamper motility, probably because of unavoidable thermal or photochemical effects. Heat is actually more of an issue with tweezers than with scissors because of the continuous beam.

Measurements of tweezers-generated heat have been conducted by Tromberg, Sonek and Yagang Liu (now at Beckman Instruments in Fullerton, Calif.), who were able to record temperature rises in irradiated regions of cells. They bound a heat-sensitive molecule, Laurdan, to either artificial cell membranes (liposomes) or Chinese hamster ovary cells in culture and measured changes in fluorescence intensity and in emission wavelengths.

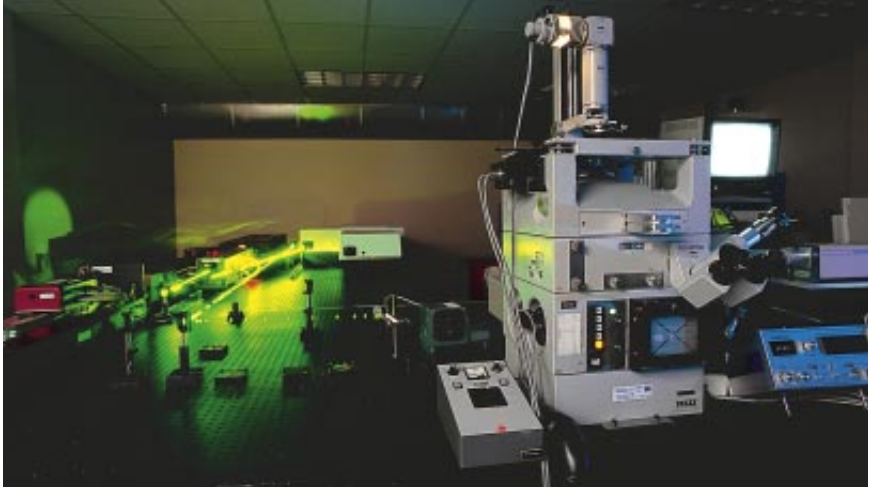
This cellular "microthermometer" detected a rise of 1.15 to 1.45 degrees Celsius per 100 milliwatts of laser power in the focal spot. Tweezers may produce 10 times that power; if heat dissipation is inefficient, deleterious changes in the rates of biochemical reactions, inactivation of heat-sensitive proteins (including enzymes) and even cell death become serious concerns. These Laurdan-dependent measurements represent an important contribution to the growing database of laser-target interactions.

Putting It All Together

Laser scissors and tweezers are each powerful tools in their own right, but techniques making use of both, either sequentially or in combination, allow for even more sophisticated and creative manipulation and alteration of cells. The first application of both laser scissors and tweezers was conducted by my former postdoctoral fellow Romy Wiegand-Steubing. She used an infrared Nd:YAG laser tweezers to move together two human myeloma cells and a pulsed ultraviolet nitrogen laser scissors to cut the adjoining cell membranes; the two cells merged into a single hybrid cell containing the genomes of both. Fused cells can combine valuable attributes within one entity, such as one cell's ability to produce a useful product with another's ability to divide indefinitely.

Furthering the sperm-trapping work, a European group led by Karin Schütze of the Harlaching Center for Laser Applications in Munich has used infrared tweezers to grasp and guide individual bovine sperm into eggs by way of a hole in the zona that was produced with scissors. This technique resulted in fertilization in a small percentage of cases, as did a comparable effort with mouse sperm and eggs.

A similar approach, if shown to be safe and effective, could provide an alternative to existing gamete-manipulation procedures in humans and almost certainly will find a role in animal husbandry. Although caution—as well as strict adherence to federal governmental policies—must clearly guide new and experimental procedures, researchers in



MICHAEL W. BERNS

MICROBEAM SYSTEM for laser scissors incorporates a pulsed laser and a phase contrast microscope. The pulses, lasting 10 nanoseconds, are visible as the discrete light bursts along the line of the laser path. The system shown is the immediate predecessor to the confocal ablation trapping system, which has enclosed beams that are not visible.

assisted reproduction have shown considerable interest in laser scissors and tweezers; two companies have already begun to market multipurpose laser workstations for eventual use in fertility clinics. Micromanipulations of sperm and eggs using laser systems should be faster and more efficient than traditional techniques.

The combination of laser scissors and tweezers makes possible unprecedented manipulations of organelles as well as whole cells. In collaboration with Edward D. Salmon of the University of North Carolina at Chapel Hill and Conly L. Rieder of the Wadsworth Center for Laboratories and Research in Albany, N.Y., we initiated studies at the organelle level that used laser scissors to cut chromosomes, which were in the midst of mitosis (cell division). Then, with laser tweezers, we moved the fragments within the cell, our goal being the study of forces exerted by the mitotic spindle, the cellular machinery that pulls replicated chromosomes to opposite ends of a cell as it divides.

Unexpectedly, we were able to freely move fragments that were outside the spindle but were unable to move fragments from the cytoplasm into the spindle. These studies confirmed the existence of a spindle "cage" that blocks foreign material, such as the newly produced chromosomal fragments, from entering the spindle. Because mitosis carries a cell's genetic material to the next generation, it makes sense that evolution developed a system that apparently blocks undesirable material from the spindle area.

These tools are being more fully exploited by Rieder and his colleagues, who have since been able to demonstrate that laser tweezers can inhibit the movement of laser-scissored chromosome fragments already within the spindle. These techniques finally make possible noninvasive studies of forces within the mitotic spindles of single cells. Because the spindle is a key player in cell division, unraveling its workings can lead to more detailed understanding of diseases related to cell division, such as cancer and birth defects.

As part of the National Institutes of Health Laser Microbeam and Medical Program Biotechnology Resource, we have now built a microscope workstation that incorporates two laser-tweezers beams and one laser-scissors beam into a confocal laser fluorescence microscope. The lasers are tunable—that is, they can be set to any desired wavelength. Having all these capabilities in a single, all-purpose workstation meets multiple needs of the cell biologist. A researcher can observe fluorescing cells or organelles through the confocal microscope during and after the period when tweezers and scissors are in operation. This joystick-controlled confocal ablation trapping system (CATS) is available for a wide range of cellular and subcellular studies, including ones that improve procedures necessary for DNA sequencing—deciphering of the order of base pairs, or codes, carried by a stretch of DNA.

My Irvine colleagues Barbara Hamkalo and Al Jasinskas are using this technology to cut out the chromosome's centromere, where the spindle microtubules attach. Investigators disagree over whether this region is likely to be genetically active, but the centromere has been extremely difficult to isolate and analyze for unique active gene sequences. Laser scissors and tweezers should help settle this controversy.

More than 80 years have passed since Albert Einstein laid the theoretical foundation for the existence of lasers. By the early 1960s, thanks to the work of American and Russian physicists, laser light became a reality. Now optical tools incorporating lasers enable biologists to become cell surgeons, probing and manipulating cells and organelles. The application of these technologies has far-reaching implications for medicine, developmental biology, the study of cell structure and function, and the unraveling and manipulation of the human genome. The future of laser-based biological research and applications should be very bright indeed. SA

The Author

MICHAEL W. BERNS is the Arnold and Mabel Beckman Professor at the University of California, Irvine. He is also president and co-founder (with his mentor, industrialist Arnold O. Beckman) of the university's Beckman Laser Institute and Medical Clinic. His research interests include genetics, cell motility, laser-tissue interactions and clinical applications of lasers in cancer, ophthalmology and reproductive medicine. He dedicates this article to Beckman, who is 98 years old this month.

Further Reading

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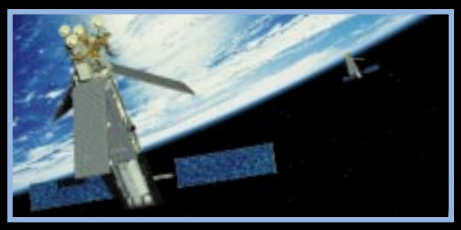
Wireless Technologies

SPECIAL REPORT

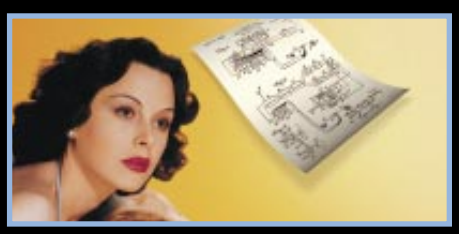


New Satellites for Personal Communications
John V. Evans

Telecommunications for the 21st Century
Joseph N. Pelton

Terrestrial Wireless Networks
Alex Hills

Moving beyond Wireless Voice Systems
Warren L. Stutzman and Carl B. Dietrich, Jr.



Spread-Spectrum Radio
David R. Hughes and Dewayne Hendricks

Today's wireless systems would be unrecognizable to Guglielmo Marconi, who invented the wireless telegraph in 1896. Four decades ago the solid-state revolution started to bring ever smaller and higher-performance radios and televisions into millions of homes. Now we can slip either one into a jacket pocket and still have room for a cell phone. Satellites continually beam television and voice signals around the earth.

Yet even more radical developments are in store. This special report details how a new generation of satellites and high-altitude platforms will form a global cellular network providing first voice and then high-speed data links to portable terminals anywhere. Together with handheld wireless computers and ground-based networks, these technologies will put civilization's collection of digital knowledge at our fingertips whenever we want. They will make us more secure and keep us close to those we need to be in touch with. Marconi's legacy is a liberating gift. *—The Editors*

New Satellites for Personal Communications

SLIM FILMS

Fleets of satellites will soon make it possible to reach someone anywhere on the earth, using nothing more than a small handset

by John V. Evans

Since the first commercial model was launched into orbit in 1965, the communications satellite has become a linchpin of global communications. From modest beginnings—that first satellite could handle only 240 voice circuits at a time—the technology has blossomed to the extent that satellites now carry about one third of the voice traffic between countries and essentially all the television signals between countries.

Much of the voice traffic handled by satellites, however, is to countries that have no access to fiber-optic cables, which are the preferred medium for carrying telephone calls. Because large communications satellites are typically put into geosynchronous orbits, where they are roughly 36,000 kilometers (22,300 miles) above the same spot on the earth at all times, it takes a quarter of a second for signals to travel to and from the satellite, delaying the responses received during a conversation. Although not all users find this delay irritating, communications satellites are increasingly being used to carry television signals and data rather than voice traffic.

All of that could be about to change. Possibly as soon as the end of this year, the first of a completely new type of satellite communications system will begin operation. Basically, these new networks will provide cellular telephone service via satellite. Among other unique characteristics, these new personal communications satellite systems will be based on a relatively large number of satellites in orbits considerably lower than geosynchronous ones; they will therefore introduce less delay into telephone conversations. A second type of system will be designed primarily for handling data, such as connections to the Internet. Over the next six or seven years, three to five of the voice-type systems and possibly upward of a dozen of the data-oriented satellite systems (which will be based on fleets of satellites) could go into operation.

How fast and big this market may grow is difficult if not impossible to say. Nevertheless, several groups have already invested billions in projects that are well along. The technical challenges and risks are significant; some of the enterprises, for example, would be unthinkable if not for the availability of a new generation of powerful communications satellites capable not only of amplifying and retransmitting signals but also of switching and routing them. In addition, some of the proposed systems will operate at very high frequencies in radio bands not previously used for satellite communications.

Telephony 101

The new satellite systems combine some of the attributes of cellular telephone systems with those of traditional satellite communications networks. Conventional cellular telephony uses a band of radio waves with frequencies between 800 and 900 million cycles per second (megahertz). (The newer personal communications services, or PCS, operate at about twice this frequency, but both systems function in the same manner.) The area to be served is divided into "cells," each with a base station and radio tower. To keep the transmit and receive signals separate, cell phones transmit to the nearest base station on one frequency and receive from it on a different frequency.

At the base station the radio-wave signals are usually converted into microwaves, a higher-frequency form of radio waves, and retransmitted to a cellular telephone switch, where they are converted back to speech signals. This conversion can also occur at the base station, and the speech can be carried on regular telephone lines to the cellular switch.

The switch both sets up calls and hands them off when a subscriber passes from one cell to another in the course of making a call. Each cellular switch is also connected to a central office switch of the public telephone network, enabling cellular subscribers to communicate with users of ordinary telephones.

The number of subscribers to cellular service has grown so large in the U.S. and elsewhere that systems are being

COMMUNICATIONS SATELLITES shown here are typical of a new generation of craft capable of switching and routing calls. Visible in this scene are two of the Iridium system's 66 satellites, which are in low earth orbits and are actually somewhat more distantly spaced than in this artist's conception. The rectangular panels at the bottom are solar collectors; the other three, cantilevered off the three sides of the 4.6-meter-long spacecraft, are the main antenna panels.

upgraded with digital technology. In traditional networks the speaker's voice is impressed onto the transmitted radio wave by varying the wave's frequency, a technique known as frequency modulation. The problem with this method is that the transmitted signal entirely occupies a piece of radio-frequency bandwidth, or channel, that is 30 kilohertz wide. To provide more capacity, engineers are seeking to make more efficient use of the channels. Therefore, many systems are now being modified to operate with phones in which the speaker's voice is converted to a stream of digital bits before being transmitted. The data can then be "compressed" prior to transmission, reducing the amount of time each transmission occupies the channel, at the price of a slight loss of signal quality.

Digital transmission of voice signals is also employed in the conventional (or "public switched") telephone network but at much higher rates—64 kilobits per second, as opposed to the eight kilobits per second typical of digital cellular systems. Digital sampling at such a high rate ensures good quality but requires even more bandwidth than transmitting the analog signal itself. So why bother to do it? Because it affords an easy method of merging many telephone calls onto a single fiber-optic cable or microwave link, as the individual data streams can be multiplexed together into one, higher-rate stream, which in turn can be merged with others into still higher-rate streams. Also, with digital signals it is easier to remedy any impairments encountered in the network, because each bit can be restored if, for example, its amplitude were corrupted in some fashion.

The local central office switches are connected together (usually via fiber-optic cables) to even larger "toll" switches that handle the long-distance calls. Calls going overseas are routed to special international switches, from which they are then carried over undersea fiber-optic cables or via satellite.

Not all the world's countries are connected via undersea fiber-optic cables, but most are linked via the satellites of the International Telecommunications Satellite Organization (Intelsat) system. Calls that must be sent via satellite are routed from the international switch to Intelsat's nearest earth station. (Intelsat is one of several organizations operating satellites in the radio-wave bands assigned for so-called fixed-satellite service.) The digital bit stream representing these calls is modulated onto a radio wave that is amplified and transmitted toward the satellite by a dish-type antenna with a diameter as large as 15 meters.

At the satellite the radio-wave signal is much weaker, because the energy in it spreads out in space, causing the strength to fall off at a rate proportional to the square of the distance it has traveled. If the communications satellite is in geosynchronous orbit, it needs another fairly sizable antenna (perhaps two to three meters across) to collect the signal, which is then amplified and retransmitted toward the receiving station on the earth. At the receiving station all these processes are reversed to re-create the individual voice signals.

Intelsat's satellites are each capable of carrying several tens of thousands of voice circuits. The satellites, which are solar-powered, also store fuel (typically hydrazine) to fire the thrusters that keep the satellites' antennas facing the earth and also counter the gravitational pulls of both the sun and moon.

Satellites as Base Stations

The new personal communications satellite systems are striving to incorporate the advantages of both satellite and cellular systems into a single global network. In these new systems the satellites will be, in effect, orbiting cellular base stations, with which the handheld or mobile phones will communicate directly. Moreover, like conventional satellite systems, the new networks will be capable of serving large areas—including ones where no service is currently available.

Advantages such as these will be achievable only with

Voice-Oriented Personal Communications Satellite Systems

	IRIDIUM	GLOBALSTAR	ICO	ELLIPSO	ECCO
COMPANY	Motorola	Loral/Qualcomm	ICO Global Communications	Mobile Communications Holdings	Constellation Communications
NUMBER OF ACTIVE SATELLITES	66	48	10	14	46
ORBIT PLANES	6 circular polar (86.5°)	8 circular inclined (52°)	2 circular inclined (45°)	2 elliptical inclined (116.6°); 1 elliptical equatorial (0°)	7 circular inclined (62°); 1 circular equatorial (0°)
ORBIT ALTITUDE (KILOMETERS)	780 (LEO)	1,414 (LEO)	10,355 (MEO)	520–7,846 (MEO); 4,223–7,846 (MEO)	2,000 (LEO)
SATELLITES PER ORBIT PLANE	11	6	5	4 per elliptical; 6 per equatorial	5 per inclined; 11 per equatorial
BEAMS PER SATELLITE	48	16	163	61	32 per inclined; 24 per equatorial
REPORTED COST (BILLIONS OF DOLLARS)	3.4	2.6	4.6	0.91	2.8

BRYAN CHRISTIE

some rather sophisticated technologies, however. One of the fundamental challenges results from the fact that a handheld phone can be equipped only with a very small antenna. It is impossible to design such an antenna so that it beams signals in a highly directional manner. Moreover, because the phones are held against the head when they are in use, the transmitted power must be kept below about one watt to allay concerns about the possible effects of radio-frequency radiation on biological tissue, such as the brain. (Low-power operation is also necessary to avoid draining the batteries too quickly.)

What these factors mean is that the signal transmitted from the phone is rather weak, and to "hear" it in geostationary orbit would require an antenna with a diameter of about 10 to 12 meters. Deploying such a huge antenna in space would be difficult, to say the least. To get around the need for such large dishes, the new personal communications satellite systems will put satellites in orbits that are much closer to the earth. Because the required signal power falls with the square of the distance, bringing the orbit down from 36,000 kilometers to 10,000 kilometers causes a 13-fold increase in the strength of the signal received from the handheld phone. Such an increase permits the antenna on the lower-orbit satellite to be about the same size—two to three meters—as those now used on geostationary satellites.

Of course, there is a trade-off. In geostationary orbit, each satellite "sees" about a quarter of the earth, so only three or four satellites are needed for global coverage. At 10,000 kilometers, on the other hand, a satellite would have an orbital period of about six hours and would see less of the earth's surface. In fact, a fleet of about a dozen or more equally spaced satellites would be necessary to cover the planet.

In addition, because the signal from the handheld phone is weak, the entire burden of completing the link is placed on the satellite. The hookup can be achieved only if the satellite employs very narrow, searchlightlike spot beams on the order of one degree or so, each covering a "cell" on the earth perhaps 150 kilometers across. Many of these beams must be employed to provide coverage of the intended service area.

In general, satellites must orbit either above or below the Van Allen radiation belt, whose energetic ionized particles would damage solar cells and perhaps other solid-state components. Thus, satellite altitudes must be above about 10,000 kilometers or below about 1,500 kilometers. For the latter option, however, the orbital period is roughly 100 minutes, and about 50 or more satellites are required to cover the globe, because each one sees only a small part. (Imagine trying to take a picture of an elephant from one meter away.) The high- and low-orbit choices have become known as intermediate circular orbit and low earth orbit.

Satellite Trade-offs

One advantage of personal communications satellite systems will be a largely unobstructed path between the satellite and essentially all subscribers, allowing operation at lower power levels. In terrestrial cellular systems, on the other hand, the radio tower is usually hidden from view, requiring stronger communications links. Because communications between a satellite and a mobile subscriber will not operate with such robust links, they will be adversely affected by blockage of the signals by buildings, trees or other obstructions. Recent studies have shown that systems operating with the higher, intermediate-circular-orbit satellites should enjoy an advantage, as the satellites are generally visible at higher elevations and cross the sky more slowly.

Higher altitudes also mean that fewer satellites are needed to cover the globe. Again, however, there is a trade-off, which is that larger satellite antennas are needed, and each antenna must form a greater number of spot beams in order to maintain overall coverage. Thus, low-earth-orbit satellites tend to be smaller, lighter and cheaper than intermediate-circular-orbit spacecraft, which will probably be less expensive than geosynchronous satellites.

Another challenge for designers of personal communications satellite systems is the handoff that is necessary when a subscriber is passed

LEO	LOW EARTH ORBIT BELOW 2,000 KM
MEO	MEDIUM EARTH ORBIT APPROX. 10,000 KM
GEO	GEOSYNCHRONOUS EARTH ORBIT 36,000 KM

Data-Oriented Personal Communications Satellite Systems

	ASTROLINK	CELESTRI	CYBERSTAR	SPACEWAY	GE*STAR	MORNINGSTAR	TELEDESIC
COMPANY	Lockheed Martin	Motorola	Loral	Hughes	G.E. Americom	Morning Star	Teledesic
NUMBER OF ACTIVE SATELLITES	9	63 LEO/9 GEO	3	20 MEO/16 GEO	9	4	288
ORBIT PLANES	Equatorial (0°)	7 inclined (48°); 1 equatorial (0°)	Equatorial (0°)	4 inclined (55°); 1 equatorial (0°)	Equatorial (0°)	Equatorial (0°)	12 inclined (98°)
ORBIT ALTITUDE (KILOMETERS)	GEO	1,400 (LEO) and GEO	GEO	10,352 (MEO) and GEO	GEO	GEO	1,375 (LEO)
ESTIMATED SATELLITE CAPACITY (GIGABITS PER SECOND)	6.0	1.5	9.0	4.4	4.7	0.5	10.0
ESTIMATED CAPITAL INVESTMENT (BILLIONS OF DOLLARS)	4.0	12.9	1.6	6.4	4.0	0.82	9.0

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from the coverage of one spot beam to that of another. The situation is just like the handoff in a terrestrial cellular system, only in reverse: the subscriber is essentially stationary, and the cells are moving past. A subscriber who has successfully placed a call is, of course, in a known beam, so it is possible to manage a beam-to-beam handoff relatively straightforwardly. More difficult is a satellite-to-satellite handoff, which is likely to occur for any low-earth-orbit system. The degree of difficulty depends on the details of the satellite system; in the best case, the transfer need not occur until the subscriber's signal is being received by the following satellite.

Some form of network control is required for all the systems described here. Call setup usually entails a signaling channel, which the handset uses initially to request a call. All the systems require that the call be handled in a different channel from the signaling channel. This is similar to the way terrestrial cellular systems operate, and it leaves the signaling channels available to others, to set up their calls. Signals received by the satellite must be retransmitted to a "gateway earth station" that is tracking the satellite as it crosses the sky. There the signals are converted back to ordinary telephone transmissions and fed into the public switched network.

Targeting Business Travelers

The designs of the announced global satellite cellular phone systems differ considerably, reflecting different assumptions about the customers who might be attracted. The largest groups of potential users are two types of business travelers: those from the developed world who do business often in less developed countries, where the local phone service may be unreliable; and those who need mobile communications in their own countries but who travel beyond the reach of terrestrial cellular systems. Other potential markets include people living in very rural areas, where there is currently no service at all, and law-enforcement, fire, public-safety and other government officials who need access to a communications network that would survive a regional disaster, such as an earthquake or flood.

Many different systems have been proposed, but only five appear to have some promise of being fielded. Four of them are U.S.-based and have received licenses from the U.S. Federal Communications Commission (FCC); the fifth is an enterprise spun off from the International Mobile Satellite Organization (Inmarsat), a treaty organization similar to Intelsat. The four U.S.-based projects are: Iridium, now being constructed by Motorola with Lockheed Martin, Raytheon and other contractors; Globalstar, a joint effort in which Loral Space and Communications (a satellite manufacturer) and Qualcomm (a maker of cellular equipment) are the principal partners; ECCO, a proposal put forth by Constellation Communications, Inc. (CCI), in Reston, Va.; and Ellipso, to be built by Mobile Communications Holdings, Inc. (MCHI), in Washington, D.C.

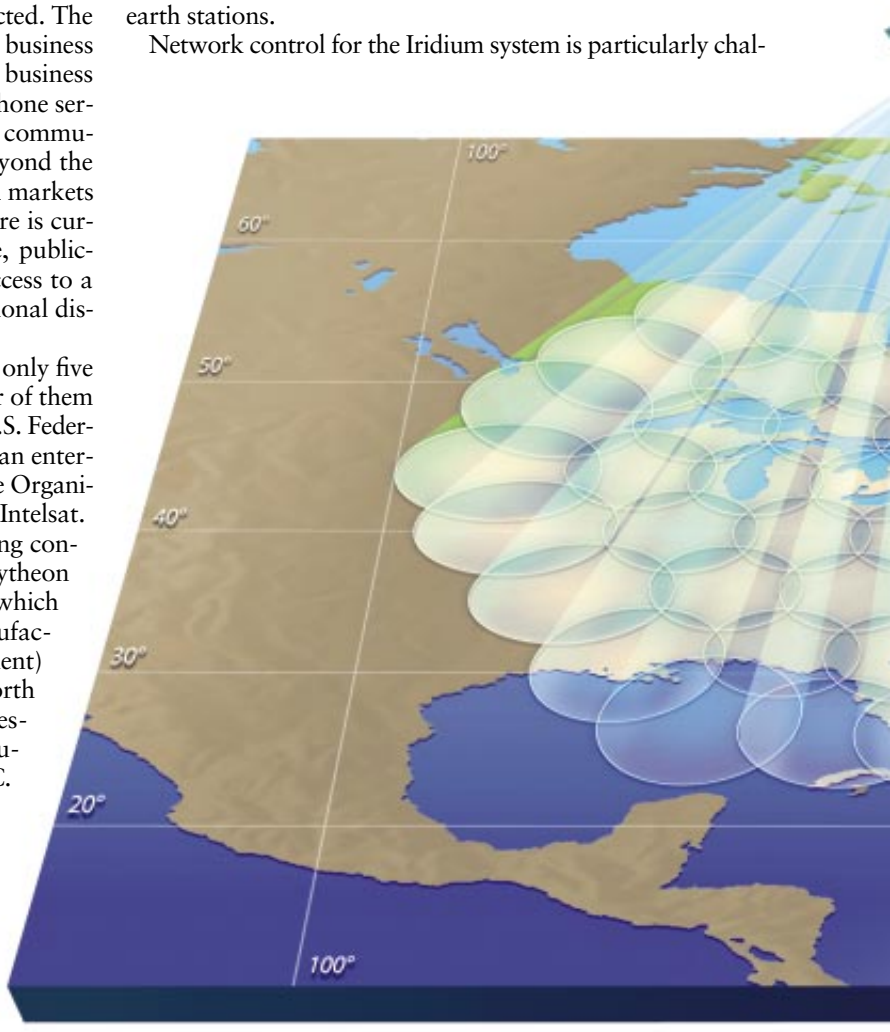
Of all the projects, Iridium, with a projected cost of $3.4 billion, is the most technically complex and also the closest to completion. Iridium's working design calls for 66 satellites, each capable of handling as many as 1,100 simultaneous calls and with enough fuel for an eight-year life. So far Motorola has launched two thirds of the satellites and plans to begin its service in the fourth quarter of 1998. They are being launched into low earth, circular polar orbits at an altitude of 780 kilometers, in six equally spaced orbital planes.

Services to be provided include voice, data at 2.4 kilobits per second and paging. The Iridium voice connection is more robust than that of the other planned personal communications satellite systems, because Motorola required that the handheld unit be usable from inside a vehicle (such as a taxi). This capability was dictated by their plan, which depends heavily on serving international business travelers.

The complexity of the Iridium system arises in no small measure from the fact that the satellites are designed to communicate not only with the earth stations but also with one another. To route traffic properly, each satellite must carry a set of stored routing tables from which new routing instructions are chosen every few minutes. Signals from the ground are transmitted in bursts, or "packets," each of which includes the address of its intended destination. At the satellite the signals are demodulated so this address can be read and the packets retransmitted to their next destination.

This destination may be a handheld Iridium subscriber unit, or it may be a gateway earth station. If neither is in view, then it will be one of the four nearest satellites—the one ahead or behind in the same orbital plane, or the nearest satellite in the adjacent orbital plane to the east or west. Although it complicates the design of the system, the use of these cross-links will permit global service with only a dozen gateway earth stations.

Network control for the Iridium system is particularly chal-



SLIM FILMS

lenging because the largest part of the network essentially resides in the satellites and their cross-links. To avoid congestion, engineers designed these cross-links so that each can handle all the traffic from a given satellite. In the event that a cross-link fails, alternate routing instructions are carried on board.

Like Iridium, the Globalstar venture will be based on satellites in low earth orbits. Unlike Iridium, however, the Globalstar system will not employ cross-links between satellites. Although that choice greatly simplifies the design of the system as a whole, it also means that a subscriber will be able to gain access to the system only when a satellite in view can also be seen by a gateway earth station. For this reason, service areas will all have to be within about 1,600 kilometers of each gateway earth station. To achieve truly global coverage would require the construction of more than 200 earth stations, an improbably large number. Thus, Globalstar is being targeted more to business travelers within a single country rather than to international business travelers.

Most of the components of the satellites have been built by Loral, and Qualcomm has developed much of the ground segment. Globalstar hopes to have its system in operation by early 1999. The satellites are currently being assembled by Alenia Spazio in Italy, and the first four were launched in February. Globalstar's plan calls for launching the space segment and franchising its use to partners in different countries; more than 100 such relationships have been established. In addition to voice, Globalstar will offer facsimile, data and other services.

The Globalstar system will employ 48 satellites organized in eight planes of six satellites each. The satellite orbits will be circular, at 1,414 kilometers and an inclination of 52 degrees with respect to the equator. The use of an inclined orbit concentrates the available satellite capacity at lower latitudes, where the largest populations exist; little or no coverage is provided beyond 70 degrees latitude in either hemisphere.

ECCO, another of the planned low-earth-orbit systems, is to make use of 46 satellites—11 in a circular equatorial orbit at an altitude of 2,000 kilometers and five in each of seven inclined orbits. The goal of the system is to offer rural telephony and facsimile service, both at 2.4 kilobits per second. CCI proposes to have these satellites built by Matra Marconi Space, a joint venture of the French Lagardère and British GEC groups.

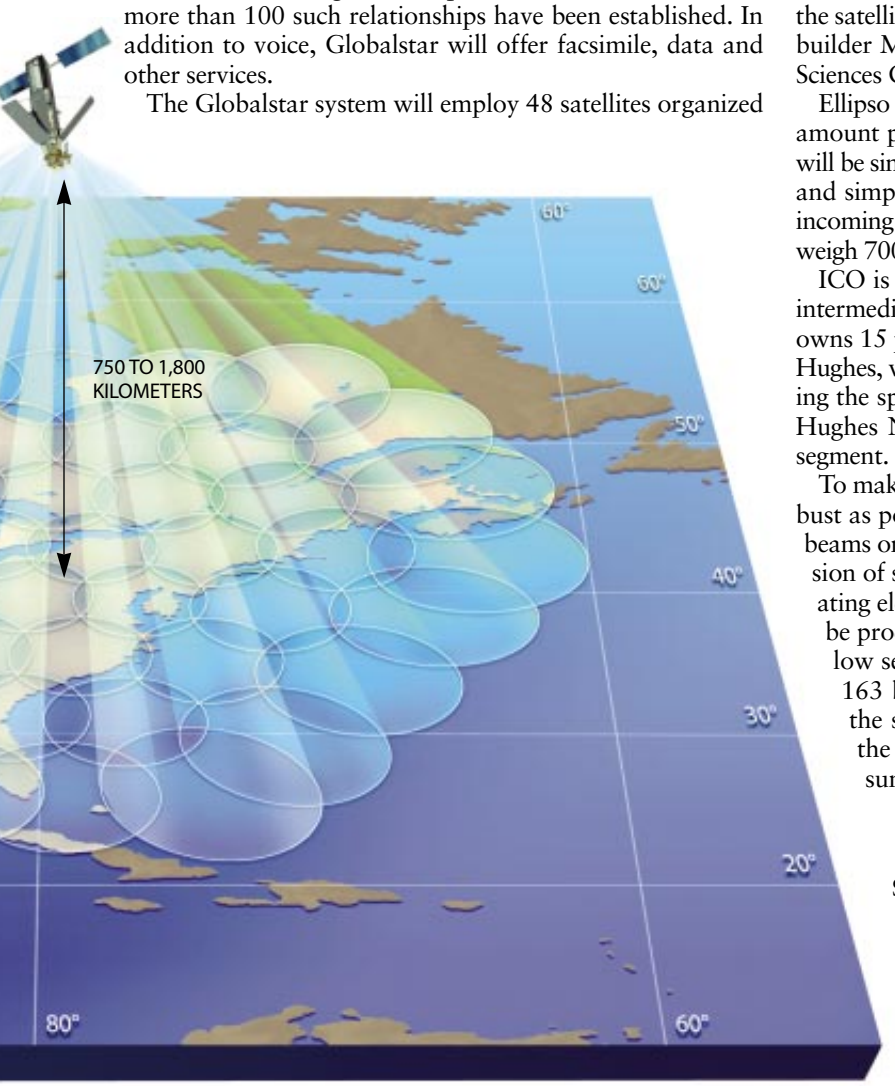
Higher Orbits

The two personal communications satellite systems that will be based on satellites in orbits higher than low earth ones are ICO, built by ICO Global Communications, and Ellipso. The Ellipso system, uniquely, will use satellites in elliptical orbits designed to take advantage of the fact that most of the world's population lies in the Northern Hemisphere. That is, an orbit is chosen that has its farthest point from the earth (the apogee) above the Northern Hemisphere, allowing the satellite to spend more time north of the equator. Systems builder MCHI intends to have its satellites built by Orbital Sciences Corporation in Dulles, Va.

Ellipso is intended to be a low-cost approach, with the total amount projected to be around $910 million. The satellites will be similar to those used by Globalstar, with 61 spot beams and simple "repeater" transponders that merely retransmit incoming signals on a different frequency. Each is expected to weigh 700 kilograms and have a lifetime of five to seven years.

ICO is the only one of this group of systems that will use intermediate circular orbits. This spin-off of Inmarsat, which owns 15 percent of the corporation, is also partly owned by Hughes, whose Space and Communications Division is building the spacecraft. A team consisting of NEC, Ericsson and Hughes Network Systems Division is building the ground segment. ICO hopes to have its system operational in 2000.

To make the link between the handsets and satellites as robust as possible, ICO chose a design that employs 163 spot beams on each satellite, a rather large number. Such a profusion of spot beams will be achieved using an array of radiating elements. The signals delivered to these elements will be processed in a digital processor in such a way as to allow several of them to contribute to forming one of the 163 beams. Digital processing is also required to steer the signals arriving from the gateway earth station to the correct spot beam. This digital processor will consume a large amount of satellite power—about two



SPOT BEAMS of an Iridium satellite each cover a "cell" on the earth perhaps 150 kilometers across. A cluster of four dozen of these relatively narrow beams provides coverage of a larger region—the eastern U.S., say. Use of the narrow beams is necessary because the signals from the handheld telephones are weak, placing most of the burden of connection on the satellite.

SLIM FILMS

NINE GEOSYNCHRONOUS SATELLITES in five orbit locations make up the constellation of the Astrolink system, one of seven satellite-based systems that have been proposed to offer data communications, primarily for Internet service. Six of the seven systems would use geosynchronous satellites, enabling them to be accessed with simpler, less expensive terminals that do not need to track satellites across the sky. Such economy could be a significant advantage in the consumer market.

kilowatts—and will be the most complicated one yet built into a spacecraft.

How many—and which—of these satellite systems can be successful is, of course, difficult to say. Nevertheless, a few salient points bear mentioning. The great amount of processing power demanded of the Iridium and ICO satellites is a clear technological risk. To date, only three satellites with significant digital processors on board have been deployed: one was the National Aeronautics and Space Administration's Advanced Communications Technology Satellite; the other two were experimental Italian spacecraft. The Iridium plan, moreover, seems to depend very much on a million or so international business travelers, whose needs might be served in other ways—for example, by cellular phones designed to operate in several modes to meet different standards around the world.

Of the global systems, Globalstar would seem to offer good prospects for a successful business because its space segment is not expensive and because the cost of the ground segment is borne by the franchised operators of the system. Furthermore, these operators are likely to have some success in cutting through the regulatory red tape that could delay or block access to their local market. The remaining systems, though less complex than Iridium, may suffer because they will not reach the marketplace until several years after the first entrants. It may also be difficult for Ellipso and ECCO to secure adequate financing, given the head start of Iridium, Globalstar and ICO.

Complicating all this speculation is uncertainty regarding the attitude of potential subscribers. Accustomed to the quality and high penetration of cellular systems, some may forgo altogether the use of satellite phones with their somewhat weaker communications links. On the other hand, there could be many subscribers who choose to buy a satellite (or cellular/satellite) phone as an insurance measure—for example, to deal with a situation such as encountering vehicle problems in a remote area of the country—but use it very infrequently.

Data and Multimedia Services

Deregulation of the telecommunications industry in various developed countries is speeding delivery of new services and prompting the investment of enormous amounts of capital in new facilities. A key factor in this activity is the explosion in the use of the Internet. During the next few years, the use of the Internet is expected to grow rapidly, from 50 million households today to perhaps 150 million by 2000, representing a market of more than $10 billion. Corporate use of the Internet may grow even more spectacularly. Increasingly, corporations are using the Internet to create their own semiprivate "intranets." Some observers believe this market could expand from the less than $1 billion spent in 1996 to over $30 billion by 2000.

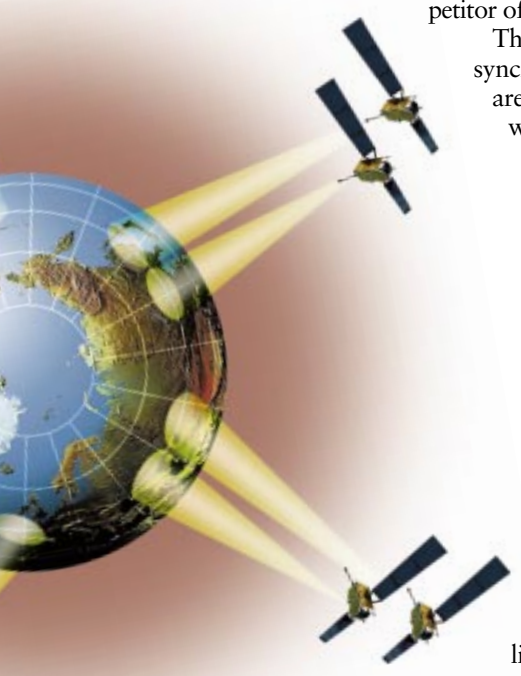
To serve these markets, many new satellite systems are planned. Because of the congestion on the frequencies currently used for fixed (as distinct from mobile) satellite services, these systems will operate in a higher range of frequencies, known as Ka-band. The choice of Ka-band is driven largely by the absence of a suitable alternative; recent developments have made it almost impossible to secure orbital locations for satellites that would operate in other bands without interfering with neighboring satellites. Worldwide, there are now believed to be more than 50 proposed Ka-band projects requiring approximately 170 geostationary-orbit locations. Most of these proposals appear to be for national or regional systems, and not much has been published about them thus far.

The main problem with Ka-band, which encompasses wavelengths between about one and 1.5 centimeters, is that signals are significantly attenuated by rain. For this reason, the use of Ka-band was confined until recently to a relatively small number of experimental satellites. For the new networks, engineers promise availability in the range of 99.5 to 99.9 percent, through the use of various strategies to get around the rain-attenuation problem.

A total of seven U.S. systems propose to offer global service [*see illustration on page 73*], although none has progressed beyond the design stage. Three of the systems would be based either entirely or partly on low- or medium-earth-orbit satellites, the other four entirely on geosynchronous-orbit spacecraft.

With their relatively large number of satellites, the two low-earth-orbit proposals would be the most expensive to deploy. Indeed, Teledesic probably remains the most advanced of all the systems being proposed and, with 288 satellites, is likely to prove rather costly. Teledesic intends to orbit the satellites at an altitude of 1,400 kilometers; the need for so many satellites was dictated partly by that orbit and partly to mitigate rain fading. (For the latter, the service area of each satellite is to be limited to a fairly narrow cone.)

Comparable to Teledesic in terms of complexity and cost is Motorola's Celestri system. The system will employ 63 satellites at an altitude of 1,400 kilometers, as well as nine geosynchronous satellites. The geosynchronous segment will be used for subscribers whose traffic is not sensitive to the delay caused by the hop to and from geosynchronous orbit. Celestri is designed to offer subscribers access at a very high data rate, from 64 kilobits per second to 155 megabits per second, and



in this regard is seen as a close competitor of the Teledesic system.

The other proposed geosynchronous-orbit systems are more modest in scope, with estimated costs in the range of $820 million to $6.4 billion. The least complex designs, by Loral and Morning Star Satellite Company, intend to provide limited global coverage with three and four satellites, respectively. At the other end of the scale, Hughes Communications's Spaceway project is designed around 16 geosynchronous satellites, augmented by 20 medium-earth-orbit satellites. In between those two extremes are the proposals of Lockheed Martin and G.E. American Communications (also known as G.E. Americom, a subsidiary of General Electric). Each would orbit nine satellites and cost about $4 billion.

Of the seven U.S. global communications satellite systems that have been proposed, it seems unlikely that there is sufficient risk capital available for more than two or three to be financed. In some sense, these projects are more risky than the voice-oriented satellite projects described earlier because the demand is less certain. This fact may aggravate the problem of raising capital—leaving the field open to those companies best able to commence their projects with their own resources. Those most committed at present, in terms of money spent on design studies, appear to be Loral, Lockheed Martin, Motorola and Teledesic.

In addition, success in a consumer market is believed to depend on terminals that cost less than about $1,000. These terminals will combine a small satellite dish antenna and a two-way radio, which may be mounted on the dish, with an indoor component that interfaces with the computer. Achieving such a low cost will most likely require the mass production of a million or more terminals, which is hardly a certainty. If, somehow, the price of the terminals can be brought down to this level, then satellites may open up a new role—that of providing "last-mile" connections to homes and businesses for broadband data, multimedia and related services, because existing telephone lines do not afford this kind of data rate (although efforts are under way to change this).

Beyond Ka-band

Despite the fact that none of the Ka-band systems described above is very far along in development, companies have already begun to file for licenses from the FCC to build systems operating at still shorter wavelengths—six and eight millimeters. Hughes and Motorola were the first to file for such systems; at last count, some 14 additional systems had been proposed. They include a total of 400 satellites and almost $40 billion in investment.

These so-called Q/V-band systems represent a significant stretch in capability beyond those planned for Ka-band. In this band, the effects of rain attenuation are still more severe, and even in clear air the six-millimeter-wavelength signals will be attenuated by a factor of three to four along paths that are as low as 20 degrees above the horizon, simply because air molecules absorb part of the electromagnetic energy of the signals. Adding to the system designers' difficulties is the fact that few active radio components will work at these short wavelengths, and their cost is quite high. These facts suggest that the Ka-band will probably be filled first, before any system is built for these still shorter wavelengths.

The development of the fleets of satellites described here will affect some of us profoundly. By 2000 it will be possible to call home from essentially anywhere on the planet using a handheld terminal similar to one of today's cellular phones. For better or worse, we need never be out of touch, no matter where we are.

Besides the obvious benefits to commerce and tourism, universal service will become possible, at least for those who can afford it, in countries where none now exists. Within a decade, it will probably be possible to live in a remote area and yet be connected to the worlds of commerce and entertainment via the Internet and other sources of multimedia at rates high enough to support movies-on-demand. The world will soon be a place where not just communications but also torrents of information will be available just about everywhere. Whether this world will seem smaller, larger or more interesting will probably depend on your point of view. SA

The Author

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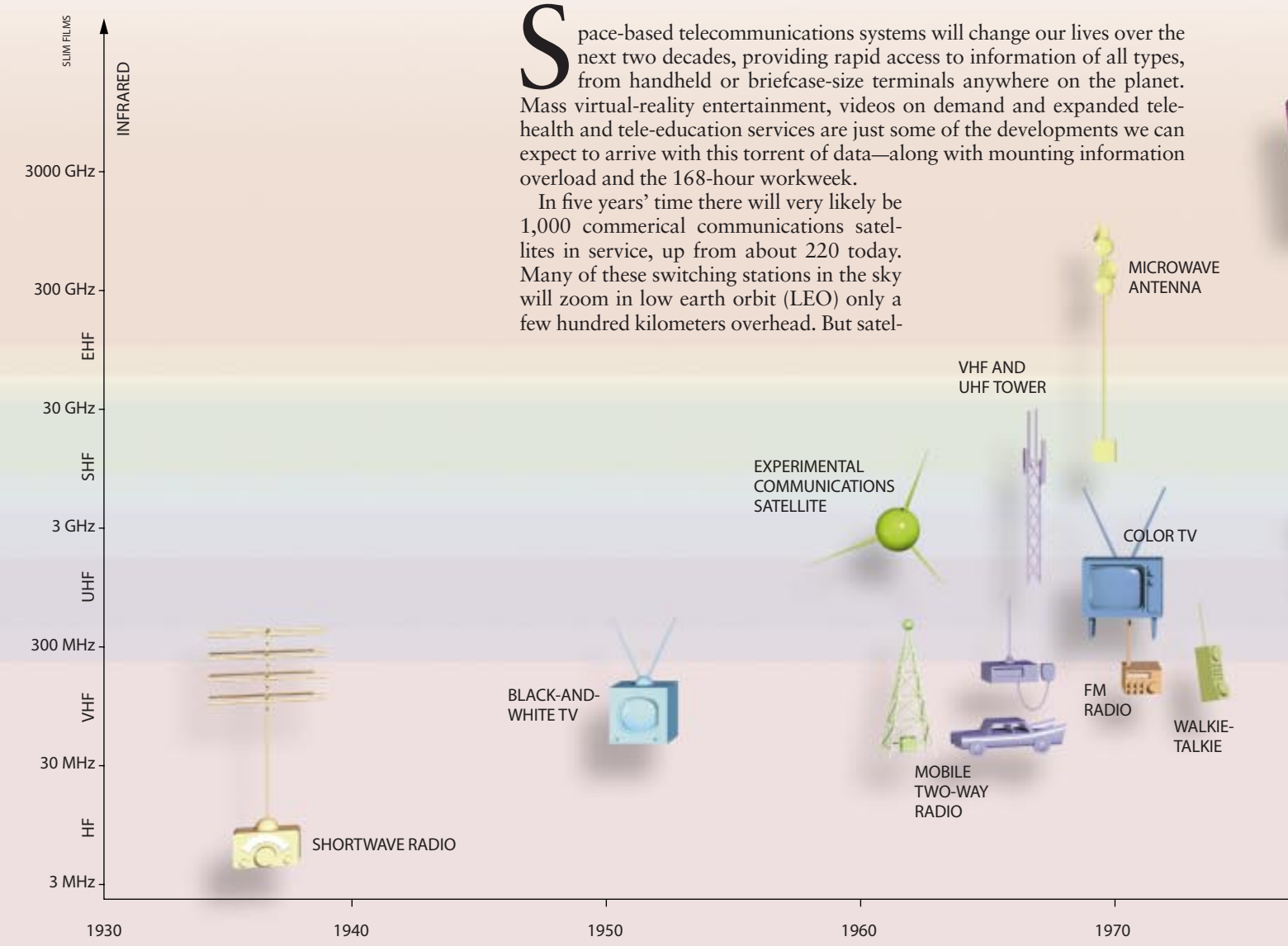
Telecommunications for the 21st Century

Systems based on satellites and high-altitude platforms will merge with optical-fiber and terrestrial wireless networks to provide global, high data-rate, mobile communications

by Joseph N. Pelton



Space-based telecommunications systems will change our lives over the next two decades, providing rapid access to information of all types, from handheld or briefcase-size terminals anywhere on the planet. Mass virtual-reality entertainment, videos on demand and expanded tele-health and tele-education services are just some of the developments we can expect to arrive with this torrent of data—along with mounting information overload and the 168-hour workweek.

In five years' time there will very likely be 1,000 commerical communications satellites in service, up from about 220 today. Many of these switching stations in the sky will zoom in low earth orbit (LEO) only a few hundred kilometers overhead. But satel-

lites in the more traditional geosynchronous earth orbit (GEO), which turn with the earth 36,000 kilometers (22,300 miles) up, will remain very much in the picture.

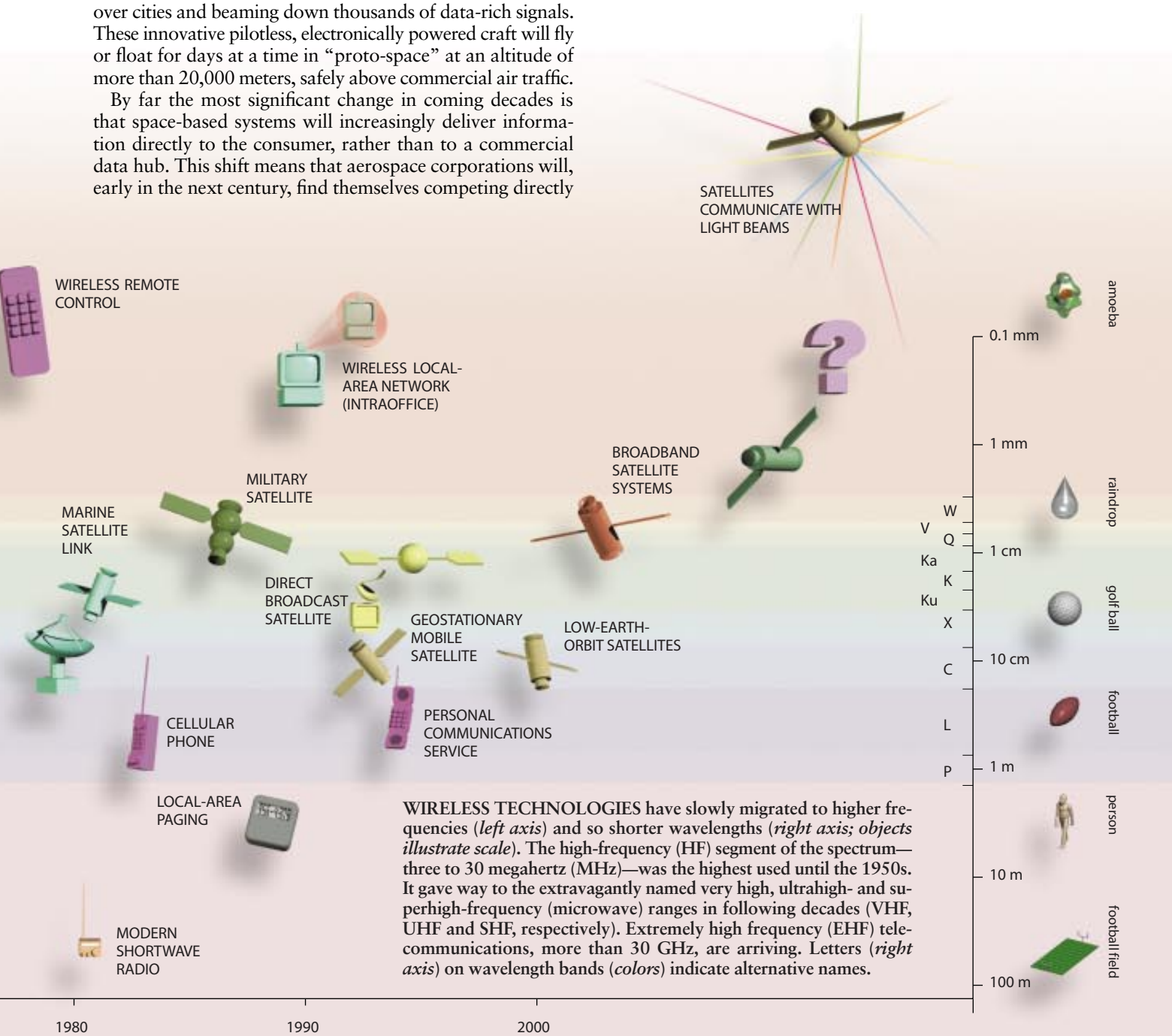
The proximity of LEO satellites offers some important advantages over today's orbiters. Signals will zip back and forth to low orbits in hundredths of a second, a decisive advantage over the quarter of a second that data take to travel to and from GEO. On the pro side of the ledger, this faster performance will make interactive global access to networks and video teleconferencing practical and appealing. On the con side, LEO systems require 20 times more satellites than a GEO system to cover the globe and five times more than a medium-earth-orbit (MEO) network.

Satellites will soon not be the only type of space-based telecommunications system. By the year 2000 we could see High Altitude Long Endurance (HALE) platforms hovering over cities and beaming down thousands of data-rich signals. These innovative pilotless, electronically powered craft will fly or float for days at a time in "proto-space" at an altitude of more than 20,000 meters, safely above commercial air traffic.

By far the most significant change in coming decades is that space-based systems will increasingly deliver information directly to the consumer, rather than to a commercial data hub. This shift means that aerospace corporations will, early in the next century, find themselves competing directly with AT&T, MCI, British Telecom (BT) and other carriers.

Only a few years ago cumbersome dish antennas were needed to obtain a satellite connection faster than simple telephone service. Moreover, such links were in short supply, and service at sea cost as much as $10 per minute. Those limitations are disappearing. The coming torrent of high-speed data from space should be a colossal boon for individuals and corporations around the world. It will be especially important in developing countries such as Brazil, India and China, which do not have extensive fiber-optic networks.

The key innovation for handling the burgeoning demand is the phased-array antenna. This sophisticated electronic device, used until now mainly for military communications, consists of multiple transmitting elements arranged in a fixed geometric array. Arrays can be programmed to send a grid of electronically formed radio beams to track moving targets or,



WIRELESS TECHNOLOGIES have slowly migrated to higher frequencies (*left axis*) and so shorter wavelengths (*right axis; objects illustrate scale*). The high-frequency (HF) segment of the spectrum—three to 30 megahertz (MHz)—was the highest used until the 1950s. It gave way to the extravagantly named very high, ultrahigh- and superhigh-frequency (microwave) ranges in following decades (VHF, UHF and SHF, respectively). Extremely high frequency (EHF) telecommunications, more than 30 GHz, are arriving. Letters (*right axis*) on wavelength bands (*colors*) indicate alternative names.

alternatively, to receive signals from only certain directions.

In concept, these antennas are something like miniature versions of the Very Large Array, the cluster of radio telescopes in Socorro, N.M., used for studying astrophysical phenomena. Phased arrays achieve directional selectivity by electronically imposing minute delays on the signals moving from (or to) different parts of the array. Beams focused in this way reduce interference, an important advantage in view of the growing demand for radio spectrum. The pressure on spectrum will intensify, because high data-rate signals need much more bandwidth—a far bigger slice of spectrum—than do low data rates.

Mounted on satellites, phased arrays can steer beams as little as half a degree across toward their intended recipients. Moreover, they are fully "adaptive": under the control of onboard supercomputers the size of a shoebox that are now being built (a spin-off from "Star Wars" research), they will be continually reprogrammed. This flexibility began a decade ago with modified parabolic antennas, and the trend will continue. Satellites of the 21st century will thus be able to "reuse" the same slice of spectrum many times over. Reuse will soon reach 100-fold on some satellites and should in time reach 1,000-fold.

We can expect phased arrays to become familiar on terra firma as well, because they can direct beams to satellites moving in known orbits overhead. In addition, these arrays can be constructed to conform to almost any desired shape, which makes them particularly attractive for aircraft and cars. Within the next five years we should even see miniature versions in handheld transceivers.

Competition from the Ground

The biggest economic hurdle for satellites in industrial countries will be competing with optical-fiber systems to provide high data-rate, or broadband, services directly to the home or office. A satellite system cannot match the transmission speed of a simple span of fiber-optic cable. In reality, however, most consumers rely on a mile or so of much slower paired copper telephone wires or coaxial cable to bring voice and data from a local distribution center.

This "last-mile problem," as it is known, is a major bottleneck for wired networks. Telephone companies have developed a way to increase data rates carried by cable and wires from tens of thousands of bits per second to a few million. Yet despite improvements in the price and performance of this technology, known as xDSL, it is still expensive and is unlikely to meet demand for broadband data.

Many home users of the World Wide Web, for example, are frustrated by delays fetching graphics. A broadband Internet connection transports data 50 times faster than a typical 28.8-kilobit-per-second dial-up telephone connection; high-definition television swallows bits at rates 20 to 30 times faster still. Many users will want multimegabits of data per second by halfway through the next decade. Consequently, satellites have perhaps a 10-year window of opportunity in the multimedia marketplace.

The coming renaissance of satellite systems was not always obvious. In 1993 Nicholas Negroponte of the Massachusetts Institute of Technology suggested that the future of telecommunications would be a huge flip-flop. Narrowband services, telephone and paging services that are now often carried long-distance by glass fiber would migrate to wireless transmission. At the same time, cost and the limited amount of available radio spectrum would force broadband services to migrate in the opposite direction, from radio waves and satellites to fiber optic and coaxial cable. This became known as the Negroponte Flip.

TELECOMMUNICATIONS SATELLITE of the next century will have two phased-array antennas, seen as hexagonal structures in this example (*right*), for transmitting and receiving signals in numerous narrow "spot" beams. Solar panels (*long rectangular shapes*) provide power for onboard electronics, including powerful processors that control the antennas and handle thousands of separate voice or data links. This satellite is in medium earth orbit, about 10,300 kilometers (6,400 miles) high.

In a dissenting article in *Telecommunications* magazine, I argued that Negroponte was wrong. The future would feature a "rich but confused" digital mixture of fiber, coaxial cable, terrestrial wireless and satellite services carrying everything from voice to broadband multimedia and video services. In this scenario, users would demand access from mobile terminals to broadband services as well as to less demanding narrowband ones. Glass fiber, satellites and terrestrial wireless networks would, I suggested, each be important in the mix, and protocols for seamless interconnection between these would become the technical crunch point.

Telecommunications dubbed this view the Pelton Merge. If correct, it meant that engineers would face the challenge of developing broadband satellite-based services that could be interconnected with glass fiber and coaxial cable-based systems. It followed that the next generation of communications satellites would have to be 1,000 times faster than even those of the early 1990s. And there would be an urgent need for new data-conversion protocols and "open systems" standards, specifications that manufacturers could use to build compatible new devices.

Breakthroughs in satellite technology are making the merge model increasingly credible. During the past five years, wireless services and satellites have been experiencing record growth. Today they can provide a telephone-line transmission at a cost below 0.1 cent a minute. Moreover, the most rapidly growing type of telecommunications service is direct broadcast satellite (DBS) television, which uses geosynchronous orbiters to beam signals to more than 20 million subscribers worldwide. Market studies have projected the total could triple by 2005. Yet according to the Negroponte Flip, television should be carried by cable.

Exploiting a Finite Resource

Satellites still face significant technical obstacles. A crucial one is the extremely high cost of launching a payload and insuring it. There is an urgent need for innovative ways to put equipment into orbit reliably and at much lower expense. New launch concepts are being investigated, including reusable rockets and jets. So far, though, none has proved itself.

Other challenges stem from the need to make the most efficient use of the finite radio spectrum. All modern systems transmit information in digital form. One important approach is to compress data digitally. DBS, for example, benefits from a new Motion Picture Experts Group standard, MPEG2, which allows transmission of high-quality video images to home TV screens using only six megabits per second. This now enables a one-gigabit-per-second DBS satellite such as

ICO GLOBAL COMMUNICATIONS; SLIM FILMS

DirecTV to transmit over 150 television channels plus many CD-quality audio channels. Some mobile systems compress voice data for the same reason.

Because high frequencies can carry more data than low ones, the bands used for wireless have steadily increased in frequency from tens of megahertz midcentury to almost 100 gigahertz in today's most ambitious schemes. But transmitting and processing thousands of signals takes considerable power—a scarce resource on satellites. It is a particular challenge for GEO satellites, which must cope with very large numbers of beams and transmit them 40,000 kilometers.

Power is also a challenge for satellites offering mobile services, because the small antennas now used in portable transceivers intercept only a tiny fraction of a satellite's signal. That increases the power and sensitivity required of the satellite. As a result, the typical solar array on a geosynchronous satellite has increased in power from around two kilowatts to more than 10 kilowatts over the past five years. This trend has been achieved partly through the use of larger solar arrays and partly by higher efficiency. Solar cells made of new materials, such as the combination of gallium arsenide and germanium, have reached efficiencies of about 23 percent, twice the figure for amorphous silicon.

Solar concentrators that reflect light so as to expose cells to

more radiation, together with multijunction devices that capture infrared and ultraviolet as well as visible light, could push efficiencies above 30 percent in the next five years. Flexible solar arrays capable of generating 60 kilowatts or more are a distinct possibility for the future, and improved fuel cells and high-performance batteries will also help.

High data rates necessitate large antennas, especially for GEO systems. Parabolic satellite antennas 10 meters in diameter can now be built, and it should be possible to extend that to 20 or 30 meters. So far the most ambitious phased-array satellite antenna is on the Japanese Gigabit Satellite. The antenna this satellite will use to receive signals is some three meters in diameter and will be made up of 2,700 cells or individual antenna elements. Larger antennas with tens of thousands of cells may become feasible as designers gain experience and manufacturers learn how to mass-produce the devices at low cost.

To win mass-market acceptance, however, service providers will need to bring the cost of ground terminals to the lowest possible levels. Better designs and the adoption of large-scale manufacturing techniques should help achieve this end. Some DBS terminals are now only 30 centimeters in diameter, and their price is falling to below $200. In the future, gallium arsenide–based phased arrays are likely to help reduce antenna costs in space and on the ground.

Location, Location—GEO versus LEO

Most communications satellites today are in GEO. Starting with the International Telecommunications Satellite Organization (Intelsat) in 1965, most of them have communicated with fixed ground stations. Over a decade ago, the International Maritime Satellite Organization (Inmarsat) pioneered mobile telephony and data links for ships, and within the last year, American Mobile Satellite Corporation and Telesat Mobile in Canada have introduced similar services in North America for land-based mobile users. By building satellites with bigger antennas, these companies have reduced costs, but their services have suffered because of transmission difficulties (and poor marketing).

The engineering challenges of geosynchronous satellites account for the surge of interest in recent years in systems using satellites in LEO, at an altitude of less than 1,600 kilometers, or MEO, at 10,000 to 16,000 kilometers. (The intervening zone is avoided because the Van Allen radiation belts threaten the operation of satellites there.)

LEO systems, besides being faster than GEO systems, can be used with smaller terminals, because the satellite is typically 40 times nearer the earth. Three new LEO and MEO global land-mobile systems—Iridium, ICO (ICO Global Communications) and Globalstar—are scheduled to start offering telephony and global paging within a year or two, with Iridium first off the blocks.

The disadvantage of LEO and MEO systems is that satellites close to the earth move across the sky in an hour or two, rather than seeming to remain at a fixed point. For good reception, users must always be able to see at least one satellite that is well clear of the horizon, because a steep "look angle" minimizes losses caused by buildings and trees. This requirement explains why MEO and LEO systems have to employ so many satellites in order to provide continuous global coverage—around 60 for LEO networks. Launching and building the multiple satellites costs billions of dollars, and stringent precautions will be needed to ensure that abandoned satellites and orbiting launch debris do not become a danger.

To offer affordable broadband services—such as interactive multimedia applications—via desktop antennas, satellite systems will have to employ the very highest frequencies, over 20 gigahertz. Even with the extensive reuse of frequencies made possible by phased-array antennas, these systems will need large slices of spectrum. Several broadband LEO and

LOW-EARTH-ORBIT satellite zooms only several hundred kilometers above the earth and will link users separated by comparable distances with very little delay. Many such satellites are needed, however, to cover the earth.

SLIM FILMS

HIGH ALTITUDE LONG ENDURANCE (HALE) platforms in coming years will hover 20,000 or more meters above the earth; they will link mobile users up to 500 kilometers apart. Some may be dirigibles, whereas others will have wings and fly like conventional aircraft.

SATELLITE in geostationary orbit some 40,000 kilometers above the earth can link mobile users many thousands of kilometers apart, but data are delayed for a quarter of a second by the long round-trip.

MEO systems are now in development, notably Bill Gates and Craig McCaw's Teledesic, Alcatel's Skybridge and Motorola's Celestri (LEO-GEO hybrid). Various consortia have proposed at least a dozen other broadband multimedia networks, most of them GEO systems. These networks would employ massive power systems to blast their signals down to microterminals, although not all of them will be built.

Tomorrow's Technologies

The high cost of broadband multisatellite systems accounts for the growing enthusiasm for HALE platforms. These craft can be launched at moderate cost, and they can be called back for servicing. Studies indicate that such platforms could support phased-array antennas with some 3,500 beams, making feasible not only mobile two-way communications but also video distribution in an area 500 kilometers across. These systems will have to reuse frequencies 100-fold, and they will talk to satellites to make global connections.

Four basic types of HALE platforms are being discussed: helium-filled, robotically piloted dirigibles stabilized by ion engines; units powered by solar or fuel cells; piston-driven platforms; and jet engine–driven platforms. These approaches face contrasting limitations: fuel- and solar-cell-powered platforms will be hard-pressed to muster enough power, but piston- and jet-powered types will stay aloft only a few days.

Another way to provide broadband services is to move to frequencies so high that less reuse is needed. Unfortunately, there is an obstacle: rainy weather. The highest-frequency satellite systems now contemplated utilize wavelengths comparable to the size of raindrops. The droplets consequently act as lenses, bending the waves and distorting the signals. This effect can be mitigated by error-correction techniques, by using more power when necessary and by employing more ground terminals (so data can follow diverse paths). These measures, however, come at a price.

Moving to wavelengths below a millimeter presents even more obstacles. Infrared and optical beams—the logical next step—are easily absorbed in the atmosphere, so in the near future they will probably be restricted to use within buildings. But experiments carried out with the Japanese Engineering Test Satellite VI in the mid-1990s have revived hopes that communicating with satellites via laser beams might one day be feasible. A laser-based network would most likely carry only very heavy streams of traffic and would rely on multiple ground stations to minimize losses incurred by bad weather.

What is clear is that wireless systems will become more dominant over the next 20 years and that they will be based on a mixture of technologies. Universities, government and industry all have roles bringing these schemes to fruition. Unfortunately, there are very few courses of study in the U.S. or in other industrial countries to train students to tackle the emerging issues.

One possibility that deserves serious consideration is to establish a global institute that would foster the requisite expertise. I and several others are now investigating the feasibility of such a plan. But even if such an institute is established, a shortage of suitable scientific and engineering skills may still be an important barrier to progress. More solutions are needed, because the benefits of better communication and education are immense for all nations. SA

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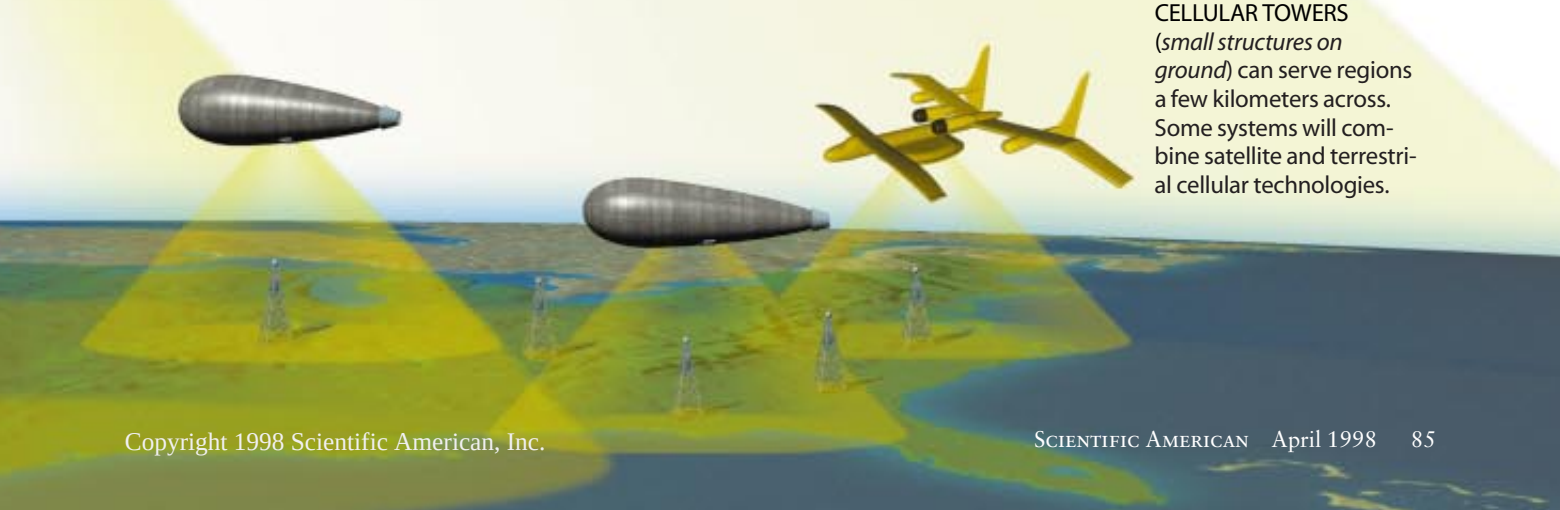


CELLULAR TOWERS (*small structures on ground*) can serve regions a few kilometers across. Some systems will combine satellite and terrestrial cellular technologies.

Terrestrial Wireless Networks

Seamless switching between networks will draw users to wireless data services. A working model is now in operation

by Alex Hills

In the past decade, cellular phones have gone from being a rarity to being commonplace. More than 50 million Americans, one in five, use these devices; one in six uses a wireless pager. In developing countries where standard telephone service is not universally available, cellular is often seen as a better alternative to conventional wired service, because wireless systems can be built quickly. Clearly, if a communications service can be made portable, convenient and affordable, demand is great.

Consumers and businesses have been much slower to adopt wireless systems for data communications than for telephone service. (Paging barely scrapes the surface of wireless's potential.) In the U.S., data communications have been estimated to account for only 3 percent of wireless traffic with mobile terminals, and the proportion is probably even less in most other countries. One explanation for this imbalance between voice and data services is that wireless telephone service has been available to consumers for longer than wireless data—since the early 1980s. And long before that, people in industrial countries were already accustomed to using telephones. Widespread use of computers, in contrast, is fairly recent, and

so applications for wireless data links are much less mature.

Partly as a consequence of this, there is no universal wireless data communications network comparable to the public telephone system. Rather consumers face a range of options, none of which meets all or even most needs. Wireless local-area networks (LANs) can serve within a building. But another network will be needed for service across a metropolitan area, and there will be several choices. A universal standard for all types of wireless data transmission would ensure that any equipped laptop or personal digital assistant could talk to any wireless network. Unfortunately, there is no such standard today.

Although data transmission by radio has not advanced as quickly as some optimists expected a few years ago, I and many other people watching the development of this technology believe it is now at last poised for large-scale adoption. Several observations support this point of view.

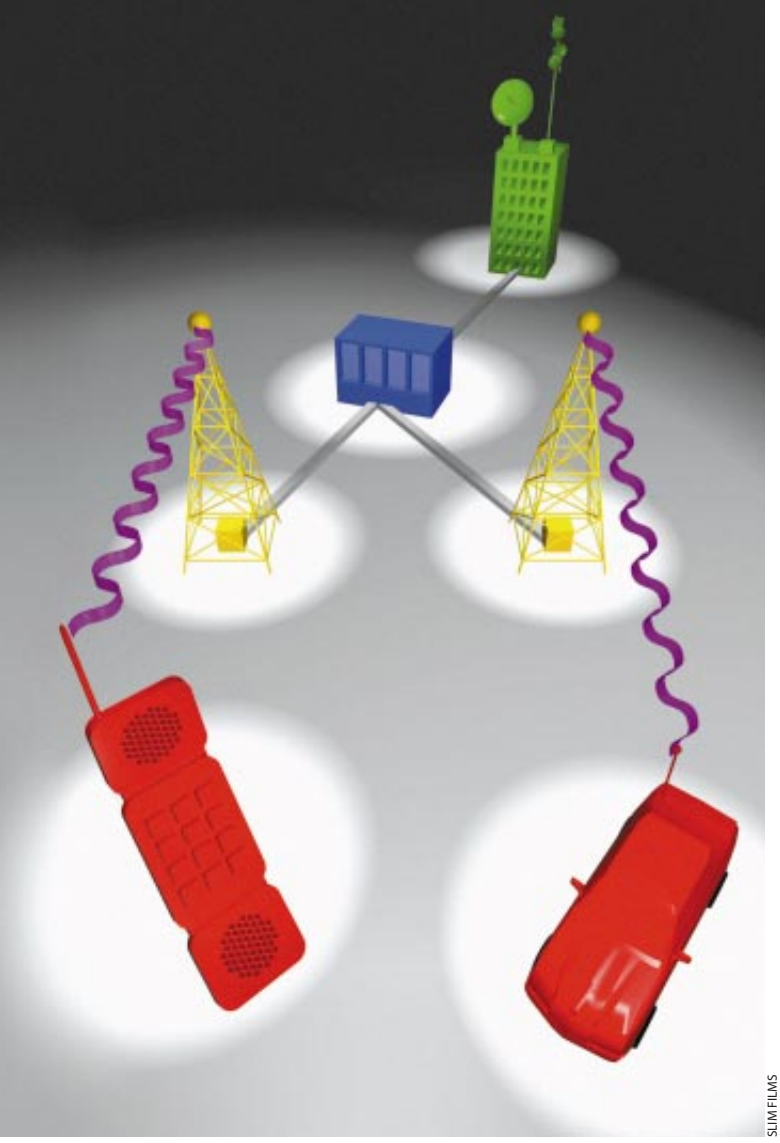
First, cellular voice service became popular once the telephones became small and light enough to slip into a pocket. When cellular telephone service was first introduced in the U.S. in the early 1980s, units were so large they were installed in the trunks of vehicles.

In the past few years, computers have also shrunk, some now fitting in the palm of a hand. Increasingly, these devices are being equipped for wireless service, making possible mobile access to the Internet and other data networks. One such device, the Nokia 9000, became available in Europe in mid-1996 and in the U.S. in early 1998. Weighing only 14 ounces (435 grams), it serves as a combination cellular phone, Internet computer, World Wide Web browser, fax machine, messaging terminal and personal organizer. As such features become more common, widespread wireless connection to the Internet and other data networks will not be far behind.

A second reason for thinking wireless data services will

DUSAN PETRICIC

IN THE NEXT FEW YEARS, convenient, lightweight computers, together with the ubiquitous cellular telephone, will spur a profusion of wireless links.



SLIM FILMS

CELLULAR NETWORK connects users (*red car* and *portable telephone*) via radio links to individual cell sites (*yellow towers*), usually a few kilometers apart. Adjacent cell sites use different frequencies to avoid interference. The cell sites are connected by fiber-optic cables to a mobile telephone switching office (*blue*), which "finds" call recipients and maintains active connections (*purple*). The mobile office is in turn connected to a public telephone service exchange (*green*), through which calls can be routed anywhere in the world by satellite, cable or microwave links.

flourish is that the Institute of Electrical and Electronics Engineers, an influential U.S. professional organization, adopted a standard for wireless LANs in June 1997. Although this standard, called IEEE 802.11, does not cover systems other than LANs, it should encourage manufacturers worldwide to build equipment that can connect with many different wireless LANs, not just with their home systems. The standard provides for operation with two different transmission techniques, but consumers might gravitate to one of them and so establish a de facto standard that will in coming years become very widely used.

A third reason for confidence is that a successful working model of a high-speed, user-friendly, campus-scale wireless data system already exists. Some colleagues and I have built a network that services about half the campus of Carnegie Mellon University and links seamlessly to a slower commercial metropolitan network. Users can move about freely with their mobile computers (usually laptops) and work with them as they would desktop machines. (I describe this system in more detail later.)

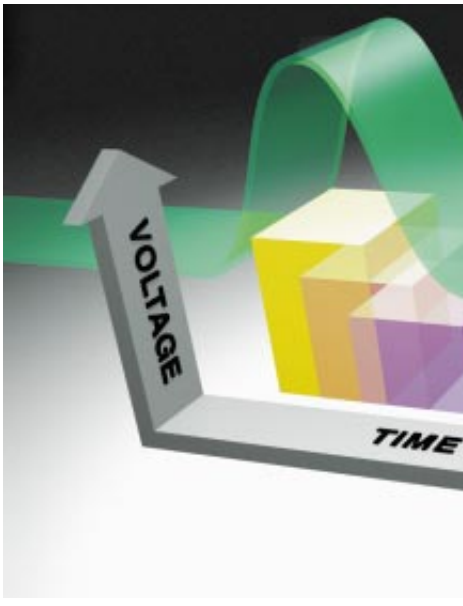
Wireless data services will never eliminate the need for wired connections. Some of the emerging applications for interconnected computers, such as video and multimedia, require extremely high rates of data exchange. Inherent physical limits restrict the maximum speed of wireless links, so the fastest connections will probably always be wired. Further, because wireless networks always require the support of a wired infrastructure as well as the transmitting and receiving equipment, they are normally more expensive than wire-only networks. But where mobility is valued, wireless links will become an increasingly attractive option.

Wireless systems are usually designed around fixed transmitter-receiver base stations that communicate with portable sets as well as with a wired network, often the public telephone system. Wireless voice networks range from cordless telephones to global satellite systems. In between are wireless private branch exchanges, which provide service within a building or campus, and cellular and personal communications service (PCS) systems, which serve a city-size area.

Similarly, data systems range from wireless LANs, which typically operate at about two megabits a second, to satellites. Paging networks and two-way "packet radio" networks, such as Ardis and RAM Mobile Data, provide slower wireless data service, up to 19.2 kilobits a second, over metropolitan or larger areas. (Packet-based networks are so called because they break a data stream into discrete packets that are "addressed" to the intended recipient.) These networks are often utilized by industries whose workers move about frequently.

Keeping the Signals Straight

Perhaps the most difficult challenge for a wireless designer is minimizing interference caused by radio noise and signal reflections. Because the batteries in mobile units have to be lightweight, systems must be designed to allow clear reception from mobile sets transmitting with less than half a watt of power. They must do this even though the radio sig-



MULTIPATH EFFECTS can distort a digital signal through "delay spread." Signals that reflect off buildings and terrain produce data bits that arrive at the receiver later (*purple* and *orange blocks*) than do the bits in a direct signal (*yellow blocks*), because their path from the transmitter is a little longer. The delayed data bits add to the direct-path bits to produce a distorted aggregate signal (*green ribbon*), which the receiver may misinterpret, resulting in a data error.

nals have to pass around obstructions. People want to use their sets wherever they happen to be, and that is often in the canyons between tall city buildings, for example.

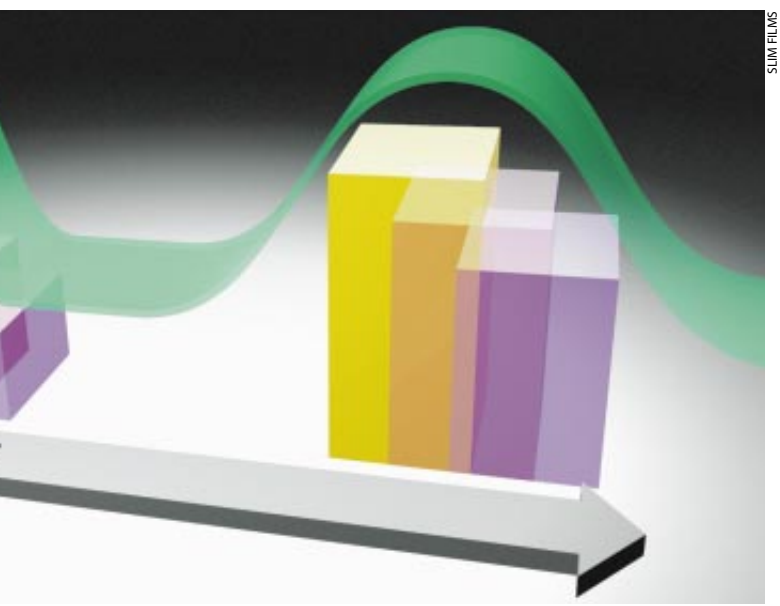
Radio signals reflected by buildings, vehicles and terrain cause a troublesome phenomenon called multipath fading. Depending on the lengths of the different paths, the deflected signals may partially cancel out the main signal. To make matters worse, the effect varies with frequency and changes as the mobile terminal moves around. Multipath fading can sometimes be heard on a car's FM radio: the signal fades in and out rapidly as you drive along.

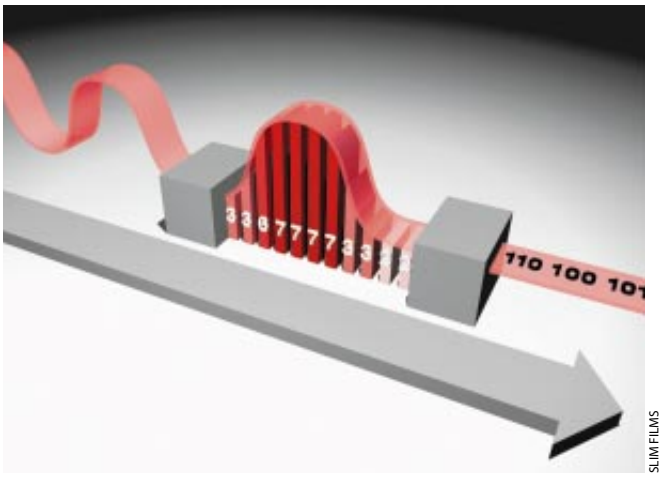
Until a few years ago, cellular telephone systems employed analog technology, transmitting a continually varying signal just like an FM or AM radio station. In more modern digital systems, the analog voice signal is first converted to a stream of binary bits at the transmitter. Typically, the signal is sampled 8,000 times per second, and then each sample is converted to an eight-bit binary number. The resulting sequence of 64,000 bits per second is often "compressed," reducing the number of bits that must be sent. At the receiver the bit stream is converted back to the original voice signal.

A digital receiver can interpret an incoming bit only as a 1 or a 0. The absence of middle ground reduces the chance of a transmission error. Multipath effects, however, can give rise to a characteristic problem called delay spread, in which data are "smeared out" in time. This distortion is often what limits the reliable speed of a wireless link.

Uncorrected bit errors could be disastrous during transmission of a computer program or vital data. But digital transmission offers good opportunities for eliminating errors. Usually some error-correction bits that depend on the identity of nearby data bits are added to a transmitted sequence. The receiver evaluates these special bits, and because it "knows" what rules are in force for generating them and what types of data corruption are most likely, it can often correct discrepancies. This technique rectifies the large majority of bit errors.

Another digital technique to combat noise and multipath fading, commonly employed in wireless LANs, is known as spread spectrum. Often used in combination with error-correction coding, it takes advantage of the tendency of multipath fading and noise to vary with frequency. Spread-spectrum techniques deliberately spread the transmitted signal over a broad range of radio frequencies. The message is then almost certain to get through on at least some of them.





MODERN TELECOMMUNICATIONS SYSTEMS convert a voice signal to a string of binary data bits before sending it long distance. An analog voice signal (*pink ribbon, left*) is measured thousands of times per second, and the result is expressed as a number (*vertical bars, center*). The numbers are then converted to groups of 1s and 0s (*pink ribbon, right*)—which commonly include eight bits each, rather than the three illustrated.

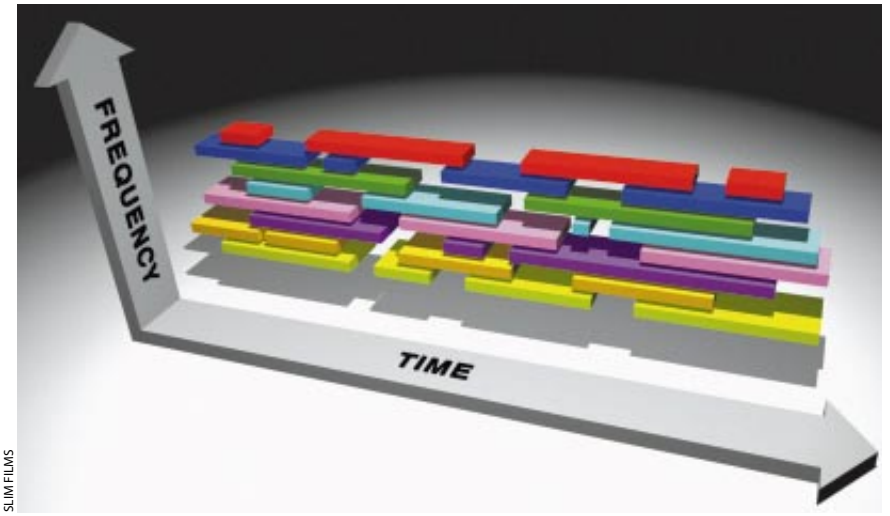
In one spread-spectrum technique, referred to as frequency hopping, the transmitter switches to a new frequency every few milliseconds. The receiver knows the sequence and follows along. Even if some frequencies do not work, others will. With data communications, the receiver can request retransmissions of corrupted data, so that the correct message can be reassembled.

Another spread-spectrum technique is called direct sequence. With this technique, each data bit is converted to a series of several transmitted bits (or chips). The sequence of chips looks random but is known to both transmitter and receiver. So a data bit 1 might be converted to the chip sequence 000100110101111 and a data bit 0 converted to the inverse sequence, 111011001010000, which is readily distinguished from the first one. Because this operation generates more bits per second than it starts with, the resulting signal spreads over a wide range of frequencies when it is transmitted, minimizing interference and multipath fading. The receiver can then reconstruct the original data with high fidelity.

To make an (imperfect) analogy, a person who is hard of hearing might misunderstand me if I say the word "hallelujah." But if I hire a choir to sing the "Hallelujah Chorus" from Handel's *Messiah*, the message will probably get across, because the music repeats the word many times at frequencies from soprano to bass.

A Voice in the Crowd

For the wireless designer, almost as problematic as eliminating errors is allowing as many users as possible to share scarce radio spectrum. Many wireless networks rely, for this purpose, on the principle of frequency reuse. Cellular telephone systems, for example, divide all available radio channels into subsets. Only one subset serves in each cell site. Geographic spacing between cells that have the same subsets



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SIMPLEST TECHNIQUE to allow multiple users (*colors*) to communicate over the airwaves is to assign each user a different frequency, a procedure called frequency division multiple access (FDMA). Receivers are programmed so they know which transmitter operates on each frequency. By tuning to different frequencies—different heights in this illustration—the receiver can separate the signals from various users, much as a listener tunes in to different stations on a radio dial. Individual signals are shown as intermittent, because channels are not in continuous use.

reduces interference and allows the same frequency to be employed many times over in separated regions. PCS and digital cellular systems operate on a similar principle.

The capacity of a cellular network can be increased further by employing "microcells" half a kilometer or so in radius, rather than the typical "macrocells," which are usually more than two kilometers in radius in the city and can be much larger in rural areas. Though not yet in widespread use, microcells offer an attractive way to bring telephone and data service to underserved areas, particularly in densely populated regions of developing countries.

Base stations use several methods to keep separate the signals from different mobile units. Traditionally, this has been done using frequency division multiple access (FDMA), in which each mobile device sends on a different frequency. The base station knows which mobile is on which frequency and sorts out the signals just as one chooses a favorite FM or AM station, by tuning to the right place (a unique frequency) on the dial.

Digital technology makes possible schemes that allow multiple users to share the same frequencies. In time division multiple access (TDMA), favored by AT&T Wireless Services, each mobile set is assigned a repeating time slot a fraction of a millisecond long in which to transmit and to receive. The base station knows which mobiles are transmitting in which time slots; thus, it can keep their signals separate.

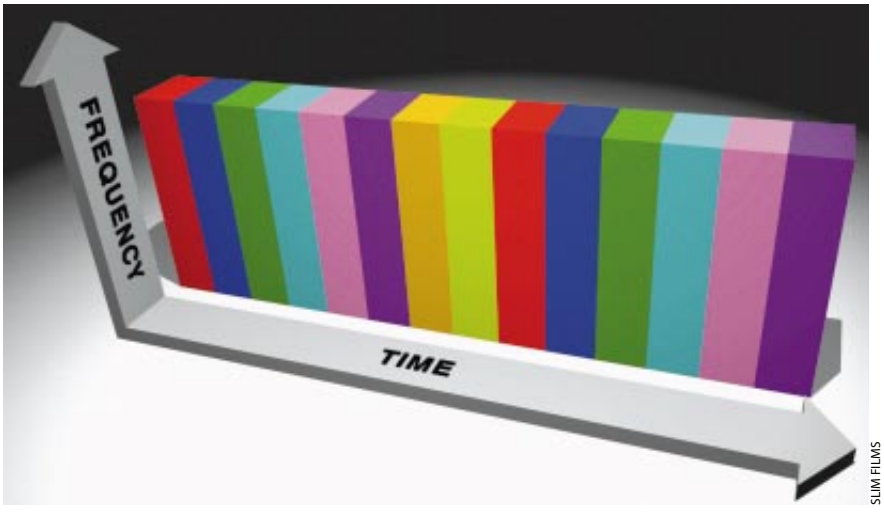
A rival technique pioneered by Qualcomm and used by U S West and Bell Atlantic—code division multiple access (CDMA)—is a little like direct-sequence spread spectrum in its mechanics. But the spreading sequence that replaces each data bit is much longer—more than 100 chips, as opposed to about 10. Moreover, the sequence is unique to the mobile station transmitting or receiving it. This feature allows multiple users to transmit at the same time.

The base station checks the aggregate of the incoming spread-spectrum signals to determine how well it correlates with each mobile unit's spreading sequence and, on this basis, determines which data bits were sent by each mobile. Many cellular and PCS companies have now adopted CDMA, which is typically combined with FDMA. To facilitate the transition to new bands and the new multiple-access techniques, some wireless carriers simultaneously operate both old and new systems and provide their customers with multimode sets.

All these technical innovations expand the potential for wireless communications. In developing countries the most urgent need is usually simply for reliable telephone service. This basic capability makes trade more efficient and enhances overall health and safety by allowing people to summon help quickly. Wireless communications can provide this service with minimal heavy construction and low initial investment: capital requirements, at $200 to $500 a line for a microcellular system, are less than half those of laying a cable network. Once installed, however, wireless systems can be fairly easily adapted for data transmission if demand grows.

Studies that Hung-Yao Yeh, also at Carnegie Mellon, and I have done indicate that wireless manufacturers will, however, need to make more frequency channels available through their equipment to exploit the full potential of wireless systems in the nonindustrial world. We have also concluded

ALTERNATIVE SCHEME for allowing multiple users to share radio spectrum is time division multiple access (TDMA). Each user (*colors*) is assigned a repeating time slot a fraction of a millisecond in length (*vertical bars*). Digital data from each user are compressed in time and sent at high frequency within that user's time slot. The receiver can separate the signals because it knows precisely when to expect each of them.



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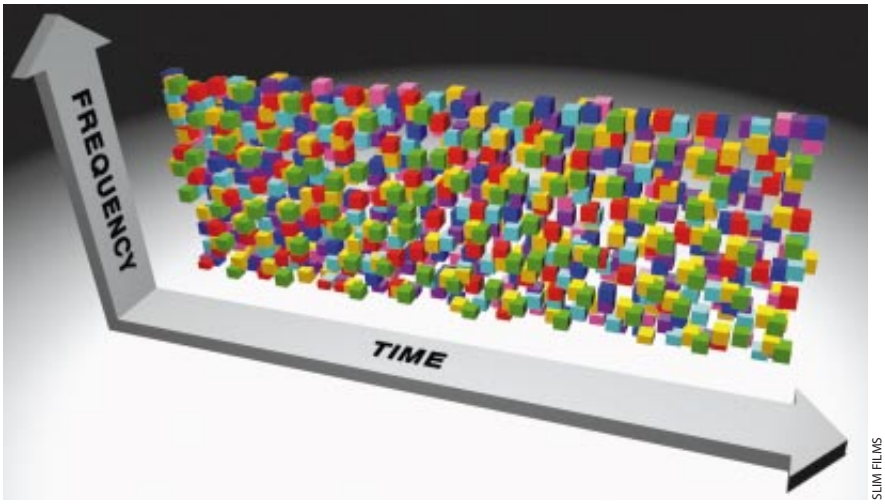
that, given the benefits to be expected from telephone service, national governments should make more radio spectrum available for wireless systems.

A Working Model

One development that would most likely encourage wider use of wireless networks for data communications would be seamless switching between networks. A consumer could then have uninterrupted access to the Internet or other data networks without being concerned about the peculiarities of the underlying wireless system.

At Carnegie Mellon, Bernard J. Bennington, Charles R. Bartel, Peter W. Bronder and I, among others, have created a test bed for seamless switching that includes a wireless LAN and a cellular-based metropolitan-area network. As far as we know, it is the biggest wireless LAN installation anywhere. Operating with equipment made by Lucent Technologies, it now has more than 100 base stations and provides data services at speeds of two megabits a second to about one half of the campus area.



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COMPLEX SCHEME is made possible by coding; code division multiple access (CDMA) allows multiple users (*colors*) to share radio spectrum efficiently without assigning them individual frequencies or time slots. Each user's signal is encoded in such a way that it "spreads" across the radio spectrum—vertically in this illustration. Spreading ensures that individual users' signals do not obliterate one another. The receiver distinguishes the jumble of individual spread signals by their unique codes.

As users move around the site, they can access the Internet and other networks from laptops or other portable machines while specific wireless connections are handled automatically. Popular applications include checking e-mail and accessing the Internet. The mobile computer becomes as effective as a wired desktop machine—but more convenient. We plan to extend service to the entire campus community by 1999.

Off-campus operation is also possible in the greater Pittsburgh area through the Cellular Digital Packet Data (CDPD) service offered by Bell Atlantic Mobile. This service, however, operates at only 19.2 kilobits a second.

Among the challenges we faced was that as a user moves about, his or her machine needs to maintain the best connection for its current location and task. This requirement sometimes means that the connection must be "handed off" from one network to another. My colleague David B. Johnson has written software that allows these handoffs to take place in a way that is not noticeable to the user.

Because many computers work in a client-server model, in which data files must be moved around, access to distributed files also requires special attention in a wireless network. Radio links function at lower speeds than wired links and produce more bit errors. Furthermore, they can fail from time to time. Distributed file systems for use with a wireless network must be designed to tolerate these imperfections. Mahadev Satyanarayanan, also at Carnegie Mellon, has been working on ways to build such file systems.

Another colleague, Daniel P. Siewiorek, builds the mobile computers themselves. He and his associates have assembled a whole series of wearable computers. These devices are convenient for a variety of purposes, ranging from navigation to providing instructions for people constructing aircraft. Many of Siewiorek's wearable computers (and similar ones devised elsewhere) are equipped for wireless, and we hope one day the vision of seamless and ubiquitous wireless connectivity will be achieved using these machines.

We have thus achieved our vision of seamlessness with wireless LANs and metropolitan-area networks. A laptop computer equipped for both can move freely from one coverage area to the other while maintaining a continuous connection. We expect that comparable systems will be installed elsewhere. These prototypes should eventually link up with satellites and other systems to form a user-friendly, international wireless data-transmission network. SA

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Moving beyond Wireless Voice Systems

Cell phones are but one application of wireless communications. The technology also enables accurate position determination and the monitoring of remote sites

by Warren L. Stutzman and Carl B. Dietrich, Jr.

SLIM FILMS

Over the next few decades, the increasingly integrated network of terrestrial and satellite-based radio systems will grow to meet the rising demand for fast, mobile communications. Desire for simple wireless conversations first spurred the construction of this infrastructure, but many other uses are emerging. Primary among these are capabilities for determining the position of a person or object and for monitoring devices at a distance.

Until recently, such applications might have sounded as though they would be helpful only to professional navigators, surveyors or technicians. But wireless technology is so versatile—and the systems so compact and inexpensive because of advances in electronics and computing—that it can benefit even routine aspects of daily life, such as driving across town or protecting a house from burglars.

Years ago the only navigational aids were the stars and systems that relied on gyroscopes. More recently, ground-based radio transmitters, such as those in the LORAN (LOng RAnge Navigation) network, have been used for position determination, but such systems suffer from a limited coverage area, and they do not give altitude information. Today, thanks to advanced satellites, people can determine their three-dimensional locations with amazing accuracy.

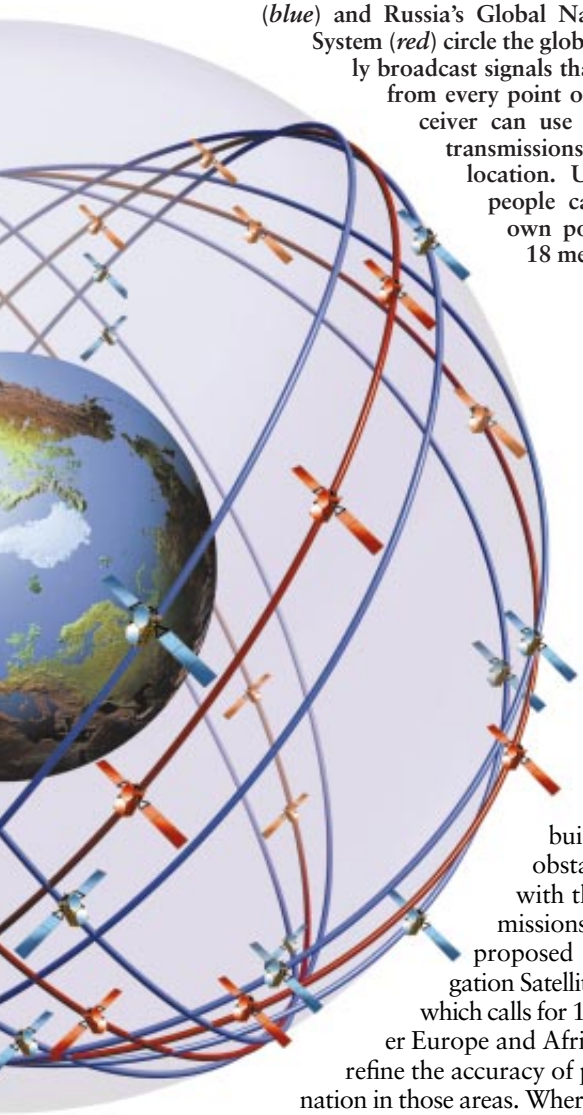
Perhaps most well known is the Global Positioning System (GPS), which consists of 24 satellites that circle the earth at an altitude of more than 20,000 kilometers (12,000 miles) in six orbital planes [see "The Global Positioning System," by Thomas A. Herring; Scientific American, February 1996]. The satellites continuously broadcast signals that can be "heard" from every point on the globe at any instant. By measuring when the timed digital transmissions arrive from at least four of the satellites (which indicates the distance to those satellites), a receiver can apply geometric principles to pinpoint its own location to within 18 meters (20 yards). The accuracy can be improved to less than one meter over a specific area when a transmitter at a known fixed location supplies additional information for fine-tuning the calculations.

The first dramatic use of GPS came during the Persian Gulf War, when troops relied on the technology to find their way in the Iraqi desert. Since then, commercial use has quickly become widespread. A few of the many applications include navigation, mapping and surveying, particularly in remote areas. Perhaps the most notable example is new cars equipped with GPS that can assist motorists in finding specific addresses. The technology is now even available to hikers in the form of handheld devices costing as little as $100.

Because GPS provides three-dimensional position information, airplanes can use the technology to fly more direct courses, rather than following dense traffic lanes between land-based radio beacons. In addition, the extreme accuracy of GPS may one day render elaborate and expensive ground-based tracking radars unnecessary.

GPS has a Russian counterpart: the Global Navigation Satellite System (GLONASS). In 1995 the last of the GLONASS satellites were deployed, completing a full constellation of 24 spacecraft, but some have since become inoperable. Planned launches of at least nine additional satellites are expected by the end of this year.

When GLONASS becomes fully operational, it will significantly increase the performance of receivers that use both the Russian and GPS signals. The improvement will be especially noticeable in "urban canyons," downtown areas where tall



SATELLITES in the U.S.'s Global Positioning System (*blue*) and Russia's Global Navigation Satellite System (*red*) circle the globe and continuously broadcast signals that can be "heard" from every point on the earth. A receiver can use the timed digital transmissions to determine its location. Using GPS alone, people can pinpoint their own positions to within 18 meters (20 yards).

buildings and other obstacles interfere with the satellite transmissions. In addition, the proposed European Navigation Satellite System (ENSS), which calls for 15 satellites to cover Europe and Africa, could further refine the accuracy of position determination in those areas. Whereas other modern satellite and terrestrial services also provide location information, they charge fees, and none are as accurate.

With all their capability, however, systems such as GPS have one major shortcoming—they lack a return link. People with handheld GPS terminals know where they are, but nobody else does. Thus, many applications require the user to have a separate transmitter.

Position can also be determined with remote determination satellite service (RDSS), which is frequently used in conjunction with two-way messaging. RDSS works on the same basic principle as GPS but in reverse: a ground transmitter sends a signal that is then received by two or more satellites in the system. By measuring the different arrival times of the signal (indicating different distances traversed by the transmission), RDSS can use geometry to calculate the location of the terrestrial radio. One current RDSS application, designed for managing a fleet of trucks, can determine the location of a vehicle-based transmitter to within about 0.3 kilometer.

A future service will incorporate a two-way pager. The user would wear a device that receives request signals over a low-earth-orbit (LEO) satellite. The inexpensive pager transmits back through the satellite to a ground station that would then determine the pager's location. Such technology could be used to monitor the whereabouts of Alzheimer's patients or small children.

Ground-based wireless networks can also handle data transfers for various remote-monitoring jobs. New innovative services take advantage of idle cellular voice and control channels to broadcast messages, such as commanding a utility meter equipped with a transmitter to report a reading. Short message bursts are then sent back from the meter on the premises to a service center connected to the cellular grid. Another use is for monitoring vending machines that send a message when product inventories are low, thereby eliminating unnecessary site visits by distributors. A different application could issue an alert with the location of a railcar or truck that has a broken refrigeration unit so that any perishable items might be saved.

Wireless technology has been a blessing for applications in out-of-the-way locations. A petroleum company is now field-testing a cellular-based system for checking the corrosion of gas and oil pipelines in remote areas. Park officials at Death Valley National Monument are using a satellite-based network to monitor the water level of the Devil's Hole pool in Ash Meadow, Nev., the only known home of an endangered species of desert pupfish.

Alarm systems are an especially important application, not only for thwarting burglars but also for avoiding catastrophes. A future device will monitor railroad crossings, issuing a wireless alert when equipment malfunctions. A dispatcher can then immediately send a repair crew to fix the problem.

In some parts of the U.S., enhanced emergency 911 service responds quickly to telephone calls even when the people in distress are unable to give their location. Recently the Federal Communications Commission has required that cellular and personal communications systems also be able to provide a caller's phone number and, starting in October 2001, to locate a user to within 125 meters two thirds of the time. To avoid the cost of outfitting every telephone with a GPS receiver, ground-based position-location technology is currently being developed.

Future wireless systems for position determination and remote monitoring will continue to require ingenuity and creativity from their designers. The applications in use today are merely the beginning. SA

The Authors

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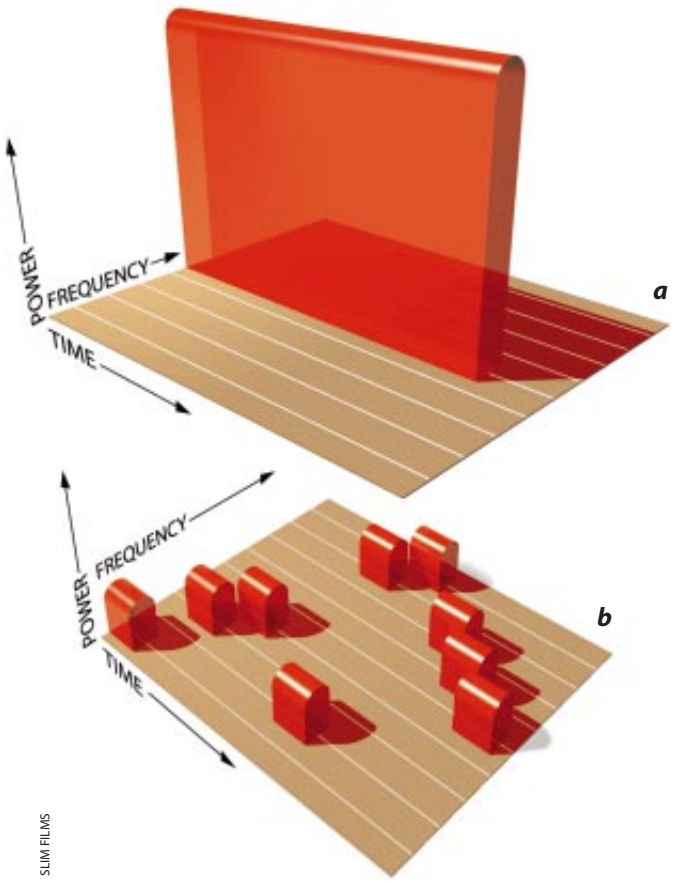
Spread-Spectrum Radio

Dicing information into digital bundles and transmitting them at low power over different frequencies can enable millions of people to send and receive simultaneously

by David R. Hughes and Dewayne Hendricks



SLIM FILMS

Conventional wisdom holds that radio airspace is a valuable—and limited—resource that has to be rationed, like water in a desert. That mind-set comes from traditional transmitters and receivers, whose operation must be restricted to narrow, dedicated slices of the electromagnetic spectrum to minimize interference. Thus, governments have parceled out and licensed radio channels like real estate. In the U.S., the Federal Communications Commission (FCC) has sometimes used a cash-bidding process to allocate precious frequency bands for a variety of purposes, including commercial television and radio broadcasts; military, marine and police transmissions; taxi dispatchers; CB communications; and ham radio operators and cell phone consumers.

Recent advances in digital communications, though, have opened the door to an entirely new model. Transmitters can now deploy so-called spread-spectrum techniques to share channels without running afoul of one another. Information can be diced into tiny electronic bundles of 1s and 0s and then transmitted over radio waves, with each packet sent over different channels, or frequencies, at low power. New studies have shown that, theoretically, millions of radio transmitters within the same metropolitan area can successfully operate in the same frequency band while transferring hundreds of megabits of data per second.

Such shared use of the spectrum challenges customary practices. In the past, when allocating narrow frequency bands for exclusive commercial purposes, the government has granted licenses to firms, such as those offering cell phone and personal communications services (PCS). Those licensees charge consumers for services, just as conventional telephone companies bill their customers. In the new economic model, the middleman becomes unnecessary: consumers can communicate with one another directly and at no charge, even when they are kilometers apart and when myriad other people are using the same radio channels. This fundamental change has led to revisions in the regulatory policies of the U.S. and foreign governments, which have now designated certain frequency bands for free, unlicensed use of spread-spectrum radios by the public.

Enough Spectrum for Everyone

What is the basis of this technology revolution? Traditional radios work by broadcasting information over a single, narrow channel with high power. By operating in as skinny a sliver of the electromagnetic spectrum as possible, a transmitter thus makes room for other devices to operate in neighboring frequencies without interference. But radio engineers now know that the opposite way of transmitting data—by smearing, or spreading, information across a wider chunk of the spectrum at low power—is more efficient.

The concept is counterintuitive: instead of carving a pie into a finite number of small slices, the technology allows a larger sharing of the whole pie by permitting an all but unlimited number of individuals to take barely noticeable bites. Although spread-spectrum radios use more bandwidth than

RADIO SIGNALS (*shown in red*) have typically been transmitted continuously over a single, narrow frequency band at high power (*a*). Engineers now know that a more efficient use of the radio spectrum is to spread a signal over different channels at low power, as shown in a technique called frequency hopping (*b*).

The Improbable Inventors of Frequency-Hopping Radio

She was gorgeous, glamorous and talented. And she had a mind for technology. In 1941 actress Hedy Lamarr, along with the avant-garde composer and musician George Antheil, filed for a patent to cover their "Secret Communication System," a device designed to help the U.S. military guide torpedoes by radio signals that would continually jump from one frequency to another, thus making enemy interception and jamming difficult.

Born Hedwig Maria Eva Kiesler in Vienna, Austria, Lamarr may have gotten the idea of "frequency hopping" while she was married to Fritz Mandl, an armament manufacturer who sold munitions to Adolf Hitler. Through a marriage arranged by her parents, Lamarr was Mandl's trophy wife, and she accompanied him to the many business dinners and meetings, where, unbeknownst to the participants, she silently learned about Axis war technology. After four years with Mandl, Lamarr, a staunch anti-Nazi, fled to London, where MGM's Louis B. Mayer "discovered" her and convinced her to move to the U.S.

In Hollywood she met Antheil, who helped her figure out a way to synchronize the frequency hopping between the radio transmitter and receiver. Their invention, which they gave to the U.S. government for free, called for two paper rolls, similar to those used in player pianos, punched with an identical pattern of random holes. One of the rolls would control the transmitter on the submarine while the other would be launched with the receiver on the torpedo. Though ingenious, the device was deemed too cumbersome for use in World War II.

Still, the seminal idea of frequency hopping lingered. By the late 1950s U.S. Navy contractors were able to take advantage of early computer processors for controlling and synchronizing the hopping sequence. Since then, the U.S. military has deployed more sophisticated techniques with ever faster processors in costly, classified devices, including satellite communications systems. And today the technology has become widespread in cell phones and in personal communications services (PCS), among other civilian applications. —*D.R.H.*

KOBAL COLLECTION; U.S. PATENT OFFICE (*inset*)

HEDY LAMARR, the Hollywood actress, was the co-recipient of a patent (*inset*) for basic technology that is now widely used in cell phones and personal communications services (PCS).

necessary, by doing so the devices avoid interference because the transmissions are at such minimal power, with only spurts of data at any one frequency. In fact, the emitted signals are so weak that they might be almost imperceptible above background noise. This feature results in an added benefit of spread spectrum: other radios have great difficulty eavesdropping on the transmission. In practice, only the intended receiver may even know that a transmission is taking place.

The covert nature of spread spectrum was initially its main attraction. During World War II, the U.S. military became interested in an intriguing device that actress Hedy Lamarr had co-patented [*see box above*]. The concept was simple enough—instead of broadcasting information over a single channel, where the enemy might stumble upon the transmission, the device switched channels continually, broadcasting a little bit of information here and a little bit there, in accordance with a secret code known only to the transmitter and the intended receiver. This repeated hopping of frequencies would make it extremely difficult for the enemy to pluck the entire transmission from the surrounding noise. But Lamarr's device was deemed impractical because it relied on an unwieldy mechanical contraption to perform the frequency hopping.

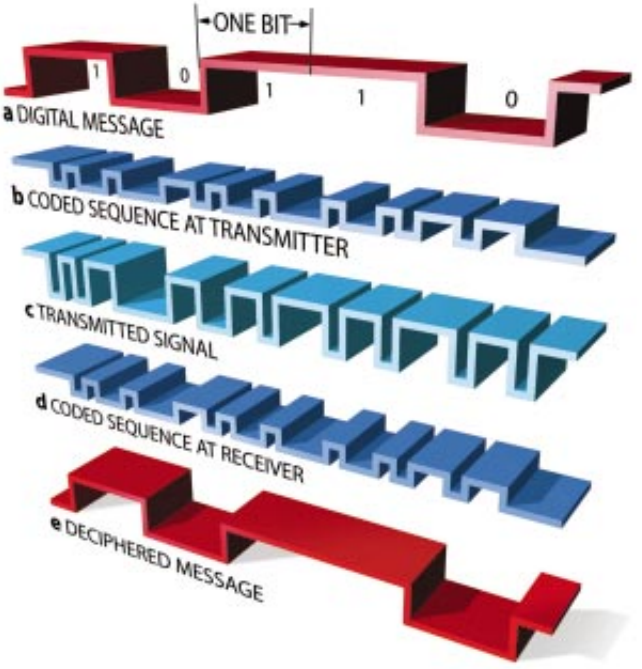
Subsequent advances in electronic circuitry, however, have made spread spectrum feasible. Semiconductor chips, crammed with thousands of transistors, can broadcast digitized packets of data in a seemingly random pattern over many channels. The receiver, designed to hear the signals in accordance with the precise and proprietary sequence of the sending radio, is able to pull the fragmented information in the right order from the different frequencies. In addition, when the receiver encounters missing or corrupted packets, it can signal the transmitting radio to resend those packets. Also, a technique called forward error correction can be used to improve the chances that the data are received correctly the first time.

Electronic technologies have enabled another method of spectrum spreading: direct sequence, in which the transmitted information is mixed with a coded signal that, to an outside listener, sounds like noise. In this alternative to frequency hopping, each bit of data is sent at several different frequencies simultaneously, with both the transmitter and receiver synchronized, of course, to the same coded sequence.

More recently, further advances in chip technology have produced digital signal processors that can crunch data at

high speed, use little power and are relatively inexpensive. The improved hardware allows more sophisticated spread-spectrum techniques, including hybrid ones that leverage the best features of frequency hopping and direct sequence, as well as other ways to code data. The new methods are particularly resistant to jamming, noise and multipath—a frequency-dependent effect in which a signal reflects off buildings, the earth and different atmospheric layers, introducing delays in the transmission that can confuse the receiver.

In 1985 the FCC finally permitted the unlicensed use of spread-spectrum radios by the public, albeit with several restrictions. The radios must operate under FCC regulations in what are called the unlicensed industrial, scientific, medical (ISM) bands. More important, the radios are forbidden to operate at greater than one watt, and the transmissions must be spread a minimum amount across the assigned spectrum.



SLIM FILMS

DIRECT SEQUENCE is another technique for spreading a signal at low power over the radio spectrum. A digital message of "10110" (*a*) is mixed with a coded sequence (*b*). The resulting signal (*c*) is then transmitted so that each bit of the original data is sent at several different frequencies. This redundancy increases the chances that the message will get through even in crowded metropolitan areas, where interference is a problem. The receiver then uses the same coded sequence (*d*) to decipher the transmission and obtain the original digital message (*e*).

These restraints notwithstanding, the 1985 (and later) FCC rules have already spawned the development, manufacture and marketing of a wide range of "no license required" products. Because mass manufacturing has yet to occur, spread-spectrum products for data transmission from the 60 or so current vendors carry premium price tags that have limited the technology mainly to large organizations, such as businesses, schools and libraries. Today a radio that can handle near-Ethernet traffic (10 megabits per second, suitable for high-speed computer communications) up to a distance of about 40 kilometers (25 miles) costs $11,000. Devices with lower capability—operation at T1 speeds (1.5 megabits per second) to a range of 25 kilometers or so—cost $1,500. For very short ranges, such as for communications within a building, wireless local-area network (LAN) cards for personal computers are priced as low as $250.

There is every reason to believe these prices will drop as manufacturing volumes increase to meet the growing market demand for higher bandwidth and secure wireless connections from PCs to the Internet. In the future, people may, for example, routinely rely on wireless transmission to reach a central system that would then connect to a traditional network of ground-based lines. We predict that reliable, secure data radios operating at T1 or higher speeds to a range of more than 30 kilometers will soon cost less than $500 each.

Where is this technology headed? Transmitters and receivers are becoming fully digital. That trend, combined with the rapid development of cell-based wireless systems, will open up a wide range of services based on spread spectrum. The services will rely on intelligent networks containing "smart" transceivers and switches as basic components. Such devices would, for instance, know which of the varied spread-spectrum techniques to use in a given situation to ensure that the information will be transmitted without error. These new networks will increasingly involve a diverse mixture of links and switches, some ground-based, that are owned by different entities.

The Internet today represents the best example of the self-regulating mechanism that will be necessary in the new radio environment. The creation of a similar, decentralized structure for the optimal sharing of the radio spectrum will require a substantial effort by a combination of telecommunications experts and entrepreneurs working with the various regulatory bodies around the world. We believe the deployment and growth of such a system is achievable through increasingly "smart" electronics, and we envision a self-governing set of protocols that are built into these intelligent devices. As advanced radios are deployed, society must tackle the crucial issue of incorporating both positive and negative incentives within the network infrastructure itself to make the best use of a shared common resource—the radio spectrum. SA

The Authors

DAVID R. HUGHES and DEWAYNE HENDRICKS recently helped to install spread-spectrum radios in Ulaanbaatar to connect eight scientific and educational institutions in that Mongolian city. Hughes is a principal investigator for the National Science Foundation Wireless Field Tests. Hendricks is CEO of Warp Speed Imagineering in Fremont, Calif.

Further Reading

SPREAD SPECTRUM COMMUNICATIONS HANDBOOK. Second revised edition. M. K. Simon, J. K. Omura, R. A. Scholtz and B. K. Levitt. McGraw-Hill, 1994.

A CHANNEL ACCESS SCHEME FOR LARGE DENSE PACKET RADIO NETWORKS in *Proceedings of ACM SIGCOMM '96*. Tim J. Shepard. ACM, 1996.

The following Web sites contain helpful tutorials and other background information: http://olt.et.tudelft.nl/~glas/ssc/techn/techniques.html; http://www.eff.org/pub/GII_NII/Wireless_cellular_radio/false_scarcity_baran_cngn94.transcript; and http://wireless.oldcolo.com

by Shawn Carlson

Making Experiments out of Thin Air

Every creature on the earth lives under the warm, nurturing and protective blanket formed by the atmosphere. Yet all this air does more than trap the sun's heat and carry gases between plants and animals. It also presses down on our world with powerful force. At sea level, a single sheet of writing paper, when laid flat, sustains 6,111 newtons—about 1,400 pounds.

One might imagine that such a burden would stress living creatures enormously. But far from hurting organisms, the weight of the atmosphere proves absolutely essential for life. Liquid water could not exist on the earth were not atmospheric pressure sufficient to keep it from boiling rapidly away. And many vital biological processes, cellular respiration chief among them, fail if the air pressure falls too low.

Of course, atmospheric pressure decreases with altitude, and the earth's surface pokes up quite high in many places. Remarkably, humans can adapt to almost any elevation on the planet. Few other species can thrive both along the coast and between the peaks of the Himalayas, nearly six kilometers (3.7 miles) above sea level. By exercising some smarts, humans can keep warm and fed even in cold, harsh environments. But our adaptability may also be an evolutionary vestige: when our wandering ancestors crossed over mountain ranges, they had to adjust to the lower air pressure or die along the way. Can plants or other organisms that do not share our nomadic roots also adjust?

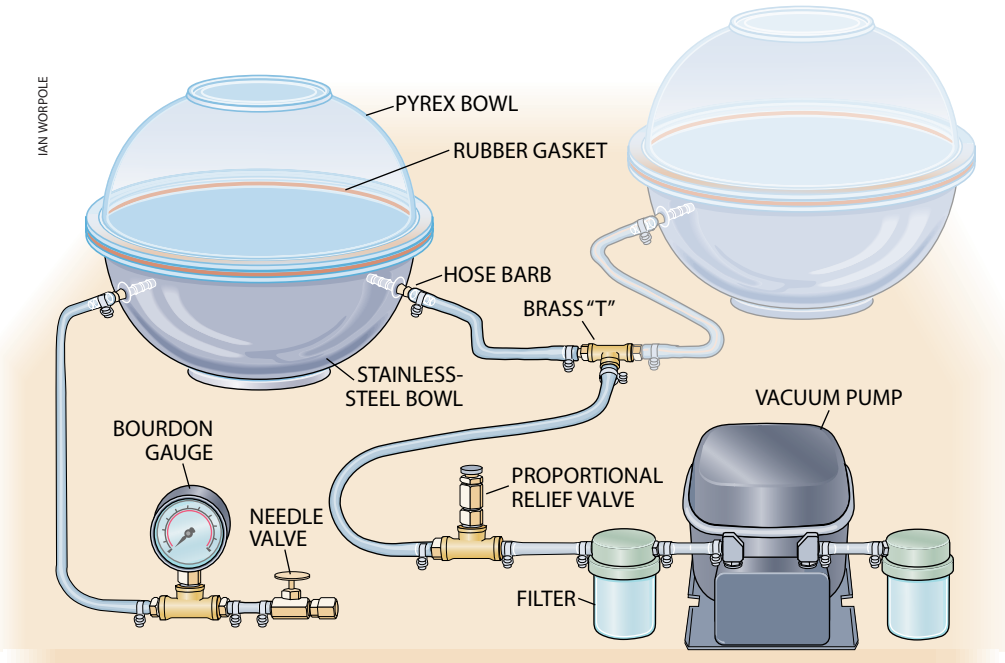
Amateurs can probe such mysteries of physiology thanks to Stephen P. Hansen, an innovative vacuum specialist in Amherst, N.H. Many science enthusiasts already know Hansen from the *Bell Jar,* his quarterly journal devoted to amateur experimentation with vacuum techniques. Inspired by the September 1965 installment of this column, which described a high-altitude chamber fashioned from a 30-gallon (113-liter) steel drum, Hansen developed a small and inexpensive version of this apparatus. Although technical complexities and ethical concerns would make it problematic to place one's pet hamster inside, this chamber is ideal for amateur investigations of less complicated organisms. Bacteria, insects or small plants, for example, serve as ideal test subjects.

Hansen's device consists of a stainless-steel mixing bowl and a Pyrex bowl. The Pyrex bowl makes a perfect see-through top for the chamber, and the stainless-steel bottom allows easy installation of vacuum ports and electronic sensors.

You form the airtight seal by pressing the bowls lip to lip into a gasket cut from a thin sheet of rubber. Hansen secured his 12-inch (30.5-centimeter) metal bowl from United States Plastics Corporation (800-537-9724 or 419-228-2242; catalogue number 84104). He bought a sheet of rubber from his local hardware store. You should be able to purchase a matching Pyrex bowl from just about any housewares merchant. Drill two holes in opposite sides of the steel bowl and epoxy 1/4-inch (five-millimeter) brass hose barbs into each. You can obtain such fittings from a well-stocked hardware or plumbing supplier.

Although just about any mechanical vacuum pump will effectively draw down the internal pressure, the high price of most models will also draw down your budget. But if you restrict your research to terrestrial conditions—pressures no less than those at the top of Mount Everest—you can get by with an inexpensive type. Hansen used a surplus dry-vane vacuum pump, which he procured from C&H Sales in Pasadena, Calif. (800-325-9465 or 626-796-2628; catalogue number PC9703), for $42.50. Regular vinyl tubing, affixed with steel hose clamps, makes fine vacuum line.

For experiments restricted to simulated altitudes no greater than 4,600 meters (about 15,000 feet), a pocket altimeter is the best choice to monitor the pressure. Edmund Scientific in Barrington, N.J. (800-728-6999 or 609-547-3488), sells one with a zero adjust for $34.95 (catalogue number 34,544). Just place the altimeter inside the chamber and read the equivalent elevation by looking at the scale through the Pyrex bowl. To mimic higher altitudes, you



IAN WORPOLE

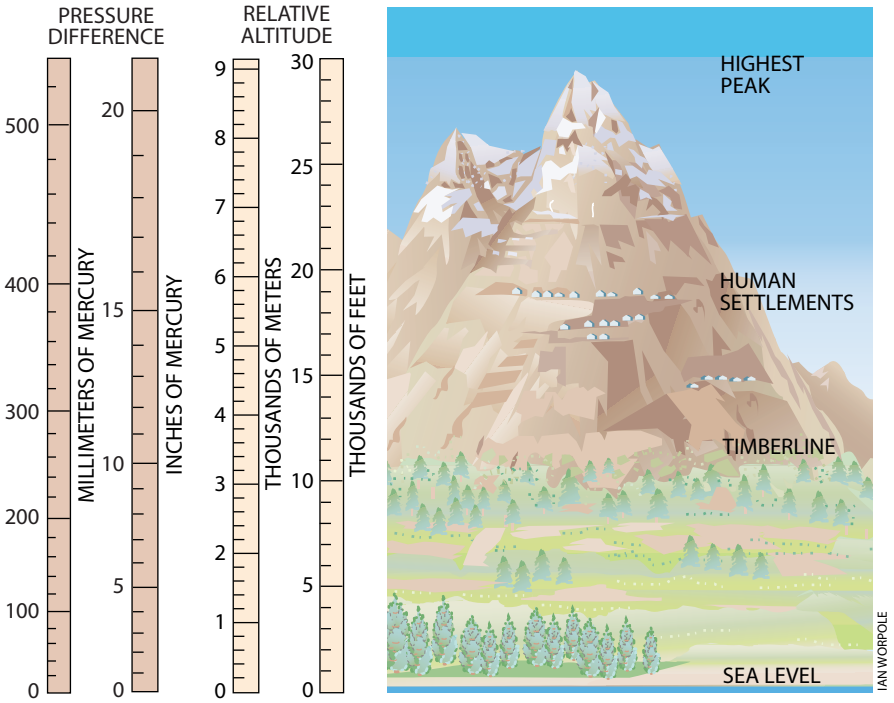
MIXING BOWLS OF GLASS AND METAL
attached to a vacuum pump make a spherical altitude chamber.

will need to hook up a vacuum pressure gauge; a Bourdon gauge would do. These units, which you can buy at an auto supply store, read in either millimeters or inches of mercury below ambient pressure. The illustration below shows the corresponding altitude.

Probably the most challenging problem you will encounter is regulating the pressure in your chamber. You could install an electronic sensor and control circuit that triggers the vacuum pump whenever the pressure climbs above a chosen set point. But such equipment is difficult to build, and commercial systems cost hundreds of dollars.

Fortunately, cheaper solutions exist. Hansen found that an $8 proportional relief valve works quite well. His choice is model number VR25, manufactured by Control Devices in St. Louis, Mo. (You can purchase one from W. W. Grainger: 773-586-0244; catalogue number 5Z-763.) The vacuum pump pulls air from the chamber, and the valve allows a weak flow of air to pass in from the outside. This adjustable leak prevents the full force of the vacuum pump from acting on the chamber, allowing the internal pressure to stay higher than it would otherwise. The needle valve allows a weak but constant stream of air to flush out any gases produced by living things inside.

Although it is a bit tricky to adjust the proportional relief valve to a particular pressure, once properly set, the chamber will maintain that level reliably. Still, you will have to keep your vacuum pump running all the while. Note that if the outside air pressure rises or falls, so will the pressure inside your chamber.



SIMULATED ALTITUDE OF CHAMBER
above its actual height is determined from the readings of a vacuum gauge.

Certain biological experiments might require you to vary the temperature and light levels. Try putting the chamber on a windowsill, resting the stainless-steel bowl on a heating pad or submerging it in a bucket of ice water. For more precise adjustments, you may place the chamber under a full-spectrum light controlled by a timer and run a heat source from a thermostat. After struggling with homemade thermostats for years, I recently gave in and purchased a $165 unit from Omega Engineering in Stamford, Conn. (800-826-6342 or 203-359-1660; catalogue number CN8590).

If you go this route, you will also need to purchase 25 feet of type T thermocouple wire (Omega's catalogue number is PR-T-24SLE-25). It consists of two wires made from copper and constantan laid side by side. Cut a length of this double wire so that it is long enough to reach from the controller to the inside of your chamber. From one end, strip two or three centimeters (about an inch) from the tips of both wires and twist the exposed leads together. Once intertwined, a tiny voltage develops that is related to the temperature of the coupled wires. Attach the other ends of the wires to the controller.

You will have to feed the thermocouple wires (and any other electrical cables required for your particular experiment) into your chamber without creating leaks. Another hose barb serves well here. Pass the wires through the barb and then secure them in place by filling the tube with epoxy. After the epoxy sets, install this assembly through the stainless-steel bowl just as you mounted the others earlier.

The controller I used can deliver a maximum of five amperes at 120 volts AC—that is, it is limited to a power output of 600 watts. Omega sells many suitable heaters, but you could probably coat the sides of the steel bowl with a sprayable foam insulation and rest the exposed metal bottom on a small hot plate, such as the kind designed to keep your morning coffee warm in the cup.

Finally, you may find it useful to build two identical chambers and tie them together with a T-shaped joint. This duplication will allow you to run two experiments simultaneously, using one chamber for tests and the other as the control. At times, you may want to keep the second chamber at full atmospheric pressure. But should you wish to vary light level or temperature only, this arrangement will let you maintain the same low pressure in both chambers. Try growing tropical plants at alpine altitudes or test whether a fly tires more quickly in thin air. With a little imagination, you can continue such rarefied pursuits indefinitely. SA

Amateurs interested in vacuum-related experiments can subscribe to the Bell Jar. *Send a check or money order for $20 to the* Bell Jar, *35 Windsor Drive, Amherst, NH 03031. For more about this and other amateur science projects, visit the Forum section of the Society for Amateur Scientists's World Wide Web site at www.thesphere.com/SAS/. You can also write the society at 4735 Clairemont Square, Suite 179, San Diego, CA 92117 or call (619) 239-8807.*

MATHEMATICAL RECREATIONS

by Ian Stewart

Repealing the Law of Averages

Suppose I keep tossing a fair coin—one for which heads and tails are equally likely, each having probability $1/2$—and maintain a running count of how many times each turns up. If at some stage I have tossed 100 more heads than tails, is there any tendency for tails to "catch up" in future tosses? Some people talk of a law of averages, based on the intuition that tosses of a fair coin ought to even out ultimately. Others assert that coins have no "memory"—so the probability of heads or tails always remains $1/2$—and deduce that there is no tendency whatsoever for the numbers to even out.

The same issues arise in diverse circumstances. If airplane crashes happen on average once every four months and three months have passed without one, should you expect one soon?

In all such cases, the answer is "no." The random processes involved—or, more accurately, the standard mathematical models of those processes—do indeed have no memory.

Still, much depends on what you mean by catching up. A long run of heads does not affect the probability of getting tails later on. Even so, after a run of, say, 100 more heads than tails, the probability that at some stage the numbers will even up again is 1. A probability of 1 normally means certain, and a probability of 0 means impossible. (In this case, we are working with a potentially infinite list of tosses, so mathematicians prefer to say "almost certain" and "almost impossible.")

I hasten to add that there is also a sense in which coin tosses do not have a tendency to even out in the long run. For example, after a run of 100 more heads than tails, the probability that the cumulative number of heads gets at least a million ahead of tails is also 1.

To analyze these apparent contradictions, take a closer look at coin tossing. I flipped one 20 times, getting the result TTTTHTHHHHHHTTTHTTTH, with 11 Ts and 9 Hs. According to the law of large numbers, the frequencies with which events occur should, in the long run, be very close to their probabilities. Here the frequencies are $^{11}/_{20} = 0.55$ and $^{9}/_{20} = 0.45$—close to 0.50 but not equal to it. Perhaps my sequence doesn't look random enough. You'd probably be happier with something like HTHHTTHTTHTHHTHTHHTT, with frequencies $^{10}/_{20} = 0.50$ for H or T. As well as getting the numbers spot on, the second sequence looks more random. But it isn't.

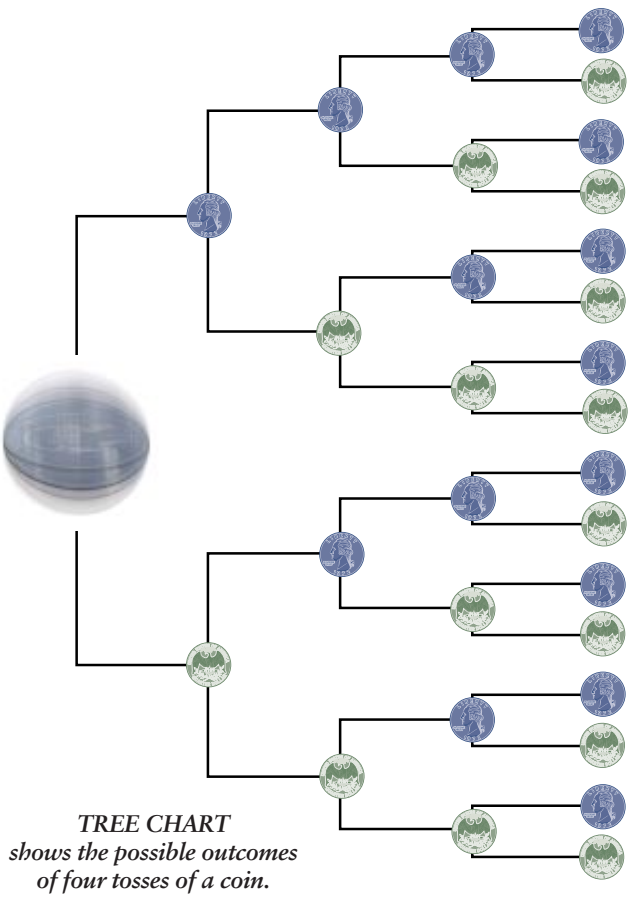
The first sequence looks nonrandom because of long strings of the same event, such as TTTT and HHHHHH, which the second sequence lacks. But our intuition is misleading: random sequences often show patterns and clumps. Don't be surprised by these. (Unless the coin goes HHHHHHHHHH-HHH… for a long time, in which case the shrewd guess is that it is double-headed.)

Suppose you toss four coins in a row. The illustration at the right summarizes the possible results. The first toss is either H or T (each with probability $1/2$). Whichever of these happens, the second toss is also either H or T. And so on. So for four tosses we get a "tree" with 16 possible routes through it. According to probability theory, each route has probability $1/2 \times 1/2 \times 1/2 \times 1/2 = 1/16$. This result is plausible, because there are 16 routes, and each should be equally likely.

Notice that TTTT has probability $1/16$, and HTHH, say, also has probability $1/16$. So although HTHH looks more random than TTTT, they have the same probability.

Again, if you toss a coin four times, on average you get exactly two heads. Does this mean that two heads and two tails are highly probable? No. In the illustration below, there are 16 different sequences of Hs and Ts, and a total of six of them contain two heads: HHTT, HTHT, HTTH, THHT, THTH, TTHH. So the probability of exactly two heads is $^{6}/_{16} = 0.375$. This is less than the probability of not getting exactly two heads, which is 0.625. With longer sequences, this effect becomes even more extreme.

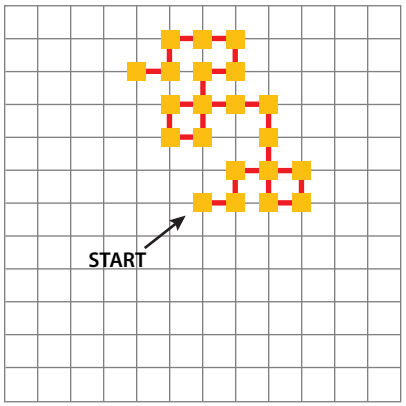
Investigations of this kind make it clear that there is no law of averages, in the sense that the future probabilities of events are not changed in any way by what happened in the past. Still, there is an interesting sense in which things do tend to balance out in the long run. Plot



TREE CHART shows the possible outcomes of four tosses of a coin.

LAURIE GRACE

LAURIE GRACE



LAURIE GRACE

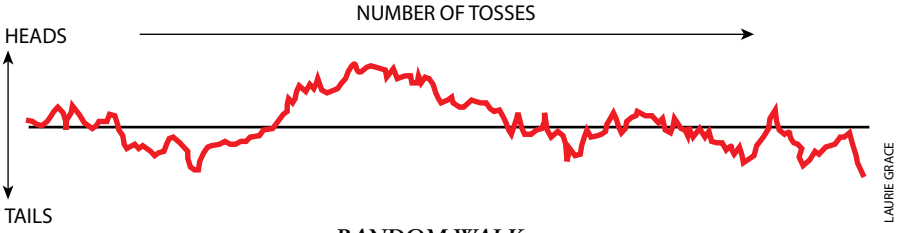
TWO-DIMENSIONAL
random walk

the excess of the number of Hs over the number of Ts by drawing a graph of the difference at each toss. You can think of this construction as a curve that moves one step upward for each H and one down for each T. Such diagrams, in which the successive steps are randomly chosen, are known as random walks.

The graph on the next page shows a typical random walk corresponding to 10,000 tosses. This kind of wildly unbalanced behavior is entirely normal. In fact, the probability that in 10,000 tosses one side leads for 9,930 tosses and the other for only 70 is about 1 in 10.

Random walk theory also tells us that the probability that the balance never returns to 0 (that is, that H stays in the lead forever) is 0. This is the sense in which the law of averages is true—but it carries no implications about improving your chances of winning if you're betting on whether H or T turns up. You don't know how long the long run is going to be—except that it is most likely to be very long indeed.

Suppose you toss a coin 100 times and get 55 Hs and 45 Ts—an imbalance of 10 in favor of Hs. Then random walk theory says that if you wait long enough, the balance will (with probability 1) correct itself. Isn't that the law of averages? No, not as that law is normally interpreted. If you choose a length in advance—say, a million tosses—then random walk theory says that those million tosses are unaffected by the imbalance. Moreover, if you made huge numbers of experiments with a million extra tosses, then on average you would get 500,055 Hs and 500,045 Ts in the combined sequence of 1,000,100 throws. On average, imbalances persist. Notice, however, that the frequency of H changes from $^{55}/_{100}$ = 0.55 to $^{500,055}/_{1,000,100}$ =



LAURIE GRACE

RANDOM WALK,
in which "heads" corresponds to a step up and "tails" to a step down, shows that the numbers of heads and tails rarely even out.

0.500005. The law of averages asserts itself not by removing imbalances but by swamping them. (For more information, see *An Introduction to Probability Theory and Its Applications,* Vol. 1, second edition, by William Feller, Wiley, New York, 1957.)

Instead of tossing a coin, imagine I roll a die and count how many times each face, 1 to 6, turns up. Assume each face has probability $^1/_6$, equally likely. When I start, the cumulative numbers of occurrences of each face are equal—all 0. Typically, after a few throws, those numbers start to differ. Indeed, it takes at least six throws before there is any chance of them evening out again, at one of each. What is the probability that however long I keep throwing the die, the six numbers at some stage even out again? I don't know the exact value, so here's a gap for Feedback to fill. But I'll show you that it's certainly not 1.

For the die problem, we need to generalize the random walk to more dimensions. The simplest random walk in the plane, for example, takes place on the vertices of an infinite square grid. A point starts at the origin and successively moves one step either north, south, east or west, with probability $^1/_4$ for each. The graph on the preceding page shows a typical path. A three-dimensional random walk, on a cubic grid in space, is very similar, but now there are six directions—north, south, east, west, up, down—each with probability $^1/_6$.

It can again be shown that for a two-dimensional random walk, the probability that the path eventually returns to the origin is 1. Stanislaw M. Ulam (formerly of Los Alamos National Laboratory and best known for his co-invention of the hydrogen bomb) proved that in three dimensions, the probability of eventually returning to the origin is about 0.35. (So if you get lost in a desert and wander around at random, you'll eventually get to the oasis; however, if you're lost in space, there is only a chance of one in three that you'll wander back to Earth.)

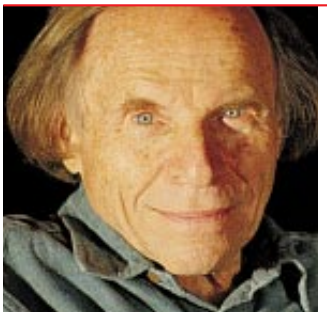
Suppose we label the six directions of a three-dimensional random walk according to the faces of a die—north = 1, south = 2, east = 3, west = 4, up = 5 and down = 6. Repeatedly roll the die and move through the grid in the specified direction. In this case, "return to the origin" means the same number of 1s as 2s, the same number of 3s as 4s, and the same number of 5s as 6s. The probability that this eventually happens is therefore 0.35. So the stronger condition that all six numbers occur equally often must have probability less than 0.35.

Even the simplest one-dimensional random walk has many other counterintuitive features. Suppose you choose a large number of tosses in advance—say, a million—and watch whether heads or tails is in the lead. What proportion of the time, on average, would you expect heads to take the lead? The natural guess is $^1/_2$. Actually, this proportion is the least likely. The most likely proportions are the extremes: heads stays in front the whole time or none of the time! SA

FEEDBACK

In "Glass Klein Bottles" [March], I asked you to cut a Klein bottle along a different curve to get just one Möbius band. Here is Alan Bennett's answer—written in glass:

ALAN BENNETT



WONDERS

by Philip Morrison

The Timekeeping ELF

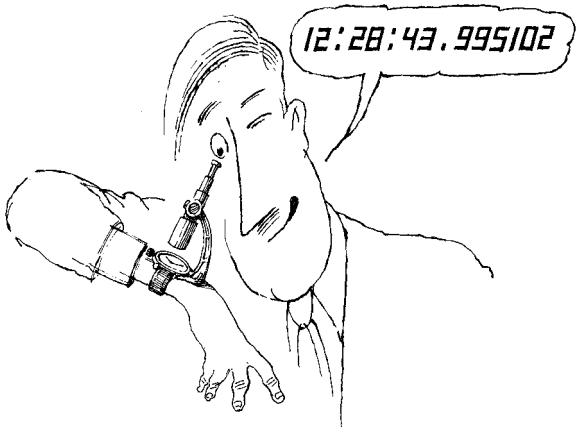
The fleeting second paces the most intimate of human rhythms, the quick heartbeat.

Since the rise of the medieval city, the mechanical clock and its progeny have increasingly ordered our comings and goings. The year marks the sun's apparent path and the seasons it rules, the month makes a rather mannered bow to the moon's real form and presence, and the day carries the certainties of darkness and light. The fleeting second, without our quite realizing it, paces the most intimate of human rhythms, the quick heartbeat. Neither the hour nor the minute hand has much to do with any natural phenomenon.

Years ago a noontime ball would drop down some flagpole at every busy harbor so that ships' navigators might check their timekeeping. That performance was a marine necessity, for 10 seconds of clock error carried a penalty of three miles (five kilometers) lost. Nowadays fewer clocks are seaborne. My ingenious friend Giuseppe Cocconi, long a particle physicist in Geneva, Switzerland, tells of one time and place when that shift began to be manifest. With World War II just over, the thrifty captains of coastwise cargo vessels and offshore fishing boats grasped that radio signals and radio beams had come to displace the long reign of the chronometer. Ships' fine chronometers began to fill the pawnshop shelves in Italian port cities at unheard-of bargains.

There are time devotees ashore whose pleasure arises more from precise timekeeping than from ornament, and Cocconi and I were among them. He could at last afford a worthy brassbound chronometer, and he learned to keep true time by recording its rock-steady pace, without any need to open the case. Ever since the mid-1920s, I have enjoyed setting my watch by the reliable time ticks on high-frequency radio.

Short-wave stations such as WWV in Fort Collins, Colo., and CHU in Ottawa still speak out Coordinated Universal Time every minute. By now these techniques have ripened. They temper the time defined by the cesium atomic clocks with "leap seconds," inserted or omitted each half-year by international agreement, to keep our public dials more or less apace with the earth's varying spin beneath the sky. A traveling listener eventually visits distant national authorities, too; I have enjoyed ticks from Cape Town, New Delhi and Xian, to say nothing of easier London.



DUSAN PETRICIC

WWV (the service of the U.S. National Institute of Standards and Technology) checks its clocks so well that it can guarantee the time of day as transmitted to within 10 microseconds. But the propagating medium for high-frequency sky-wave radio is not under laboratory control. The active sun juggles the wavebands on seasonal and longer scales, and daily effects fuzz by milliseconds the precision of the received time tick. No listening ear straining to hear a zero beat can split the milliseconds; such potential accuracy is solely the realm of the machine.

Turn your attention to station WWVB. Its antenna is a single capped tower that stands 120 meters above a wire ground screen. Its radio signal is at an extremely low frequency (ELF) of only 60 kilohertz, just above five kilometers in wavelength. WWVB tells its machine audience in a simple code the carrier frequency correct to five parts per trillion and the right time to 100 microseconds a day. There are no voice announcements at all. Although practical ELF antennas are too small compared with the multikilometer wavelength to be very efficient as radiators, their ELF signals travel well as surface waves. Their feet drag on the lossy earth or water, the varying electrical field not quite as vertical as the antenna. The slow decline with distance of two-dimensional waves somewhat offsets their loss of power downward. Artificial interference is low, because the noise sources also have inefficient short antennas! Lightning bolts cause natural noise, nearby storms are loud but few, and the many faraway storms give a steady background, lower at night. The stability of the ELF ground wave ends any practical differences between the accuracy as sent and as received, allowing for a transit delay close to that imposed by the speed of light.

For about a year now, American consumer electronics suppliers have offered a cheap and marvelous device, the self-setting precise clock of which I had long dreamed. For about $50, one can buy a small desk clock with the usual quartz-driven digital display—no hands—that decodes WWVB a few times a night, using a few centimeters of rod antenna. It displays radio time precise to a second, attending to daylight savings and

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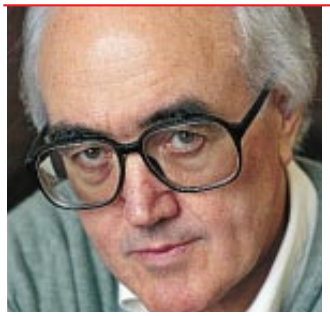


CONNECTIONS

by James Burke

Sheer Poetry

It came to be known as the Langevin sandwich: a layer of quartz between two layers of steel.

"Give me your tired, your poor,
Your huddled masses yearning
to breathe free...."

I was reading the poem on the base of the Statue of Liberty recently and thinking how often the best-laid plans get hit by Murphy's Law. In 1871 France had just lost a war to the Prussians and were beginning the soon-to-be-familiar pattern of governments imitating cuckoo clocks (in and out, on the hour). In the politically unstable climate of the times, yo-yoing between monarchy, revolutionary terror and moderate republicanism, those partial to the last were eager to find some way of warding off a return of the old guard.

A gigantic statue—to be built by the French, dedicated to republican ideals and erected in New York Harbor (the gateway to the nation whose independence the French had bankrolled a century earlier)—would remind any French citizen wishing to go back to the bad old days of the link between the two countries and of France's natural republicanism. A good plan, it would seem, but 15 years later this political ploy had been thwarted by the no-fool Americans. Thanks to Emma Lazarus's ode to America, engraved on the monument's pedestal, the Statue of Liberty was, already at its inauguration in 1886, perceived to be less an acknowledgment of the debt to France and more an exclusively American statement of the country's open-door policy to immigrants (even to those escaping persecution in France).

DUSAN PETRICIC

The engineer who built Liberty was Gustav Eiffel, the hottest monumental type around, with dozens of bridges and aqueducts to his name. A few years later he realized his dream of building the highest tower in the world, using the lightweight, trussed wrought-iron structures he had so successfully employed on the great Lady. When, in 1889, he finished his famous tower, it rose 986 feet (300 meters) above Paris and came in under budget. Anticipating criticism, Eiffel designed the structure so as to be easily dismantled (it nearly was in 1909, but in the new era of radio telegraphy, the height of its antenna saved it).

Eiffel, and many others, took advantage of the tower's height to conduct experiments that might otherwise have required balloons. He studied the falling behavior of various airfoils. Results were encouraging enough for him to place a wind tunnel (it kicked off scientific aerodynamics) down at the base of the tower. At one point soon afterward, the president of the Aero Club of France carried out similar aerodynamic free falls, then set up a 900-foot manometer on the tower to test the pressures of diverse liquids and gases.

He was pressured into this activity by his quest for extreme cold. Louis-Paul Cailletet ran his father's foundry and may have been looking for ways to provide the oxygen needed for the new Bessemer steelmaking process. If the oxygen were cold enough, you could store it compactly as liquid (if you could keep it cold). Anyway, in 1877 Cailletet managed to liquefy oxygen, using a technique that involved the drop in gas temperature that follows a drop in its pressure. Yet before he could report success, a cable arrived from Geneva. Sent by a refrigeration engineer named Raoul-Pierre Pictet, it claimed he had done the same, only differently. Pictet's approach was to use a "cascade" process, in which coolant gases, each of which liquefied at a progressively lower temperature, chilled the next and finally made oxygen liquefy.

Hot on his heels, a Scotsman named James Dewar, who had an obsession for getting to absolute zero, used these methods and in 1898 succeeded in liquefying hydrogen. At –259 degrees Celsius, liquid hydrogen was within 14 degrees of Dewar's frigid goal. Dewar's invention of an insulating jacket (which would solve Cailletet's problem of storing oxygen for steelmaking) did well keeping cold things cold, by creating a vacuum between two silvered layers of steel or glass. Dewar's reputation for being the ultimate in cool attracted the attention of anybody who wanted to see how his or her favorite project would do in the freezer. Pierre Curie, of recent radium fame, was keen. Dewar helped Curie investigate the behavior of radium and in particular the gases it would absorb at very low temperatures.

Pierre and his wife, Marie Curie, had found radium by dumping pitchblende by the ton into vats and boiling it down, then quantifying the ensuing characteristics. One result was that the concentrate very slightly charged up the atmosphere immediately around it. So slightly as to be almost immeasurable, until the Curies employed a piezoelectric

crystal to measure the charge. Piezoelectric crystals (such as quartz) react to even an infinitesimally small charge by changing their shape.

An ardent supporter of the Curies' work (indeed so ardent, he later became Marie's lover) was Paul Langevin, who for many years assisted the couple in their lab. Langevin explored another feature of piezoelectric crystals: under pressure, they give off an electrical charge. By 1917 he had produced what came to be known as the Langevin sandwich: a layer of quartz between two layers of steel. Zapping the quartz with electricity made it change shape regularly, thus causing it to resonate.

When placed in the hull of a ship, for instance, the outer steel layer transmitted a powerful, undulating signal into the water. (Langevin killed many a fish in his early water-tank experiments.) On hitting an enemy submarine (or any solid object, such as a reef), the echo bounced back, creating vibrations in the steel plate. The crystal would thus resonate, setting up an electrical charge that produced a ping, the one so familiar from all the underwater war movies. Sonar.

First discovery of this crystalline behavior was made around 1802 by the canon of Notre Dame Cathedral in Paris, René-Just Haüy. Haüy founded modern crystallography when he investigated why crystals seemed to shatter into uniform, identically shaped bits after he hit them. As a result of this smashing performance, Haüy was loaded with honors and important positions but lived a frugal life, spending all his money on the work of his brother, Valentin.

In 1784 this conscience-driven sibling founded the first Institute for Blind Children in Paris. In 1826 Louis Braille became one of its teachers. Three years later he published the reading system still used today: six dots arranged in two rows of three, offering 63 embossing combinations with which to express the alphabet, punctuation, numbers and so on. The Paris school was later visited by Samuel Gridley Howe, who in 1832 became director of one of the first American educational institutions for the blind—the Perkins school in Boston.

It was Howe's wife, Julia Ward, who wrote the words for and published the other great hymn to America, besides the one inscribed on Miss Liberty: the "Battle Hymn of the Republic." SA

Wonders, *continued from page 105*

leap seconds as they fall. In a year it has never deviated from the best check I can make with WWV by ear and eye. The output power was tripled at the end of 1997 to 40 kilowatts. The signal from WWVB routinely covers North America, from the Yukon south nearly to Panama and out some way into the oceans. At that distance, its signal power is 50 or 100 times greater than the threshold signal of a good communications receiver, plenty for the clock and its minimal magnetic antenna.

The trick is in part repetition; the clock's chip picks up the sharp pulse rise at every passing second, but it also notes the width of each pulse, for that encodes one additional bit of information about the time. The device needs only minutes to read the time in seconds, the date and the day, comparing seconds with its own quartz crystal rate. With such tools, accurate automatic time should become a commonplace.

Time precision is serious engineering. Frequency separation between signal channels and time division for shared channels—often to microseconds—are major tools for the effective use of bandwidth along the beams, wires and fibers of this world. Only the wonderful satellite navigational Global Positioning System offers an alternative: direct point-to-point propagation of time by microwave from orbit. GPS time comes down to a tiny outdoor antenna with a daily error almost always less than 20 nanoseconds, one part in 10 trillion. The U.S. Naval Observatory, official source of U.S. time, carefully monitors GPS performance (and provides time by telephone to any caller). For personal computers enlisting the right software, the system measures and corrects for phone-line delay, to offer accuracy at a millisecond level.

There are lessons for living in all this. How can one not welcome the fulfillment of one small dream, held over 70 years? My self-setting little Time Machine is right every day. (It took a few days to adjust it to daylight savings, because here in coastal New England a confusing signal from station MSF in Rugby across the sea demands extra attention: the same ELF frequency but a different code.) Yet the satisfaction I felt as a caring timekeeper faded a little once precision became effortless. Is it better to travel hopefully than to arrive? SA

WORKING KNOWLEDGE

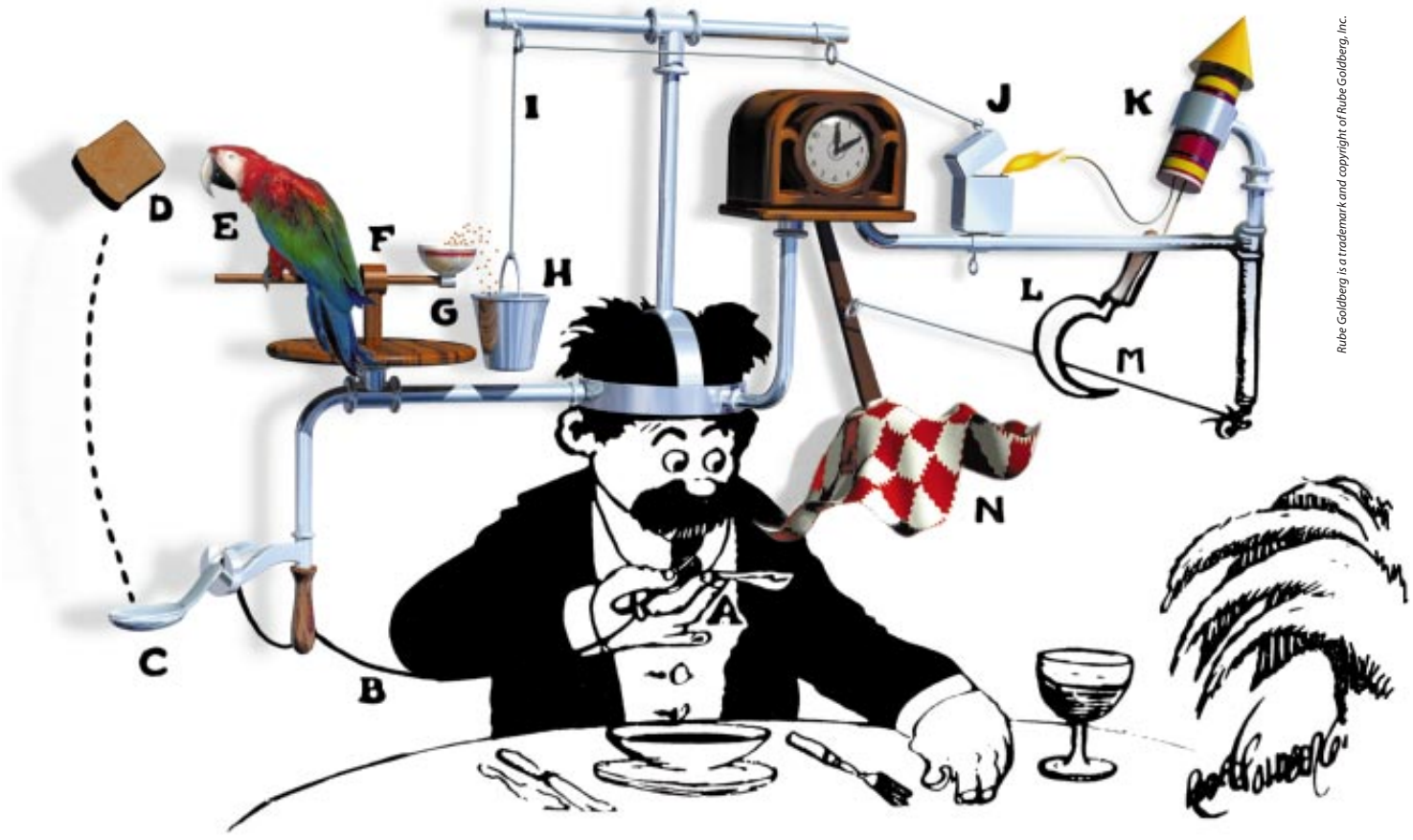
SELF-OPERATING NAPKIN

by Rube Goldberg

In recent years the international epidemic of embedded schmutz has captured the attention of the scientific and public health communities. Researchers discovered that persistent topical contact with common foodstuffs presents a grave health threat. Studies found that the random graham cracker crumb or the milk mustache can lead to a markedly diminished use in human populations of the oscultatory appendage—referred to in the scientific literature simply as kissy lips. In seeking to counter this imminent danger to the continued survival of the species, public health officials launched a worldwide campaign to seek technology that would automate the osculatory decontamination process.

The global search led to the discovery of the self-operating napkin. The idea can be attributed to one anonymous but heavily mustachioed academic. This estimable professor happened to be walking barefoot in his sleep on the first day of April. Upon contact with the thorns of a cactus, the good professor immediately awoke and screamed out the idea for his invention.

The device functions by applying the napkin to the mouth after the diner's fork or soup spoon is raised to the lips. The worthy professor's patent application also outlined how, after a meal, a harmonica could be substituted for the napkin, enabling guests to be entertained with a little bite music.



RAISING SPOON TO MOUTH (A) pulls string (B), thereby jerking ladle (C), which throws cracker (D) past parrot (E). Parrot jumps after cracker, and perch (F) tilts, upsetting seeds (G) into pail (H). Extra weight in pail pulls cord (I), which opens and lights automatic cigar lighter (J), setting off skyrocket (K), which causes sickle (L) to cut string (M) and allows pendulum with attached napkin (N) to swing back and forth, thereby wiping off your chin.

