SENDING HUMANS TO MARS: SPECIAL REPORT

SCIENTIFIC AMERICAN

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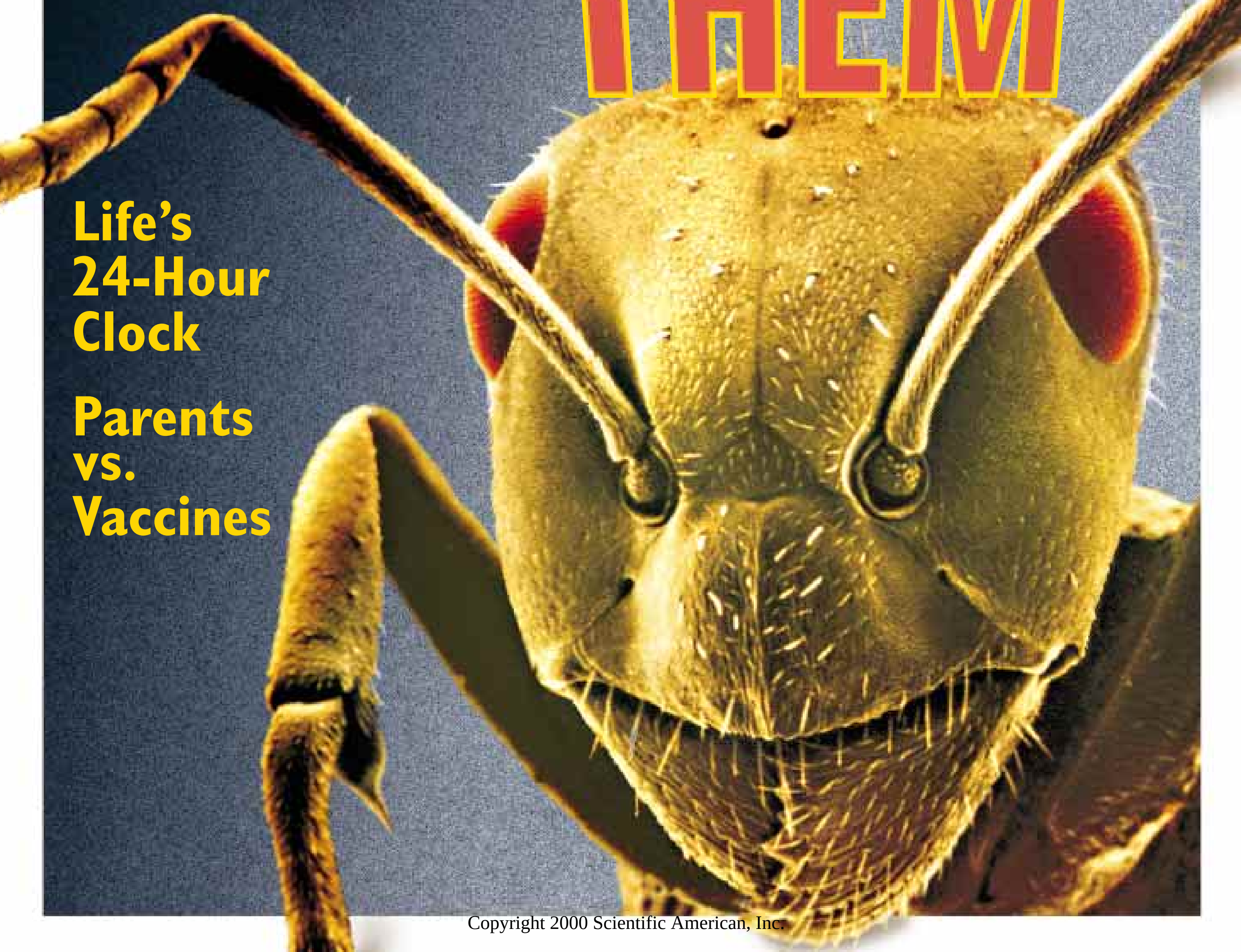
Parents vs. Vaccines



SCIENTIFIC AMERICAN

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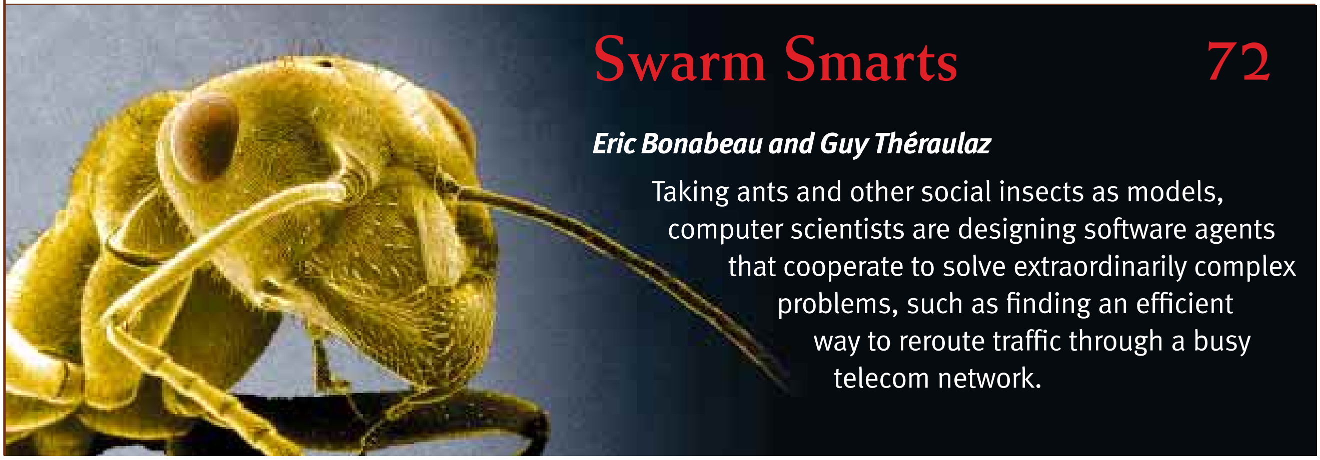
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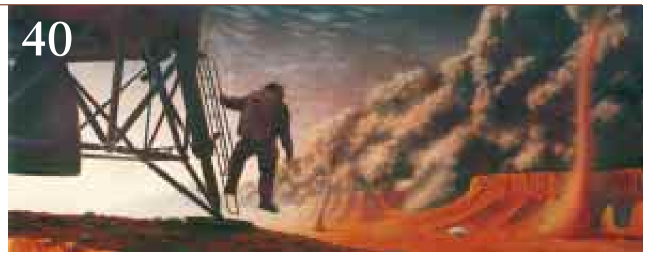
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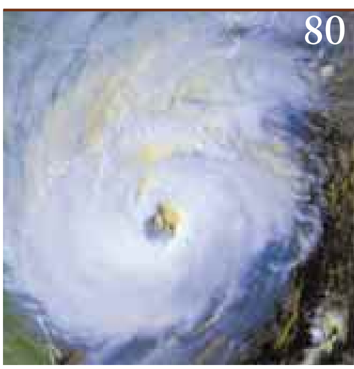

DEPARTMENTS

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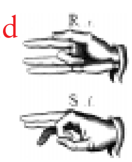

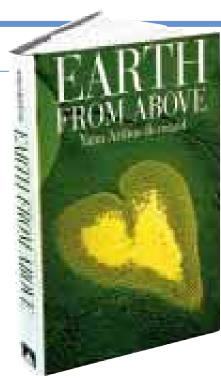

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Discover why a mother's immune system ignores the child in her womb: www.sciam.com/explorations/2000/012400preg

Check every week for original features and this month's articles linked to science resources on-line.

About the Cover

Micrograph of an ant by Dennis Kunkel/Phototake.

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From the Editors

The Second War of the Worlds

H. G. Wells famously ended *The War of the Worlds* by having the Martians laid low by terrestrial microorganisms; as the flu season settles around New York, I know how they felt. (By the way, if the Martians' oversight seems dumb for an allegedly superior civilization, remember that Wells published his story in 1898, just 20 years after Pasteur published the germ theory of disease.) But all indications are that Wells had the situation backward. We humans will be the technologically advanced race invading Mars. The special section on human exploration of our reddish neighbor, beginning on page 40, describes how we might do it within the next few decades. Cross-contamination by terrestrial or hypothetical Martian microbes will be one of the concerns for mission planners.

What dangers might Martian germs pose to human colonists or to Earth dwellers if they were accidentally brought back and escaped? The catastrophic line of speculation says that microbes hardened to life on Mars would run amok in Earth's cushy biosphere. But I'll climb out on the opposing limb and suggest that the poor things would get stomped. Our oxygen-rich atmosphere could be highly damaging. More significantly, because terrestrial life has evolved to survive in a competitive milieu, cells used to the quiet, arid emptiness of Mars might not have adequate defenses against our own hungry, territorial biota.


ERICA LANSNER

The real victors would be microscopic.

For the same reason, I suspect that if earthly microorganisms were to escape the confines of human shelters on Mars—and assuming they could cope with the searing radiation, bitter cold and lack of moisture—they might rapidly hijack a Martian biosphere, if one exists. In a complete inversion of Wells, microbes would help the invaders take over a world. But then, microorganisms are the real masters of any planet.

Disagreeing with my scenarios is easy, of course. Rather than defend them, I'll just offer the hope that these experiments are never performed unwittingly.

Readers know that this magazine is blessed with some of the finest artists in the business. Look no further than the gatefold painting of tyrannosaurs that appears in the September 1999 issue (a part of which also appears on the cover) by freelance artist Kazuhiko Sano, with art direction by *Scientific American*'s Edward Bell.

The Society of Illustrators has selected that painting for inclusion in its 42nd annual exhibition, being held at the society's gallery in New York City from February 12 through March 11. Congratulations to Sano, but let me also thank all our other artists. Our magazine would be immeasurably poorer without the life their work breathes into every page.

JOHN RENNIE, *Editor in Chief*
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LETTERS TO THE EDITORS

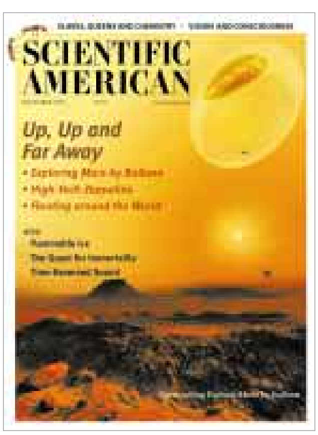
Readers responded in large numbers to "The Fate of Life in the Universe," by Lawrence M. Krauss and Glenn D. Starkman, in the November 1999 issue. Some were disturbed by the authors' conclusion that "life, certainly in its physical incarnation, must come to an end," whereas others enjoyed the imaginative speculation. In that vein, Lawrence Howards writes via e-mail, "There is a huge source of energy and data that the authors have ignored. If it exists, Hell must be included in their calculation of available energy and matter. Its structure, described by many sources as a place of great heat and energy 'hidden from the face of God,' resembles the description of a black hole. Intelligent life-forms might be able to duplicate the manner of transport and collection of energy and data used to create Hell—namely, by creating a black hole. Of course," Howards continues, "as more life-forms become immortal, fewer will die and the number of the damned transported to Hell will decrease, allowing 'Hell to freeze over,' as is classically described. When the containment field of the damned is released, a huge source of radiation and data will become available to life-forms within the Universe. This energy should greatly extend the ability of life to exist."

In reply Krauss offers, "If there is a Hell, there are also probably other important energy sources we have neglected, such as Heaven." Additional comments regarding this article and others in the November issue follow.

FATE BEYOND IMAGINATION

I was struck by many of the conclusions drawn in the article "The Fate of Life in the Universe," by Lawrence M. Krauss and Glenn D. Starkman. Trying to imagine today how we will have developed several billion years from now is like *Homo habilis* looking up from his crude stone tools and envisioning an Apollo rocket hurtling toward the moon—except that the gap between him and us is only about two million years, easily one thousandth the distance between our future selves and us. For all we know now, in several billion years we will easily be able to modify the very physics that the universe obeys, not to mention our physical state. Perhaps in the year A.D. 1,000,000,000 we will change the constant *pi* to 2.8 and the speed of light to one meter per second, and our consciousness will reside in wisps of gas. Then again, the very fact that these transpirations can be imagined probably means they would seem relatively simple to our far-off descendants. Simply put, the authors of this article are assuming *Star Trek*–type technology at a date when a measly fraction of accumulated human knowledge would make *Star Trek*–type technology look like *H. habilis*'s stone tools.

JEFF HEMINGWAY
Surrey, British Columbia



HYDROGEN FOR AIRSHIPS?

I was very interested in "A Zeppelin for the 21st Century," by Klaus G. Hagenlocher, as I have been fascinated by airships ever since (so I was told) I was terrified by the sight of the R34 when it roared over my hometown in the early 1920s, on its way to the United States. I have a question, which has been puzzling me for years. There must be some hydrogen-helium mixture that will not burn, so has this been considered for balloons or airships to give extra lift? It seems such an obvious idea, but I suspect there may be a snag in it—I can think of several! I have never seen anything authoritative on the subject, however.

SIR ARTHUR CLARKE
Sri Lanka

Hagenlocher replies:

A number of people have suggested mixing helium, which is expensive, with a cheaper gas such as hydrogen. Hydrogen is 10 percent lighter than helium and therefore would provide 10 percent more lift; however, to get a nonflammable mixture, one must mix 20 percent hydrogen with 80 percent helium. Thus, the advantage for the lift is only 2 percent, and the price advantage is small for companies that purchase large quantities of helium. Because people still tend to connect the name "Zeppelin" with the hydrogen-filled *Hindenburg*, our company has decided against using any hydrogen in our airships.

THE SHORT AND THE LONG OF IT

The article "Down in Front," by Steve Mirsky [News and Analysis, Anti Gravity], said that if you are short it is a good thing for your health and you might live longer. This sounds great for me, because I am four feet, six inches tall at age 11 and of course the shortest in my class. This is very convenient because if anyone ever teases me about my height, I have a snappy retort.

MATT GOLDFOGEL
Bellingham, Wash.

EYE OF THE BEHOLDER

In "Vision: A Window on Consciousness," Nikos K. Logothetis makes the point that the two perceptions of the Necker cube "optical illusion" compete with each other for entrance into consciousness. Artists exploit this effect by deliberately giving each form in their picture a double, or spatially ambiguous, reading—creating the equivalent of an optical illusion—and thereby evoke strong three-dimensional images. The tension resulting from spatial ambiguity is pleasurable. By compounding the ambiguities in a particular drawing structure, an artist can increase the tension and with it the pleasure it affords. When

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such pleasure becomes sufficiently intense, we call the sensation beauty.

GEORGE GILLSON
New York City

HYDRATE HAVOC?

With regard to "Flammable Ice," by Erwin Suess, Gerhard Borhmann, Jens Greinhert and Erwin Lausch, several years ago I read a description of the physical conditions that resulted when a handful of methane hydrate crystals were pulled up through warm seawater. It occurred to me that if a large quantity (over a large area) of that substance were released from the sea bottom through some sort of seismic disturbance, the effect would mimic the description radioed by victims of the Bermuda Triangle in the throes of their difficulties: a green, boiling sea and an impenetrable fog (also greenish and nearly indistinguishable from the sea). Also, the electrostatic effects of all that methane changing states from solid to gas could probably wreak havoc with most primitive electrical navigational systems, resulting in the loss of ability to judge up and down.

RUDY VOLKMANN
via e-mail

Suess replies:

The mechanism by which gas hydrates and free methane gas are released from the seafloor is now better known, and it is difficult to envision it causing an event of such magnitude. We simply don't have evidence connecting large-scale gas hydrate release to catastrophic events. Also, there are many considerably more active seismic and plate tectonic regions that would be affected more than the Bermuda Triangle, yet such legends have not arisen in other areas.

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

ERRATUM

In the caption on page 77 of the November 1999 issue, 500 meters was mistakenly converted to 1,064 feet. The correct conversion is 1,640 feet.

50, 100 AND 150 YEARS AGO

SCIENTIFIC AMERICAN

MARCH 1950

THE HYDROGEN BOMB—"Here are some technical conclusions that one must draw about the fusion bomb: First, it can be made. Second, it cannot be smaller than a fission bomb, since it must use a fission bomb as detonator, but it can be many times, perhaps thousands of times, bigger. Third, while fission can be controlled in an orderly way to produce useful power in a reactor, the fusion reaction offers no prospect at the present time of any use except in terms of an explosion. The decision to make the superbomb has been taken, and in the world of hotly nationalistic fear and jealousy that we now inhabit, one can suppose that it is the right decision—that is, for the arms race. —Louis N. Ridenour" [*Editors' note: This article was the first in a four-part series on aspects of the fusion bomb. The first bomb was detonated November 1, 1952, at Eniwetok Atoll.*]

EXPERIMENTAL NEUROSES—"Neurotic aberrations can be caused when patterns of behavior come into conflict either because they arise from incompatible needs, or because they cannot coexist in space and time. Cat neuroses were experimentally produced by first training animals to obtain food by manipulating a switch that deposited a pellet of food in the food-box. After a cat had become thoroughly accustomed to this procedure, a harmless jet of air was flicked across its nose as it lifted the lid of the food-box. The cats then showed neurotic indecision about approaching the switch. Some assumed neurotic attitudes. Others were uninterested in mice. One tried to shrink into the cage walls."

MARCH 1900

MAGNETIC FIELDS AND RADIATION—"M. Becquerel has given an account to the Academie des Sciences of a remarkable phenomenon. He finds that when radio-active matter is placed between the poles of a powerful electro-magnet, the radiation which it emits is changed in direction. In one experiment, between the pole pieces of an electromagnet were placed two soft iron disks. Near the center of one disk was disposed the radioactive matter, containing the supposed new element, radium. Against the other was placed a fluorescent screen. Upon exciting the electromagnet, the phosphorescence excited in the screen contracted into a luminous spot and became more intense."

MARINERS' LIGHT—"A few miles off shore of Cape Hatteras are the justly dreaded Diamond Shoals, on which futile attempts have been made to erect a lighthouse. It would seem as though the only practicable way to protect shipping from this graveyard of the deep is to moor above the shoals a lightship able to meet the exceedingly trying local conditions. Such a vessel has been designed and is now nearing completion at the yards of the Fore River Engine Company, of Massachusetts. She will be steam-propelled and electric-lighted. The lights, three in number on each mast, will be of 100 candle-power and 100 volts each."

MELTWATER FLOODS—"The setting aside of the Medicine Bow forest reservation in the Rocky Mountains recently by the general government was due to the efforts of certain farmers of northern Colorado. While the destruction of the forests has made no perceptible difference in the amount of precipitation, it has made a marked difference in the flow of water in the mountain streams. Instead of the snow beds being protected from the sun's rays by a dense shield of pine boughs, upon the arrival of spring they melt with great rapidity and fill the mountain streams with roaring torrents whose volume cannot be properly and economically controlled by the present ditch and reservoir facilities."

MARCH 1850

AWAKE AND INSANE—"Dr. Brigham, of New York Asylum for the insane, expresses the opinion that the most frequent immediate cause of insanity is the want of sleep. 'Long continued wakefulness disorders the whole system. The appetite becomes impaired, the secretions diminished, the mind dejected, and soon waking dreams occur and strange phantoms appear, which at first may be transient; but ultimately take possession of the mind, and madness or death ensues.'"

WHERE IS THE WILDERNESS?—"At the beginning of this century it was in Ohio and Indiana. Last year it was in Minnesota Territory. Next year we will have to seek it in Nebraska and around the lake of the Woods. Where the steamboat goes, there the wilderness disappears."

Aid to navigation: a steam-powered electric lightship

NEWS AND ANALYSIS

IN FOCUS

GRANTING IMMUNITY

Despite rising parental fears and rumors of dangers, vaccines are safer than ever

TOM HOLOUBEK *Beloit Daily News/AP Photo*

***YOU MIGHT FEEL A PINCH:** More parents are joining their children in hating vaccines. Health officials concede that they haven't done well in allaying fears.*

Although the reports have attracted little notice in this country, health officials overseas are battling an outbreak of one of the most contagious diseases on earth. But before you cancel your travel plans to the jungles of Africa or South America, take note: this hot zone is actually in Holland, and the disease, measles. Over the past year Dutch doctors have identified at least 2,300 cases of measles. According to the latest figures, three children have died from the disease, and 53 were hospitalized with complications such as pneumonia or encephalitis. Most of the cases occurred in children between the ages of six and 10—the vast majority of whom had not received the readily available vaccine against measles.

Antivaccine sentiments are popping up everywhere. Religious reasons sometimes play a role, as in the Netherlands measles deaths. Increasingly, though, it is not religious conviction that prevents children from receiving vaccines but rather parents' fears that the shots might either cause the diseases they are intended to prevent or even contribute to other ailments, ranging from cancer to multiple sclerosis. An array of advocacy groups with authoritative-sounding names, such as the Virginia-based National Vaccine Information Center, encourage parents to reconsider giving their children vaccines. In response, officials at health organizations such as the U.S. Centers for Disease Control and Prevention (CDC) are scrambling to reassure parents that vaccines are not only safe but are crucial for their children's health and for public safety.

In the first year of life, shots come early and often. A standard course of vaccines and boosters today includes a series of some 10 injections against diphtheria, tetanus and pertussis—whooping cough—(DTaP), *Hemophilus influenzae* type b (Hib), measles, mumps and rubella (MMR), and polio (IPV), all before a child's first birthday; doctors recommend at least another six boosters during childhood and adolescence. In addition, physicians and parents can now opt for one or both of two new vaccines: against chicken pox (known as the varicella vaccine) and against hepatitis B (Hep B).

Years of medical research and continual monitoring of vaccines by organizations like the CDC, the U.S. Food and Drug Administration and the National Institutes of Health indicate that the overall risks from immunizations are far less than those associated with contracting one of the vaccine-preventable diseases such as measles or polio. Nevertheless, as with any medical procedure, vaccines can have side effects. Most are minor—a sore arm or perhaps a low-grade fever; a tiny fraction of children have allergic reactions to vaccines. But on extremely rare occasions, severe side effects occur—for example, contracting polio from the oral polio vaccine, which relies on a weakened but live virus.

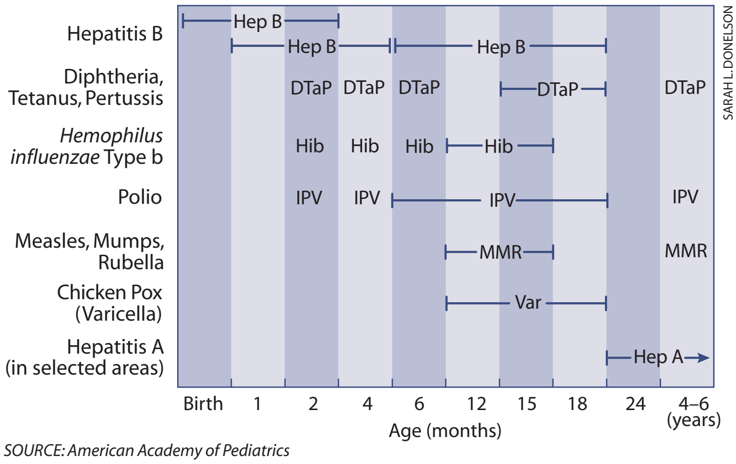
Uncommon though they are, such events can have a profound effect on parents, stirring up persistent fears. Stories of kids coming down mysteriously with autism, diabetes or juvenile arthritis not long after receiving an inoculation abound, particularly on the Web. And with just a few clicks of the mouse, parents can find themselves at sites describing not only how dangerous vaccines are but also how the federal government is supposedly using immunization records to monitor civilian activity. Yet studies have repeatedly failed to find any connection between receiving vaccines and coming down with serious ailments such as autism or diabetes.

Neal A. Halsey, director of the Institute for Vaccine Safety at the Johns Hopkins School of Public Health, speculates that with so many children being immunized so frequently, there are bound to be instances in which a condition like arthritis becomes apparent within a week or a month of that child's receiving a vaccine: "When anyone develops an illness that seems to come out of the blue—something like diabetes or asthma—it's human nature to ask, 'What happened? What was done to me?' " The problem arises, Halsey says, when people assume that the vaccine was the culprit.

Vaccines are commonplace in developed countries, thanks mostly to government regulations. In the U.S., immunization rates for most vaccines are more than 90 percent. The rate is high, explains Michael A. Gerber of the NIH's National Institute of Allergy and Infectious Diseases, because states require that children receive the standard shots before they can enter day care or public schools. In the case of inoculation against chicken pox, however, protection is much lower. Slightly more than 40 percent of children receive the varicella vaccine, Gerber says: "Only about 18 states require it, but the number is increasing all the time." For much the same reasons, the vaccination rate against hepatitis B is also somewhat low, at 87 percent.

Although researchers like Gerber encourage parents to inoculate their children against chicken pox and hepatitis B, many are resisting. With these diseases the issue is not so much safety as it is necessity. In discussion groups on the Internet, for instance, parents tell of organizing "chicken pox parties" to expose their kids to the disease, just to "get it over with" in the traditional way.

But Gerber emphasizes the importance of the two vaccines: before the varicella vaccine, he notes, chicken pox "was the most common cause of death from a vaccine-preventable disease." Chicken pox, typically a mild affliction for most kids, resulted in an estimated 100 deaths a year and some 11,000 hospitalizations before the vaccine was introduced. No one is sure exactly how some infants contract the hepatitis B virus, which is often transmitted through decidedly adult activities such as sexual contact or the sharing of infected needles. But because half the world's population faces a 60 percent chance of contracting it at some point, and because no treatment exists to destroy the virus once it infects, childhood inoculation against hepatitis B makes sense.



RECOMMENDED SHOTS include series of injections given at specific ages. For example, the first hepatitis B vaccine should be given between birth and two months; the second between one and four months; and the third between six and 18 months.

To combat the sentiment against vaccines, Halsey observes, physicians need to do a better job of reassuring parents. "It is important to tell parents that there are—rarely—serious complications that do occur. But we have a careful system in place to monitor vaccines," he states. As an example, he points to a recent safety-related recall of the vaccine against rotavirus, a viral infection that causes diarrhea, fever and vomiting. In mid-May of last year, after the vaccine had been on the market for just nine months, officials at the CDC noted that the Vaccine Adverse Event Reporting System, a joint program of the CDC and the FDA, had received nine reports of infants who had developed a dangerous blockage in their bowels not long after receiving the rotavirus vaccine (all recovered). The researchers immediately called for an investigation. By mid-July the CDC recommended that physicians refrain from administering the shot; in October the manufacturer recalled the vaccine. "The decisions were made very quickly," Halsey says, "and were based on good data."

Such procedures have made physicians confident of existing vaccines, and researchers are constantly reevaluating the drugs and formulating even safer ones. For example, a recent study by David W. Scheifele of the Vaccine Evaluation Center at British Columbia's Children's Hospital in Vancouver reports that a new pertussis vaccine now in use in Canada eliminates most of the fever and irritability commonly associated with the original shot. And starting this year, doctors in the U.S. will phase out the oral polio vaccine in favor of an injectable vaccine, which uses inactivated virus and thus cannot cause polio. But with new parents programmed to worry, the question of vaccine safety won't go away anytime soon. For pediatricians, boosting parents' confidence will be just as critical as boosting their kids' immunities. *—Sasha Nemecek*

FIELD NOTES

RUNNING THE DAM GAUNTLET

In the name of science, a rubber fish serves as stunt double

Every year in pageants that are as ancient as they are majestic, recently spawned salmon, steelhead trout and other fish make their way down the Columbia River, on the Oregon-Washington state border. As they do, they attempt to run a sometimes lethal gauntlet of six to eight hydroelectric dams.

The massive structures, including the legendary Bonneville Dam outside Portland, Ore., have elaborate and labyrinthine fish bypass systems to help the creatures past the turbines. Nevertheless, at Bonneville as many as 45 percent of the fish go through the turbines in the summer. The enormous, propellerlike blades, which can reach 75 revolutions per minute, are too large and slow to purée the fish. Rather they subject them to turbulence, rapid changes in hydrostatic pressure and strong shear forces. Of the creatures that go through Bonneville, up to 12 percent perish as a result of their injuries—or, more likely, because they are no match for predators in their weakened state.

Now, in an effort to better understand the forces that affect the fish, engineers at Pacific Northwest National Laboratories (PNNL) are testing a six-inch-long, sensor-packed rubber fish that will act as their eyes and ears inside the turbine. They hope that data from the sensors will allow developers to make turbines that are more fish-friendly as well as more efficient.

The rubber-fish experiment is part of a U.S. Army Corps of Engineers study in which scientists are releasing live salmon smolts to make their way through modified and unmodified turbines. Equipped with radio transmitters, the fish are located and recaptured downstream and inspected for injuries. With these live fish, researchers see the results of the turbulent encounters but learn nothing of the forces that injure the creatures.

Out on the upper deck of Bonneville Dam on an early December afternoon, Thomas J. Carlson, manager of PNNL's sensor-fish project, strolled in a chilly rain, a rubber fish in his jacket pocket. "We're hangers-on to the biological testing program," he explains, waiting for a pause in the corps' live-fish experiment. Finally, he enters the plywood shed where test fish are released into tubes that guide them down into the turbine. A few tense moments pass as the fish at first refuses to power up. At last it's a go, and Carlson drops it down the tube.

Each sensor fish—at $5,000 apiece—does not swim; it just goes with the flow, measuring and storing information as it passes through the turbines. Inside are a pressure transducer and accelerometers that account for directional acceleration from gravity. Microprocessors inside the fish send digitized data from the sensors to onboard memory. Researchers download the data by plugging lead wires in the rubber fish's tail into the serial port on a desktop computer.

Fifteen seconds after Carlson releases the fish, its journey through the turbine is over. Moments later the radio crackles as technicians in patrol boats down at the base of the dam call in with good news. "We have the signal," a worker reports, much to Carlson's relief. Six chemically activated balloons attached to the fish have inflated to golf-ball size, bringing the sensor fish to the surface. "Sensor fish is in the boat," the radio chatters.

A successful release and catch is no small feat. The previous week, nylon lines connecting the balloons to the first two test fish sawed through one another, sending $10,000 down to the bottom of the Columbia. The project team, working feverishly over Thanksgiving weekend, used metal rings to attach the balloons more securely to the remaining fish.

Keeping the sensor fish's delicate instruments dry is another challenge. In fact, on this run the fish leaks, and the data are lost. "It's about as messy of a sensor job that you might want to do, outside of something in space," Carlson notes. The next day's run is more successful, generating good data.

The timing is perfect. The old federal hydropower system, an economic mainstay of the Pacific Northwest, where electricity rates are among the lowest in the U.S., "has been patched together over the years, and now it's time to replace the turbines and generators," Carlson explains. "This opportunity for rehabilitation comes around only once every 50 to 60 years."

Happily enough, it turns out that a more streamlined turbine blade design that creates less turbulence and more laminar flow is not only better for energy production but also better for the fish. As a result, Carlson says hopefully, modified turbine design may be "one of the few fish survival enhancements that can end up paying for itself."

—Pat Janowski at Bonneville Dam

CRAIG STRONG *Gamma Liaison*

GOING WITH THE FLOW: A rubber fish records the forces that affect live fish when they swim through the turbines of the Bonneville Dam on the Columbia River.

PAT JANOWSKI is a freelance writer in Portland, Ore.

BURNING TIMES FOR HOT FUSION

ITER scientists remain determined to take the next step in fusion

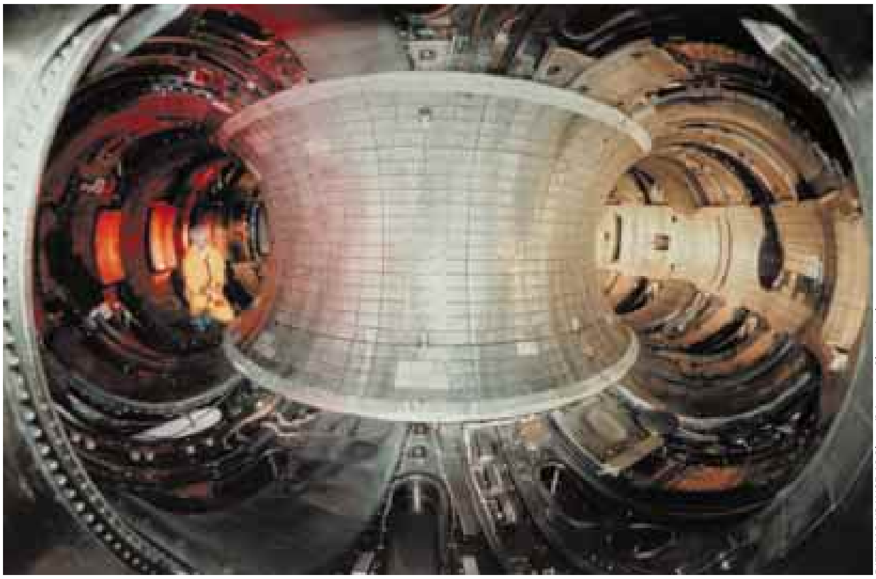
Electricity from fusion could be real in 50 years, a group of European scientists insisted in a Munich seminar last November. Moreover, they concluded, the International Thermonuclear Experiment Reactor (ITER) is still the correct next step. The conviction comes at a seemingly odd time for fusion in doughnut-shaped rings called tokamaks, a technological disappointment if ever there was one, at least from a commercial point of view. ITER, once a $10-billion collaboration begun in 1986 by the U.S., Russia, Europe and Japan, was to be the first tokamak to achieve a self-sustaining fusion burn. Skeptical of the design and concerned with the high price, the U.S. dropped out two years ago; because of its economic woes, Russia will only commit staff, and Europe and Japan still might pull back future funding.

Tokamak fusion relies on a mixture of the hydrogen isotopes, such as deuterium and tritium. Superconducting magnets confine the fuel in a torus; the fuel is then heated to 100 million degrees Celsius. The mixture becomes a plasma—a soup of free electrons and ionized atoms—and deuterium and tritium nuclei fuse, yielding energetic neutrons and alpha particles (helium atoms). The alpha particles heat the plasma; if there's enough of them, they will keep the plasma burning and the fusion going, so that the reactor generates more energy than it consumes. So far, though, no fusion reactor has even achieved breakeven.

ITER was supposed to be the penultimate step toward a practical fusion reactor. But skepticism ran high, reaching an apex in 1996, when two U.S. physicists wrote that the original ITER scheme would fall far short of its energy output goals. The reason was the size: in a mammoth machine such as ITER, turbulence in the plasma would cause significant heat loss. The U.S. bailed out of the ITER program in 1998.

Faced with a reduced budget of $3 billion, ITER scientists retrenched. The new 27-meter-high design, advanced by ITER director Robert Aymar at the November seminar, would generate 400 megawatts: "Ten times the energy injected, during a pulse of 500 seconds," he said. In contrast, the original ITER was to produce 1,500 megawatts and stand 31.5 meters high. At the reduced output the machine will not ignite the plasma, as previously designed. This sounds disappointing, but "the need to go to ignition is not necessary at all," Aymar says. "For a commercial reactor, ignition is a large amplification factor of 50"—that is, 50 times as much energy comes out as goes in. With an amplification of 10, he thinks, ITER will serve as the bridge to reach that goal.

ITER proponents cite reasons to be



DIETMAR KRAUSE AP Photo/Princeton Plasma Laboratory

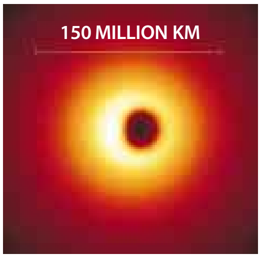
ABANDONING TOKAMAK FUSION, the U.S. cut funding, which forced the tokamak at Princeton University to close in 1997, and later withdrew from the ITER project.

IN BRIEF

Heart of Darkness

Astrophysicists have predicted in the January 1 *Astrophysical Journal Letters* that the shadow of the supermassive black hole thought to be at the heart of the Milky Way may be detectable against a bright background of plasma. The results, simulated below for the case of a rapidly rotating hole, would be the first direct images of a black hole's event horizon, the point of no return that even light cannot escape. Such observations, however, would require sophisticated very long baseline radio interferometry at wavelengths shorter than a millimeter and may be a decade away. Astronomers have also shown that freely drifting black holes, ones without a companion to devour or tug on, are also detectable. At the January meeting of the American Astronomical Society, David Bennett of the University of Notre Dame reported finding two errant holes, 3,000 and 6,000 light-years away, by the way they amplify the light of stars they happen to pass in front of. The finding hints that black holes may be 10 times more common than previously thought and might constitute a good portion of the galaxy's elusive dark matter.

—Graham P. Collins and George Musser



HEINO FALCKE *Max Planck Institute for Radio Astronomy*

Shadow of a hole

Superbug Cleans Up

Cleaning up underground nuclear waste may entail the radiation-resistant bacterium *Deinococcus radiodurans,* capable of withstanding exposures of 6,000 rads per hour (1,000 will kill a person within days). Scientists revealed in the November 19, 1999, issue of *Science* that they have sequenced the microbe's genome and unveiled some of its secrets for survival. Now researchers have engineered the bug to detoxify metal and organic wastes. The superbug was concocted by placing into the bacterium the genes required for breaking down toxic mercury and toluene. Success with this recombinant, reported in the January *Nature Biotechnology,* suggests that future strains can have varied pollution-fighting attributes. *—Diane Martindale*

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In Brief, continued from page 19

Moon Illusion Explained

Lloyd Kaufman and his son James H. Kaufman, working at the IBM Almaden Research Center, have gathered concrete data to explain the ancient optical illusion that causes a full moon near the horizon to appear bigger than a moon seen overhead. By measuring viewers' perception of the distance to artificial moons projected onto the sky, the researchers showed that the "apparent distance" to the moon—rather than the real distance—determines its perceived size. When the moon is on the horizon, the brain picks up distance cues from the surrounding terrain and interprets the moon as being farther away. This, in turn, causes the brain to see a larger moon. (The new work opposes alternative explanations based on "apparent size.") The study appeared in the January 4 *Proceedings of the National Academy of Sciences*. —D.M.

Seemingly farther

RICHARD T. NOWITZ *Corbis*

Lou Gehrig's Virus?

Providing the strongest evidence yet that infection is the cause, a French-U.S. collaboration has uncovered a virus associated with amyotrophic lateral sclerosis (ALS), or Lou Gehrig's disease. The researchers found that 15 of 17 people with the wasting condition harbored a virus similar to Echovirus-7, which causes meningitis and rare cases of encephalitis. In contrast, the virus appeared in only one of 29 people who died of causes other than ALS. How the virus infects the motor nerves of the spinal cord and whether it is actually responsible for ALS and not simply a bystander remain to be determined. The work appears in the January *Neurology.* —Philip Yam

Surrogate Cat

Playing surrogate mom in an effort to rescue the world's endangered small cats, Cayenne, a six-year-old domestic housecat from New York City, was implanted with the embryo of an African wildcat and subsequently gave birth to a healthy wild kitten named Jazz. The work, by Betsy Dresser of the Audubon Institute Center for Research of Endangered Species in New Orleans, is the first successful interspecies frozen-thawed embryo transfer (previous efforts used fresh embryos). Future breeding plans include bongo antelopes, tigers and whooping cranes (see www.auduboninstitute.org). —D.M.

More "In Brief" on page 26

optimistic. Klaus Pinkau, co-chair of the ITER Working Group, reported that heated plasma has self-insulating properties that would facilitate the plasma burn. And other reactors have delivered promising results. By 1998, says Hideyuki Takatsu of the Japan Atomic Energy Research Institute (JAERI), "the JT-60U, the largest tokamak in Japan, achieved equivalent breakeven conditions." That is, if the JT-60U could use the energy-richer mixture of deuterium and tritium rather than just deuterium, it would have achieved breakeven. The Joint European Torus (JET) in the U.K. got close, delivering 16 megawatts from fusion while consuming about 25 megawatts.

Could turbulence undermine the cheaper ITER? Not likely, according to Carlos Alejaldre, director of the National Fusion Laboratory of Spain's center for energy and technology research (Ciemat). His team performs fine plasma diagnostics in Spain's TJ II Stellerator, and he concedes that turbulence leads to some uncertainty but that "simulations and experiments at JET and other machines have given us the confidence that ITER will achieve its goals." More problematic in the long run, Alejaldre thinks, are the energetic neutrons that would make the device radioactive. Without appropriate shielding, future commercial reactors might be uneconomical.

For ITER supporters, the immediate concerns remain political, such as agreeing on a country to host the reactor and getting sufficient funds. The withdrawal of the U.S. was, in their view, a political decision, and the lukewarm U.S. interest has more to do with the fact that the country has big oil and coal reserves. Japan considers the fusion option as a "kind of energy security for our country," Takatsu explains. "We have very limited energy resources."

European and Japanese agencies will decide their funding strategies in June, which could dictate how quickly ITER progresses. ITER could be built in 15 years and see results within 25. But it's clear that the U.S. withdrawal hurts. "We would be delighted if it would go forward," says Richard Hazeltine, head of the Institute of Fusion Studies at the University of Texas at Austin. If money comes in the next two years, he does not discount the possibility that the U.S. would consider a "renewed participation." —*Luis Miguel Ariza in Munich*

LUIS MIGUEL ARIZA is a freelance science writer based in Madrid.

NEUROBIOLOGY

BRAIN TERRAIN

Mapping the functions of various areas of the human brain is difficult—and controversial

In the 19th century, practitioners called phrenologists divided the surface of the human brain into 35 different regions, each of which was thought to contribute to a certain aspect of personality, such as "spirituality," "mirthfulness" or "conjugality." The phrenologists claimed to discern someone's character by the location and size of the bumps on his or her head. A protrusion over the "conscientiousness" area, for instance, meant that the person was punctilious to the degree that that particular brain region had grown from use, much as a muscle does after repeated exercise.

Now, more than 150 years later, some researchers have begun to ask whether modern attempts to "map" the functions of various regions of the cortex—the brain's "gray matter"—essentially come down to using high-tech methods to do the same thing the phrenologists claimed to do. "There are people who scorn the idea that various areas of the cortex have unique functions," observes Robert Desimone, director of the National Institute of Mental Health's Division of Intramural Research Programs. "They call it 'neurophrenology.' "

And those who believe that fine functions—such as seeing colors or hearing certain sounds—can be attributed to small patches of cortex sometimes disagree strenuously over where to draw the margins of those patches. In 1998, for instance, a scholarly battle raged in the pages of *Nature Neuroscience* between Roger B. H. Tootell and Nouchine Hadjikhani of Massachusetts General Hospital and Semir Zeki and his colleagues at University College London. At issue was whether Tootell, Hadjikhani and their co-workers had identified a new area responsible for conscious color perception within the visual cortex, which is at the rear of the brain, or if they had simply "rediscovered" an area that Zeki had previously laid claim to. The issue still has not been settled.

Part of the problem arises because some researchers analyze the brains of rhesus macaques, whereas others focus on imaging human brains or studying patients who have suffered injuries or diseases that affect only particular brain regions. Often areas that appear to have one function in monkeys do not play the same roles in humans. In addition, the brains of individual monkeys and humans can differ slightly, making it very difficult to be certain that researchers are looking at the same spots in two or more brains.

Pinning down the function of particular brain areas has been made feasible by the development of functional magnetic resonance imaging (fMRI). Unlike other imaging methods, fMRI allows researchers to monitor local cerebral blood flow—a marker of brain activity—without administering radioactive materials or magnetic contrast agents. But fMRI machines are expensive to run, and so far relatively few neuroscientists have them.

Josef P. Rauschecker and his colleagues at Georgetown University Medical Center have recently used the fMRI technique to create a detailed functional map of the auditory cortex, which is situated on either side of the brain. They have found that the auditory cortex is divided into separate fields that process sound information in a hierarchical fashion. Core areas at the center of the region analyze pure tones; so-called belt areas surrounding the core areas respond to several tones combined into a more complex, buzzlike stimulus.

The idea of hierarchical processing—that the brain initially extracts from stimuli their most basic features and then builds them up again to reflect the complexity of the world—originated in the 1970s with studies of the visual cortex. But for many years, scientists favored the view that the auditory cortex decomposed sounds into many single frequencies and processed them in parallel.

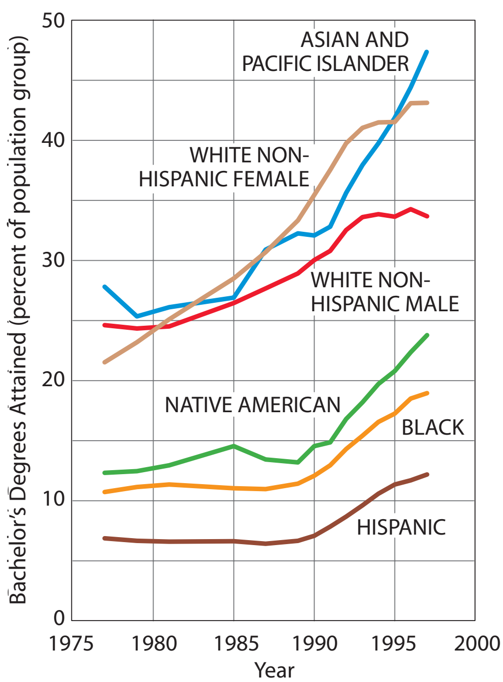
Rauschecker's new work should stir the pot. "There are people who think that pure tones are the best to map," he comments. "But you have to put the information together again to hear a voice or a complicated sound." *—Carol Ezzell*

BY THE NUMBERS

Minorities and Bachelor's Degrees in the U.S.

The proportion of young people awarded bachelor's degrees rose from 2 percent in 1900 to 19 percent in 1950 (when millions of veterans surged onto campuses via the G.I. Bill) to 32 percent in 1999. The growth of higher education after World War II was accompanied by increasing emphasis on admission based on merit rather than ability to pay, merit being measured mainly by high school grades and performance on tests, including the SAT. But by the late 1980s the merit principle was colliding with affirmative action, the practice of giving special consideration to minorities and women. Affirmative action in higher education had roots in the Civil Rights Act of 1964, which disallowed the use of tests that had a discriminatory effect. It soon became apparent that Asian-Americans and white females had little need of special treatment, as they tended to score well on the SAT. Because the average SAT scores of black, Mexican-American and Native American applicants were well below that of non-Hispanic whites—by 19, 14 and 9 percent, respectively, in 1999—they were held to a lower test-score standard to compensate for poor schooling.

Despite affirmative action, the proportion of blacks, Hispanics and Native Americans graduating from college is still much smaller than that of whites and Asians. The proportion of white non-Hispanic males earning bachelor's degrees has leveled off since 1993 for reasons that are not clear [see "Men, Women and College," By the Numbers, October 1999]. Reverse discrimination against white males is probably not a major impediment to a bachelor's degree, except perhaps in elite universities.



SOURCE: National Center for Educational Statistics and U.S. Bureau of the Census. Data are annual estimates of the percentage in each group that were awarded bachelor's degrees, calculated by dividing the number of degrees conferred by the number of 22-year-olds in the corresponding group.

The progress of disadvantaged minorities, unsatisfactory as it may seem, has provoked a powerful reaction against affirmative action, most notably in California, where in 1996 voters approved Proposition 209 by 55 to 45 percent. Prop. 209 bars preferential treatment on the basis of race, sex, color, ethnicity or national origin, including preferential treatment in public education. The surprising consequence has been to push the eight-campus University of California system into a potentially more effective way of raising minority enrollment. Affirmative action as practiced in the system was a more or less passive procedure, but under the new dispensation the campuses are now working far more vigorously with high schools and even elementary schools to achieve the kind of academic record that presumably will lead to disadvantaged minority students being accepted by the university system.

Whether the new outreach program will ultimately be effective won't be known for some time. The number of minority freshmen from the three disadvantaged groups entering the University of California system fell from 1997 to 1998, the first year in which the new restrictions applied, but in 1999 it partially rebounded on the two most selective campuses, Berkeley and Los Angeles. Riverside, the least selective university campus in the system but the one with the most vigorous outreach program, increased its proportion of disadvantaged minorities between 1997 and 1999.

—Rodger Doyle (rdoyle2@aol.com)

RODGER DOYLE

In Brief, *continued from page 22*

One Last Stretch

It may be shocking to family members and cause them to question the brain-death diagnosis, but many dead patients can have spontaneous movements, such as jerking of fingers, bending of toes and even stretching of arms and folding them over the chest. Jose Bueri of J. M. Ramos Mejía Hospital in Buenos Aires examined patients over an 18-month period and found that 39 percent of persons with brain death had motor movements up to 72 hours after diagnosis, far higher than previously thought. The study, in the January *Neurology,* determined the movements to be caused by spinal reflexes only, not brain activity. *—D.M.*

Shrinking to Survive

Shrinking is typically viewed as a sign of weakness, but 18 years of data have now convinced scientists that it's beneficial, at least for Galápagos iguanas. To boost survival during food shortages (caused by El Niño weather), the algae-eating reptiles shrank as much as 2.7 inches—up to 20 percent of body length. As reported in the January 6 *Nature,* bone absorption accounted for the shrinkage, which led to smaller mouths more efficient at harvesting the tiny amounts of available algae. When the supply returned to normal, specialized hormones probably triggered renewed bone growth, restoring the iguanas to size. The finding may lead to insights in treating osteoporosis. *—D.M.*

When shrinkage matters

GALEN ROWELL *Corbis*

Organic Space

Life's molecules seem more common in space than previously thought. Sun Kwok of the University of Calgary and his colleagues have found complex organic molecules—including aromatic rings and possibly carbon 60 (buckyballs)—in planetary nebulae, the debris that sunlike stars cast off as they die. The compounds formed rapidly (in about 1,000 years) despite the seemingly unfavorable conditions of low temperature and density. In separate work, Sonali and Sandip K. Chakrabarti of the Bose National Center for Basic Sciences in Calcutta calculate that the DNA base adenine could form in interstellar clouds. Both studies will appear in *Astronomy and Astrophysical Letters.* *—G.M.*

SA

ANTI GRAVITY

C-A-T-T-T-T-T-T-T-T

The fog comes on little cat feet," wrote Carl Sandburg. The great poet and historian may merely have been attempting to animate water vapor, but he presciently put his finger on one of modern life's more vexing problems. Feline feet can indeed induce a fog, as when you return from grabbing a cup of coffee and find that the cat has done a foxtrot all over the computer keyboard. Four furry paws can turn the "Now is the time for all good men" that was left on screen into "Now is the time for all good mennnnnbbbbbbbvcccccc-cxzzzzzzxcvbnm,;/////////ppoooo," a decidedly less cogent, if more original, thought.

We human beings are not completely without our wiles, though. Faced with this epidemic of cat hacking, a member of our species named Chris Niswander set his mind to cat-proofing computers for the benefit of all humanity. What sparked his thinking, Niswander says, was his sister's cat, whose footwork crashed a running program and uninstalled some software. "It was kind of impressive," he said of the cat feat.

Curiosity killed the keyboard.

STEVE MIRSKY

Niswander, a 30-year-old software engineer and president of a Tucson software company called BitBoost, ultimately created PawSense, a program that allegedly discriminates between people and cats. Should it decide that a series of strokes was most likely the footwork of a cat, PawSense cuts off further keyboard input until it is absolutely convinced that a person is back in charge. Whatever anthropic endeavor may have been left half-done and unsaved because of an impulsive fridge trip, mail run or bathroom break is thus kept safe from cat curiosity.

How PawSense tells a cat from a person is, like good comedy, mostly a matter of timing. "The difference between human typing and cat typing is not that cats type gibberish," Niswander notes, because humans also type stuff that looks like gibberish, such as some odd computer language. "The way that you detect cat typing is by analyzing the combinations of key presses and the timings of those key presses in the combinations," he explains. Were I, a typical human, to describe something I've seen, I would type the letters s, a and then w. Were I a cat attempting to share its experience of the world, however, I'd probably press those three letters simultaneously and trigger the software's alarms. Were I Hunter S. Thompson, I might find that the software stifles my creativity.

I recently tested PawSense, using a borrowed cat named Schrier. The software worked surprisingly well, blocking Schrier from her attempts to improve sketchy works of questionable literary value. Once the software makes its decision that a cat has commandeered the keys, the monitor screen turns gray and boldly warns, "Cat-Like Typing Detected." It also runs a choice of incredibly annoying sounds, such as a harmonica, bad operatic song stylings and general hissing that, at least in theory, may drive a cat away from the computer.

A human has two ways to reestablish keyboard dominion. One may type the word "human" to prove that one in fact is one. Or, based on the assumption that a cat cannot manipulate a computer mouse with anything resembling the decapitating dexterity the species exhibits with an actual mammalian mouse, a person can click a bar on screen that reads, "Let me use the computer!" An added benefit of the software is that it may train your average human to be at least a slightly better typist—I triggered the program once when I mashed a bunch of keys typing this story.

Of course, PawSense is but a stopgap. The day is dawning when voice-recognition technology will remove the keyboard from the computer-human interface. Cats may then creep on their silent haunches back to their usual haunts. Such an evolutionary development should open up a new niche: parrots seem destined to be the bane of tomorrow's computer users, with some future "BeakSense" software presumably designed to monitor obsessive use of the word "cracker." *—Steve Mirsky*

BRAIN INVADERS

A new auditory prosthesis implanted directly into the brain stem may restore hearing

For tens of thousands of profoundly deaf adults and children worldwide, cochlear implants have provided a useful substitute for natural hearing. These devices electrically stimulate the auditory nerve within the cochlea, enabling many users to carry on a conversation without visual cues, such as over the telephone. But for patients whose nerve endings have degenerated or whose auditory nerves have been destroyed, the only hope for restoring hearing is to access later stages of the auditory system. Now California researchers are gearing up to do just that, going beyond cochlear implants with a device that will plug directly into the brain.

At the Huntington Medical Research Institutes (HMRI) in Pasadena, Calif., neurophysiologist Douglas McCreery shows off a cat that is already using the new device. Like a cochlear implant, it consists of an external speech processor and a receiver implanted under the scalp. But the wires from the receiver bypass the cochlea and instead travel all the way to the brain stem. They end in an array of six iridium microelectrodes that penetrate the ventral cochlear nucleus, one of the auditory centers that normally receive input from the cochlea. The implant isn't meant to enable McCreery's cat to hear—its natural hearing is in fact still intact. Rather McCreery records the neural signals the implant produces and finds that the signals convey the frequency-coded information appropriate for the comprehension of speech.

Auditory brain stem implants are not entirely new. Researchers at HMRI and at the House Ear Institute (HEI) in Los Angeles developed a prototype device in the late 1970s, and it was further refined in collaboration with Cochlear Ltd. in Sydney, Australia, the leading manufacturer of cochlear implants. The hope was to aid patients suffering from the inherited condition neurofibromatosis type 2 (NF2). In young adulthood these persons develop bilateral tumors on the eighth cranial nerve, of which the cochlear nerve is a part. To save lives, surgeons must resect the tumors, but the surgery often plunges the patient into permanent and total deafness.

In its current form the brain stem implant features an array of eight flat electrical contacts that are simply placed against the surface of the brain stem near the ventral cochlear nucleus. The recipients of these devices—about 150 people globally—get enough auditory information to improve their lip-reading skills and to perceive environmental sounds, but they rarely attain good speech comprehension in the absence of visual cues.

According to Robert Shannon, an auditory psychophysicist at HEI who is collaborating with McCreery, the limited effectiveness of the current brain stem implants is a consequence of the architecture of the ventral cochlear nucleus. Within the nucleus, different frequency bands are represented by layers of neural tissue stacked parallel to the brain surface: the deeper the layer, the higher the frequency. You can add all the surface contacts you want, Shannon says, but they will usually generate sound perceptions of about the same pitch. As a result, the current multichannel brain stem implants are not much better than the original single-channel cochlear implants, which simply generated noise bursts in the rhythm of speech. (Single-channel cochlear implants have long been supplanted by 8-, 16- and 22-channel models.)

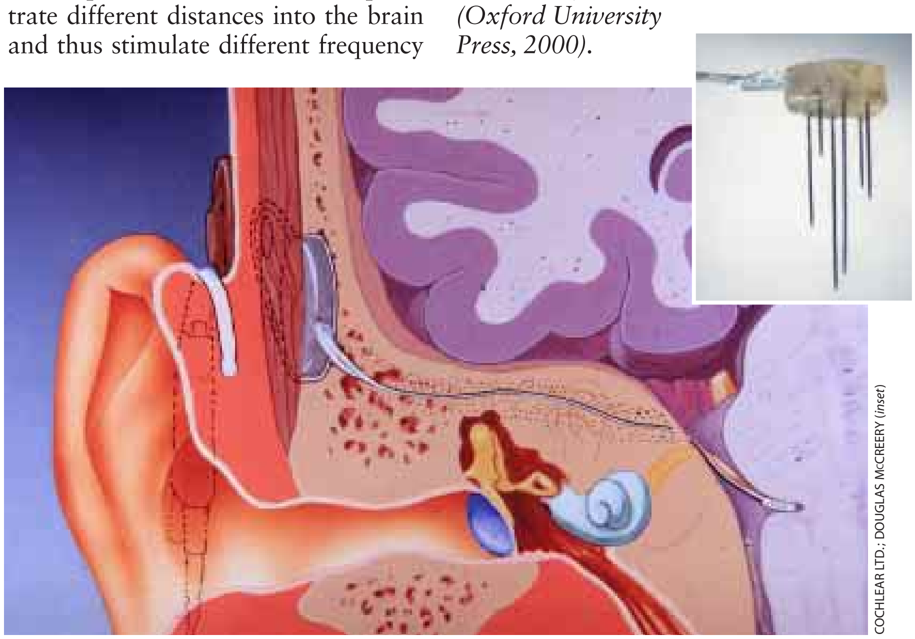
According to Shannon, the comprehension of speech requires a minimum of about four frequency channels. In the new implant, six microelectrodes penetrate different distances into the brain and thus stimulate different frequency bands; the array may therefore make phone conversations possible.

Initially the six-electrode array will be used in conjunction with Cochlear's existing brain stem implant. This way, McCreery says, the recipients will at least have the current device to fall back on. Because it takes difficult and invasive surgery to reach the brain stem, the devices will be offered only to people who must undergo the surgery anyway—principally NF2 patients. Ultimately, though, McCreery envisages that the devices will be implanted stereotaxically—that is, by means of a needle that is guided to its target by reference to a three-dimensional computer model of the patient's brain. This technique could make the implants available to a much wider group of deaf people, such as those in whom pathological bone growth has rendered the cochlea inaccessible to implants.

The timetable for human testing of the new device is uncertain, because engineers at Cochlear must first integrate it into their current implant. But William Hitselberger, the HEI neurosurgeon who will most likely be the first to implant the device, is ready: he has already practiced the maneuvers required to get the fragile electrode assembly to its destination deep within the head.

—Simon LeVay

SIMON LEVAY is a neuroscientist turned science writer based in Los Angeles. He wrote Here Be Dragons: The Scientific Quest for Extraterrestrial Life *(Oxford University Press, 2000).*



COCHLEAR LTD.; DOUGLAS McCREERY (*inset*)

***AUDITORY IMPLANT** bypasses the cochlea and terminates in six microelectrodes* (inset) *that penetrate the brain stem to different depths.*

PROFILE

Between Burb and Burg

The father of New Urbanism, Andres Duany, is reshaping suburbia—and the practice of architecture

It was 9:30 P.M. on a November evening when the nation's premier critic of suburbia decided to cross the road. Town planner Andres Duany had just started a weeklong design session in Huntersville, N.C., and we went out for dinner. The first place we tried was closed, so we left the car and set out in search of another. What were we thinking? Sidestepping Texaco pumps, pushing through a hedge, scampering down an embankment, hopping over mud puddles and dashing across four lanes, we made it to an isolated stretch of sidewalk by a drive-through bank teller. "Sometimes I forget where I am," Duany told me the next day. "They all look the same."

Duany came to this suburb of Charlotte, one of the fastest-growing cities in the U.S., to help it map a way out of the sprawl. Across the country he and his wife, Elizabeth Plater-Zyberk, are forging amalgams of burb and burg: pedestrian-friendly neighborhoods rather than more subdivisions, more mini-malls, more parking lots and more traffic. Talk of "smart growth" owes much to their insights. But are they also achieving their broader goals of social engineering? Duany argues that modern architecture shouldn't be a game of one-upmanship, as it often becomes, but a means to strengthen communities: "Success is not just to say, 'My house is in better taste,' but, 'My daughter has more friends than before.'" By those standards, however, their success is uncertain.

DONNA BISE *Gamma Liaison*

***YOU CAN'T BUY MILK** in most suburbs without taking the car, says pedestrian-friendly planner Andres Duany.*

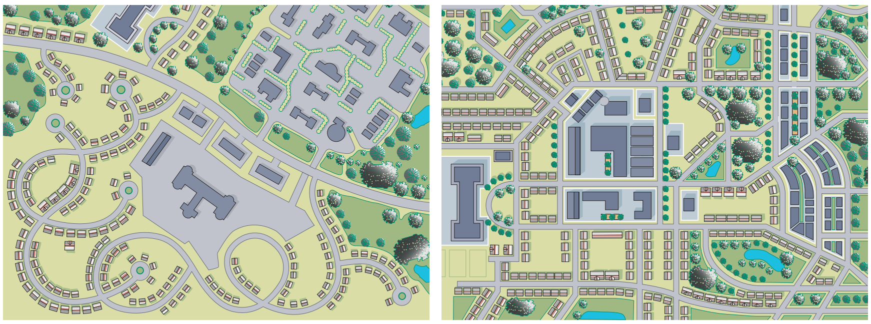
Born in New York City in 1949, Duany grew up in Cuba in a family of property developers, leaving at age 10 during the revolution. He met Plater-Zyberk at Princeton University, and together they went to graduate school at Yale University in the early 1970s, studying under the famous architectural historian Vincent J. Scully. From 1976 to 1980 they designed high-rise condos at a high-powered architecture firm in Miami. Then came the epiphany, which Duany attributes to a series of talks by Léon Krier, an urban theorist from Luxembourg. With Robert S. Davis, an idealistic local developer, the couple drove around the hamlets of the South in a Pontiac convertible, collecting ideas for a small town of their own. The result was Seaside, a gingerbread-and-picket-fence resort near Panama City, Fla., that quickly became a mecca for architects and planners (and later the set for *The Truman Show*). Thus began the New Urbanist movement. Today there are 124 neotraditional developments, 31 of which the couple's firm designed. Plater-Zyberk is now dean of the University of Miami's school of architecture.

"There are people who love suburban sprawl," Duany explains. Suburbia does, after all, provide a standard of living unavailable in cities except to the wealthy. "The problem is that those who do not love it are not being provided for." For them, the New Urbanists have resuscitated the principles that governed pre-1945 town planning—in particular, the integration of the houses, shops, offices and civic buildings that postwar zoning keeps strictly separated. In New Urbanist developments, no house is more than a five-minute walk from a neighborhood center with a convenience store, coffee shop, bus stop and other amenities. Neighborhoods also mix different housing types—apartments, town houses, detached houses—and therefore different income levels and age groups. The segregated layout of conventional suburbia, Duany argues, is the origin of its complaints, such as loss of open space and slavery to the steering wheel.

He and Plater-Zyberk are also renowned for their attention to the little things: garages and parking lots are tucked away behind buildings, sharp street corners discourage speeding, sight lines end with important buildings or interesting views. Conscientious design compensates for the higher housing density. In conventional suburbia, Duany says, people make the opposite trade-off: buildings, front lawns and streets are out of proportion, cheap detailing passes for craft.

I have come to Huntersville to see the lesser-known side of New Urbanism, how it builds consensus as well as streets. Along with half a dozen of the idealistic twentysomething architects that his firm attracts, Duany transforms the town council chamber for a week into a design studio, replete with black lamps, white posterboard and the whiz-grind of pencil sharpeners. Every day utilities engineers, parks officials or fire marshals come to meet. Every evening Duany presents the latest plans at a public meeting. The effort—known as a charette, a French idiom that connotes an intense project—is more than the usual boring town meeting. It is a chance for a community to take stock of its future and to see whether Duany's practices really do nurture openness and communal problem solving.

In Huntersville the task is easier than elsewhere. The town, having seen its population swell from 3,000 to 26,000 in a decade, scrapped its traditional zoning ordinances and adopted a New Urbanist code in 1996. Now the town, working with private developers, wants to renovate an abandoned century-old textile mill and its 32-acre site, located near the remnants of the downtown and on a rail line slated for eventual passenger service.


IAN WORPOLE

***SUBURBAN LANDSCAPE** often consists of subdivisions of malls, corporate parks and housing* **(left)**, *whereas New Urbanism mixes shops, offices and homes* **(right)**.

Still, Duany gives the pitches demanded of him in less sympathetic places. To developers and bankers, wary of deviating from established formulas, he talks about the profits his projects have earned and about the desire in a growing number of communities to stop development altogether. "The New Urbanists are what's going to save the development industry in this country," he says. To residents and small-business owners, cynical about change and anything political, he talks about ensuring that growth will improve rather than diminish the community (not to mention their property values). "The choice isn't whether people come or not," he says. "It's how much land they'll consume."

To elected officials he talks about how the project, one of the few to incorporate public transit from the outset, will be a model for the nation: "There's an open-mindedness in North Carolina. I've always found it easier to work here." Never does Duany downplay the challenges; to the contrary, he seeks to make everybody his co-conspirator: "The great gamble here is that this project gives density a good name, so Charlotte doesn't become like Atlanta, where all anyone talks about is the traffic."

Duany naturally dominates whatever group he is with. If he stops walking, everyone stops; if he starts talking, others hang in midsentence. His perfect posture makes you conscious of slouching. At times, however, he starts to overplay his charisma and celebrity. On the second day of the charette, a representative of Norfolk Southern Railway disputed Duany's description of the planned train line as a light-rail link among neighborhoods. Rather, he said, it would provide rapid commuter service into downtown Charlotte. The dispute was not merely semantic. The railman wanted a wide right-of-way, which could isolate the project and leave Huntersville without a coherent town center.

Duany raised his voice; the Norfolk Southern representative crossed his arms. Off to the side, I shifted in my seat. Duany was doing just what he told me he tries not to: enter into direct debate on a local issue and potentially set himself up as the bad guy. But suddenly he stood up, went over to one of his staffers and brought back a piece of tracing paper with two parallel lines an inch apart. It was a scale drawing of the right-of-way that the railman wanted. The two of them hunched over the plan and maneuvered the tracing paper until the tracks fit in. In little negotiations like this, New Urbanism adapts to local conditions and gains experience for future projects.

After one evening presentation, Duany and I go to see *American Beauty,* praised by critics for its take on suburban alienation. "At the beginning of the movie," he tells me afterward, "I said, 'I can't take suburbia anymore, I've got to get out of this business.'" Successful though his cajoling and compromising usually are, he insists he's getting tired of it all. He plans to spend more time on teaching and writing (including his first book for the general public, *Suburban Nation: The Rise of Sprawl and the Decline of the American Dream*). Yet if his energy is waning, it doesn't show in his vehement responses to his critics, tapped out on a Psion handheld computer in the interstices of the charette.

Environmentalist skeptics want New Urbanists to reclaim cities and older suburbs, rather than collude with developers to devour more land. But Duany insists he's only being pragmatic. Although New Urbanist insights are also needed in urban areas, they generally materialize in green fields because that's where the new development is. Other critics mock the Georgian or Craftsman architecture found in most New Urbanist projects, which they see as sappy nostalgia rather than the stuff of real towns. But they overlook the designs, such as one for Jersey City, N.J., that incorporate contemporary architecture. "I don't care about style but about harmony of style," Duany explains. He views his plans and codes as modern versions of those that guided the development of the world's most vibrant and livable cities, from Siena to Savannah.

One criticism is not so easily dismissed. The very popularity of New Urbanist developments drives up their prices and undercuts one of Duany's stated goals: diversity. The cheapest house now on sale in Seaside is a 1,000-square-foot cottage for $510,000. His own staffers told me they cannot afford to live in the places they design. It is an issue that Duany says he still struggles with. Underdesigning homes—making the closets smaller, say—holds down their value. "To make it affordable, you have to make it less pleasant," Duany says. The absolute price level, however, is set by scarcity. According to Robert L. Chapman of the TND Fund, a Durham, N.C.–based investment group, neotraditional development has doubled since 1998 but still accounts for only $1 in $460 of new housing.

Before leaving the cinema, Duany and I eavesdrop on teenagers hanging out in a nook of the lobby. "I need to understand teenagers better," he confides. Which is interesting, because nearly everything he does already seems directed at them. Conventional suburbia is almost custom-made to frustrate young people. How will they respond to the New Urbanism? Will the children of Huntersville want to settle in their hometown or be able to afford to? A generation will pass before we know whether New Urbanism really does make a lasting difference in how people live and interact. It takes a child to raise a village.

—George Musser in Huntersville, N.C.

FOSSIL SELLING

BIDDING ON BONES

Internet auctions are putting fossils out of paleontologists' reach

Fossil shark, $5,300. Ichthyosaur skeleton, $10,000. Too pricey? Try a shard of a dinosaur egg for less than $10. Place your bid and own a piece of the past—it's all just a mouse click away.

Paleontologists have always cringed at the thought of significant fossils disappearing into the living rooms of private collectors. But now on-line auctioneers are snapping up fossils along with Depression-era glass and Pokémon trading cards, expanding commercial markets and driving up prices. That's good news for fossil dealers but not for paleontologists who want to study the specimens and preserve them for the public.

"I just bristle at the thought of our fossil heritage being available for sale to the highest bidder," says Mark B. Goodwin of the University of California at Berkeley's Museum of Paleontology. Goodwin had a personal run-in with the commercial appetite for fossils: a tyrannosaur jaw missing from the museum since 1994 finally turned up last June after passing through the hands of a dealer in Germany.

Goodwin and other paleontologists fear that the popularity of on-line fossil sales will accelerate the demand. They are particularly irked by the Discovery Channel, which staged an on-line auction last August with Amazon.com. The researchers considered the auction to be a slap in face, because the Discovery Channel relies on the cooperation of paleontologists for many of its television and on-line documentaries.

Moreover, esteemed University of Chicago dinosaur expert Paul C. Sereno and other investigators are outraged that their research—featured in the documentary "When Dinosaurs Ruled" that was broadcast last August on the Learning Channel (a cable network under the Discovery umbrella)—was used to promote the on-line auction. Amazon.com advertised the program to entice viewers to buy a dinosaur tooth from the same African locale in which Sereno was fossil hunting—a tie-in that even fossil dealers admit could compromise professional integrity.

Complicating matters is the fact that Discovery actively promotes science. Over the past five years, Discovery networks have devoted 75 hours of TV programming to paleontology, and Discovery's expansive Web site features live reports from fossil-hunting expeditions. During a dinosaur dig in Alaska last summer, Discovery Online helped to finance a helicopter rescue of a dinosaur skull trapped in a secluded valley.

"You can't stop people from selling fossils, but why does an organization like Discovery Channel support it?" asks Kevin Padian, a paleontologist at Berkeley. "We would like to see them dissociate themselves from any type of fossil sales." The "we" Padian refers to are members of the Society of Vertebrate Paleontology (SVP), an international organization that opposes the sale of scientifically significant vertebrate fossils to private parties.

SCULPTURE BY BRIAN COOLEY, COURTESY OF THE FIELD MUSEUM

SKY-HIGH PRICES—$8.36 million in the case of* T. rex *Sue—have mobilized paleontologists against rare-fossil sales.

Padian and others would like to see laws passed that help to deflate the fossil demand by making it illegal to export vertebrate fossils from the U.S. and that reinforce the sanctity of public lands against commercial fossil exploration. Taking a stand with Discovery is one step toward those goals. Shortly before the annual meeting of the society's 1,900 members in Denver last October, Padian and his colleagues encouraged paleontologists not to cooperate with journalists working for Discovery.

"We were out to get a little bit of prehistory into people's hands," explains Bill Allman, senior vice president and general manager of Discovery Online Networks. "As a kid, that's the kind of thing that got me into science." After catching wind of the impending boycott, Allman hopped a plane to Denver to hear the SVP complaints. "We agree with their sentiment 100 percent—rare fossils don't belong in the hands of private collectors," he adds.

The complaints came as a surprise, Allman says, because Discovery had already hired a paleontologist to make sure that none of the fossils in the auction were rare or illegally acquired. But their expert was suspect in the eyes of many SVP members because he is also the owner of the for-profit company that provided the fossils for the sale.

In any case, deciding what's scientifically significant and what's not is not that simple. Rick Hebdon, a Wyoming-based fossil dealer and owner of Warfield Fossils, says that even the big-ticket item in the Discovery auction—the skeleton of an Ice Age cave bear that sold for $40,000—is not "endangered." Yet as Padian points out, researchers covet complete skeletons of any large vertebrate animals because a single specimen can reveal hints about the general population. Knowing exactly where and how deep the fossil was buried, for instance, yields clues about how long and how far the species roamed.

Still, selling fossils that are legally acquired is "the American way," insists Hebdon, who has seen the market bloom in his more than 20 years of selling fossils. "What these paleontologists ought to be doing is raising money to buy the fossils from the private sector." Hebdon says he has an extensive collection of fossil birds that caught the eye of a paleontologist from the Smithsonian Institution, but the museum hasn't managed to meet his $80,000 asking price.

Sometimes scientists get lucky, as they did in 1997 when Sotheby's auctioned off Sue, reputedly the world's largest and most complete *T. rex* skeleton, for $8.36 million. McDonald's and Walt Disney World Resorts footed much of the bill for the bones, which will make their public debut in May at the Field Museum of Natural History in Chicago.

Without corporate help even the richest museums have little hope of purchasing the *T. rex* skeleton that a Kansas fossil dealer put up in mid-January for on-line bidding on a Lycos auction site. Starting bid: $5.8 million. (As of press time, no bids had been made.)

SVP officials don't expect Lycos to match Discovery's conciliatory approach. And although Allman says he can't promise that another Discovery auction won't happen in the future, he has invited SVP representatives to come to Discovery headquarters in Bethesda to discuss their concerns further.

"Their response, as it was conveyed at that time, was exactly what we would have asked for," SVP president John J. Flynn says. "The ultimate proof is in the action." *—Sarah Simpson*

GENE THERAPY

WORKING UNDER PRESSURE

Pushing DNA into cells makes a safe form of gene therapy work

Investigators working on virus-based gene therapy are still trying to regroup after a participant in one study suffered a fatal reaction last September. A radically different approach to gene therapy, however, is attracting more favorable attention since evidence has emerged that it can benefit patients—perhaps the clearest indication yet of a favorable response to any kind of gene therapy.

Researchers at Harvard Medical School are using a chemically modified form of DNA under pressure to treat veins being grafted into patients as substitute arteries. The basic grafting procedure—bypass surgery—is performed 500,000 times a year in the U.S. to treat coronary arteries that are becoming blocked as a result of atherosclerosis. Another 75,000 procedures relieve similar problems in leg arteries. The body has more veins than it needs, so surgeons use leg veins for the grafts. The grafts often fail within a few years, however, damaged by a rapidly progressing form of atherosclerosis. The disease accelerates because veins change their cellular structure in reaction to the higher pressures in the arterial circulation.

A group led by Victor J. Dzau of Brigham and Women's Hospital and Harvard Medical School has been using a short synthetic variant of DNA called an oligonucleotide to turn off specific genes within grafted veins. The genes are essential for cells to divide. If the cells cannot divide, the vein will not undergo the changes that set the stage for galloping atherosclerosis.

The investigators treat the veins for a few minutes in a device that subjects them to a solution of the oligo under pressure. A tube inserted into the vein boosts pressure to about 2.5 times normal arterial pressure; the pressure outside the vein is increased, too, to prevent it from inflating. The treatment is quick and easy, so it can be done in the operating room while the patient is in surgery.

The pressure seemingly drives the oligo into cell nuclei, where it works as a decoy that fools an important molecule called E2F. This substance normally attaches to genes crucial to cell division, thereby activating them. The synthetic oligo binds itself to E2F, however, thus preventing it from doing its job and so inhibiting cell division in the graft.

Dzau's group has demonstrated that E2F-decoy oligos—but not oligos with random sequences—can inhibit genes and slow cell proliferation when used this way to treat veins grafted into legs. The first phase of the study included only 41 patients, most at high risk of a graft failure because their veins were themselves diseased. Grafts treated with the decoy failed at a rate less than half that in untreated grafts during the first year after surgery: 30 percent as compared with 69 percent, a significant difference. Subsequent phases will bring up to 2,000 patients into the clinical trial.

Dzau says several companies have expressed interest in making the oligo pressure treatment available commercially, and he expects to license the technique to one of the companies in the near future. Michael J. Mann, a member of Dzau's group, notes that the treatment is very safe, because the active agent, the oligo, is never introduced into patients. The group is now conducting a study with heart-bypass patients in collaboration with researchers in Germany.

Oligos might also be useful to inhibit genes that promote rejection in transplanted organs. Dzau's group has used a different oligo, also under pressure, to treat animals' hearts before they were transplanted. This oligo inhibits a molecule that interacts with the recipient's immune system, and the treatment seems to make transplant recipients tolerate grafts, Mann says.

Pressure treatment is not even limited to oligos: other animal experiments show that pressure makes tissues take up whole genes, Dzau points out. It seems pressure treatment could in principle be used in a variety of medical settings to alter the activity of specific genes.

Researchers at the Stanford University School of Medicine are looking hard at pressure treatment of hearts with oligos prior to transplantation, and Jon A. Wolff of the University of Wisconsin is studying pressure delivery of genes to muscles in monkeys. Wolff has found that a simple blood pressure–measuring cuff can increase blood pressure enough in an arm or leg to make almost 40 percent of cells take up therapeutic genes. Pressure delivery's apparent promise means that Dzau and other investigators are themselves under pressure—to gather enough data to prove that it can be used routinely to help patients.

—Tim Beardsley in Washington, D.C.

ROGER RESSMEYER *Corbis*

HEART-BYPASS grafts may last longer with pressure-driven gene therapy.

BIOTECHNOLOGY

BIOAGENT CHIP

A sensor to detect a biological warfare attack in seconds

Speed is of the essence in successfully containing a biological warfare attack. Quickly identifying the agent and how to treat those who have been exposed are keys to controlling an outbreak and minimizing its destructiveness. A handheld device containing a laboratory-on-a-chip may just be the answer. The result of breakthroughs in biology, chemistry and micromanufacturing, the instrument can immediately alert investigators to even the slightest hint of anthrax or smallpox in the air.

Although there are myriad proposals for building these biosensors, the double whammy of identifying a particular bioagent in less than two minutes, and doing so given a sample of only a few cells, has been difficult to achieve. "There are many diseases that are as effective as influenza—they can affect you at the single- or a few-particle level," says Mark A. Hollis, manager of the biosensor technologies group at the Massachusetts Institute of Technology Lincoln Laboratory, where a collaborative effort with M.I.T. biologist Jianzhu Chen and his colleagues hopes to deliver a prototype biosensor in less than 18 months. The work is part of the Defense Advanced Research Projects Agency's four-year, $24-million Tissue Based Biosensors program, which funds research by about a dozen universities and private firms.

Mouse B cells power the device. Part of the immune system, B cells express antibodies on their surfaces that bind to particular infectious particles. For example, most humans harbor B cells for pathogens that cause colds, polio, tetanus and other diseases. When a B cell binds to the intruder that it is built to recognize, a biochemical cascade occurs in the cell, triggering the body's immune system to rally to the defense. "We're leveraging off probably 600 to 800 million years of genetic engineering that nature has already done to recognize an infectious agent," Hollis observes.

With the design legwork out of the way courtesy of basic biology, Hollis's colleagues genetically engineer the B cells to respond to particular biowarfare agents. To know that the B cells have actually gone into action, the researchers plug into B cells another gene—from a jellyfish called Aequorea. This gene enables the jellyfish to glow with the bioluminescent protein aequorin. The aequorin instantly emits light when triggered by calcium ions—a substance that is produced when the bioagent-induced cascade occurs in the B cell. The entire process, from detection to bioluminescence, takes less than a second, beating any human handiwork to date.

Other methods have matched either the speed or the sensitivity of the B cells, but not both. The record for analyses using the polymerase chain reaction of a bioagent, Hollis says, is about 12 minutes, based on a pristine sample containing more than 20 organisms. Immunoassay techniques, which also use an antibody-capture methodology, are approaching the requisite speed but lack sensitivity: a sample containing at least several thousand copies of the organism is needed to identify an agent. In contrast, "only one infectious particle is sufficient to trigger a B cell because that's the way nature designed it," Hollis notes. "It's a beautifully sensitive system."

Currently the biosensor is a 25-millimeter-square plastic chip that has a meandering flow line running through it. One- to two-millimeter-square patches, containing 10,000 B cells engineered for an individual agent, line the surface of the channel. A strict diet combined with a room-temperature climate keeps the cells in their place by naturally discouraging cell division. Even hungry and cold, they stick to the task at hand.

Elegant microfluidics, also developed at Lincoln, direct the sample and nutrient media through the channel, where a charge-coupled device (CCD) like those found in camcorders detects even a single B cell firing. Identification based on five to 10 particles per sample has been demonstrated, and Hollis expects no problems detecting deadly bioagent particles in even the smallest numbers.

The biosensor, too, is naturally robust: exhaust, dirt and other contaminants that make the working environment considerably less than hospitable, compared with a B cell's traditional home inside the body, don't trick the cells into misfiring. "There's a lot of stuff in your blood, and these things are designed not to respond to any of it other than the virus they're intended for," remarks Hollis, who points out that the same B-cell–based biosensing technology developed for military use could be employed for instant viral identification in a doctor's office.

The last big question on Hollis's research agenda—whether the cells will reset after having fired—may not even matter in the group's latest vision for a handheld biosensor: a proposed optical-electronic box would read the photons emitted by a swappable and disposable biosensor chip, which would cost just a few dollars. "If you are hit with a biological attack," Hollis says, "you'll probably want to take the chip out and send it off to Washington for confirmation." Probably so. *—David Pescovitz*

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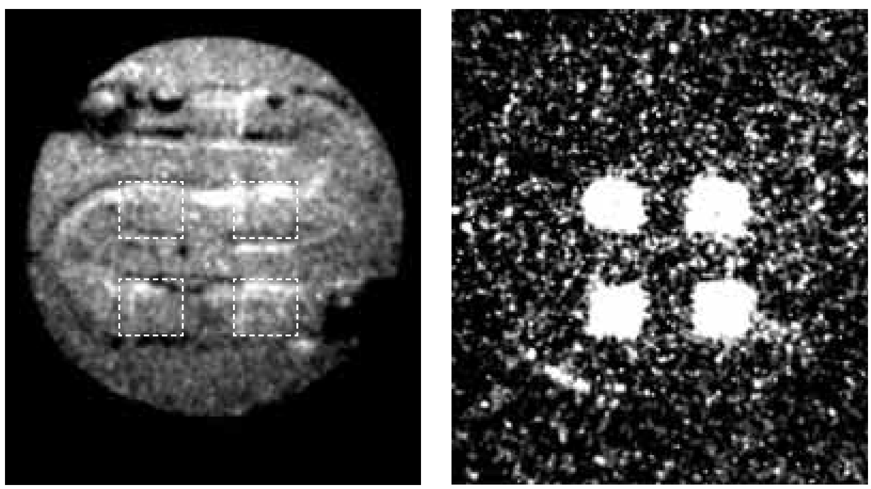


M.I.T. LINCOLN LABORATORY

***PROTOTYPE BIOHAZARD CHIP* (left) *quickly detects deadly bacteria. Air flows through the winding channel, meeting B cells* (located in the dotted squares). *The modified B cells glow when they encounter an infectious agent* (right).**

Mobilizing the Internet

A November 1999 research report from Cyber Dialogue, an Internet database marketing firm, warned e-commerce companies that they were going to have to work harder in the future: the stampede onto the Internet has slowed in the U.S. The survey cites three constraints to growth. First, it takes money to get connected, and many of those off-line simply can't afford Internet access. Second, a third of American adults believe that they have no need for the Internet and have no intention of getting on-line. Third, 27.7 million Americans have tried the Internet—and dropped it; the number is triple that measured in 1997. Only about a third of those individuals expect to go back on-line anytime soon. In other countries the boom continues. Expectations are that usage in China and Latin America is set to explode over the next few years.

Cyber Dialogue's conclusion is that e-commerce companies have to work harder to hold on to their customers—nothing new in the on-line world, where "churn" is a long-standing and familiar problem. What isn't clear is whether the limitation is in the Internet itself or in the way people access it. As mass market as it appears in comparison with its earliest incarnation, the Internet is formidably intimidating. The computers people must use to access it are complex and difficult (yes, even Macs), and the Internet itself is a collection of bewildering new concepts, even if the action of pointing and clicking seems simple (physically, it's not, as anyone knows who's watched someone completely new to a mouse try to use one).

The news comes at a time when the Net seems to be on the verge of reinventing itself yet again, first as high-speed access referred to as broadband rolls out and enables always-on connections, and second as mobile devices with built-in Internet access become widespread. A Palm VII user can stand on a city street, look up the nearest Barnes and Noble store and search its database of books. Mobile phones with built-in microbrowsers can display streamlined content—at the moment, mostly sports scores, stock prices and news headlines from services like My Yahoo. But major European content providers are already designing WML (Wireless Markup Language, the wireless version of HTML) versions of their Web sites.

Early reviews say that microbrowser-equipped mobile phones aren't ready for prime time, but that may be partly because they're trying to emulate the existing computer world. It's a logical first step, just as the first movies were films of theatrical plays. But my guess is that wireless access to the Web will quickly morph into something different. Sending instant, short text messages over mobile phones is already the latest teen craze in Europe—sort of ICQ without the heavy machinery. One intriguing possibility is mobile-phone access to Net-based radio: it's easy to imagine selecting from a series of menus using the number pad and then storing favorites in the phone's memory.

Pundits—usually computer geeks—talk about speed as important, but the big cultural shift really comes when connections shift to always-on. There is an immense difference between logging on to get e-mail and knowing that your e-mail is *there* whenever you feel like looking at it, as there is between having to save a list of Web pages to check on your next session and clicking over whenever a thought comes into your head. In this way of life, speed matters less: if a file is going to take hours to download, you don't care; you just go to bed. This carefree attitude is especially true for non-U.S. users, who wouldn't have to pay by the minute as they do for their dial-up connections. Wireless is quite likely to go through the same shift; reports of next-generation wireless anticipate that data will be deliverable the way incoming phone calls are now, and even battery life won't be a problem, as the heavy drain occurs only during transmission.


DAVID SUTER

That is a wholly different world of Internet access, one in which any device's natural abilities could be augmented by a connection (wireless or wired) and a constrained set of options. For example: Why shouldn't a television find and display in a corner the full cast and production details of the movie you're watching? Or your kitchen contain an appliance that can scan the codes of food containers and suggest recipes from the processor's collection?

In a typical discussion on London's electronic conferencing system CIX (Compulink Information eXchange), people complained about the new Web-enabled phones: some network operators have blocked off access to all but the Web services they want to provide (and bill for). The received opinion was that these firms would learn—just as telephone companies rolling out digital subscriber lines (such as British Telecom) have had to discover—that their users do not want video-on-demand from telephone companies but simply the freedom to roam far and wide on the Net. I think that argument is wrong, at least for large parts of the mass market. Constraining choices is of course a loss of freedom; but all-in-one simplicity made possible by convergence of features must have its virtues, or else no one would buy cars with automatic transmissions. Such bundling is much like what Donald Norman was talking about in his 1999 book *The Invisible Computer:* people, he said, used to buy electric motors and attach all kinds of whizmos to them. Now you just buy gadgets and take the electrical innards for granted, just as people who think they don't own computers forget about all the chips in their cars, washing machines and VCRs.

In 1998 I visited friends whose earlier lives revolved around the developing Internet, and we talked about the seeming impossibility that the Internet could pervade the farm culture around them. In their secluded mountain village in Crete, only one person they knew other than themselves had a computer—that's what he calls the remote control for his TV set. Ten years from now he could be right. —*Wendy Grossman*

WENDY GROSSMAN is based in London. She described on-line trading in the January issue.

WHY GO TO MARS?

In the first of this group of articles about human missions to Mars, staff writer Glenn Zorpette *examines the main goal: looking for life*

For centuries, explorers have risked their lives venturing into the unknown for reasons that were to varying degrees economic and nationalistic. Christopher Columbus went west to look for better trade routes to the Orient and to promote the greater glory of Spain. Lewis and Clark journeyed into the American wilderness to find out what the U.S. had acquired in the Louisiana Purchase, and the Apollo astronauts rocketed to the moon in a dramatic flexing of technological muscle during the cold war.

Although their missions blended commercial and political-military imperatives, the explorers involved all accomplished some significant science simply by going where no scientists had gone before. The Lewis and Clark team brought back samples, descriptions and drawings of the flora and fauna of the western U.S., much of it new to the colonizers and the culture they represented. The Apollo program, too, eventually gushed good data. "Our fundamental understanding of the overall geological history of the moon is largely derived from the last three Apollo missions," says Paul D. Spudis, a geologist and staff scientist at the Lunar and Planetary Institute in Houston.

FIRST WALK on Mars would be even more dramatic if dust storms were swirling nearby. The ascent vehicle, in the background at the right, would later loft the astronauts to an orbiting craft for the return trip.

Today Mars looms as humanity's next great terra incognita. And with dubious prospects for a short-term financial return, with the cold war a rapidly receding memory and amid a growing emphasis on international cooperation in large space ventures, it is clear that imperatives other than profits or nationalism will have to compel human beings to leave their tracks on the planet's ruddy surface. Could it be that science, which has long been a bit player in exploration, is at last destined to take a leading role?

The question naturally invites a couple of others: Are there experiments that only humans could do on Mars? Could those experiments provide insights profound enough to justify the expense of sending people across interplanetary space?

With Mars the scientific stakes are arguably higher than they have ever been. The issue of whether life ever existed on the planet, and whether it persists to this day, has been highlighted by mounting evidence that the Red Planet once had abundant stable, liquid water and by the continuing controversy over suggestions that bacterial fossils rode to Earth on a meteorite from Mars. A conclusive answer about life on Mars, past or present, would give researchers invaluable data about the range of conditions under which a planet can generate the complex chemistry that leads to life. If it could be established that life arose independently on Mars and on Earth, the finding would provide the first concrete clues in one of the deepest mysteries in all of science: the prevalence of life in the universe.

"If you find any life at all, what you'll have proven is that the processes that lead to the development of life are general," author and astronautical engineer Robert Zubrin said last fall in a speech at a conference at the Massachusetts Institute of Technology. "It's a question of vast philosophical importance, and Mars is the Rosetta stone for answering it."

Solid Evidence for Liquid Water

One of the reasons why the idea of sending people to Mars captivates at least a segment of the public is that it is already possible—the U.S. has the money and the fundamental technologies needed to do it. More important, recent discoveries about the planet's environment in the distant past have presented a clear and compelling scientific incentive for sending people: to search for evidence of life.

The theory that liquid water was once stable on Mars has been bolstered by the Mars Global Surveyor probe, which photographed a channel last year that appeared to have been deeply incised by water flowing for hundreds if not thousands of years. Global Surveyor's important findings followed the successful Mars Pathfinder lander, which touched down on the planet in July 1997 and was among the first fruits of the National Aeronautics and Space Administration's "cheaper, faster, better" paradigm for robotic space exploration. Under this strategy, the agency has been undertaking more frequent, less expensive and less ambitious space missions.

Pathfinder was hailed as a vindication of the paradigm, but the affirmation was short-lived. The back-to-back failures of the next two spacecraft, the $125-million Mars Climate Or-

PAT RAWLINGS

biter and the $165-million Mars Polar Lander, were reminders of how much can go wrong even on relatively straightforward robotic missions.

The failures will almost certainly mean a longer wait before people are sent to the planet. Although NASA does not now have any official mandate to send people to Mars, some of its planned robotic probes were to perform experiments specifically designed to help prepare for human missions. After the success of Pathfinder there had even been informal talk within NASA of a human mission around 2020. Such a timetable now seems optimistic.


NASA/JPL/MALIN SPACE SCIENCE SYSTEMS

HIGH-RESOLUTION IMAGE of Mars taken on January 1, 2000, shows unusual surface textures formed by unknown processes that may be uniquely Martian. The northern hemisphere terrain is in a region called Nilosyrtis Mensae.

Fossil Hunting on Mars

Rather than dwell on the recent setbacks, proponents of human exploration are using the controversial meteorite findings and the stunning Surveyor results to deliberate on discoveries and advances that experts could make on Mars. Zubrin, for example, says that "if we are serious about resolving the question of life on Mars—and not just whether it's there but also how far it may have evolved in the past—humans are required." To buttress his claim he notes that hunting for fossil evidence of ancient life would involve "traveling long distances through unimproved terrain, digging with pickaxes, breaking open rocks, carefully peeling away layers of fossil shales and lightly brushing away dirt. This stuff is way beyond the capabilities of robotic rovers."

A thorough hunt for any Martian life that might be hanging on—despite the present harsh conditions—would also have to be undertaken by humans, according to some experts. Such life will be hidden and probably microscopic, says Pascal Lee, a research associate at the NASA Ames Research Center. "Finding it will require surveying vast tracts of territory," he explains. "It will take a high degree of mobility and adaptability." Robots might be up to the task sometime in the distant future, Lee concedes. But relying on them to survey Mars completely for life would take an unrealistically long time—"decades if not centuries," he believes.

To accomplish the same scientific goals as a series of human missions, far more robotic missions—and therefore launches—would be required. The greater number of launches would mean that the robotic program would take much longer, because opportunities to travel from Earth to Mars are rather limited. They occur only once every 26 Earth-months, when the planets are positioned so that the trip takes less than a year. Some doubt whether a program lasting many decades would sustain the interest of the public and their elected officials. "Who's going to support a series of Mars missions that come up with negative results all the time?" Spudis asks.

Another reason why humans may have to be on site to conduct a thorough search for life stems from the fact that if any such life exists it is probably deep underground. Mars's atmosphere contains trace quantities of a strong oxidizing agent, possibly hydrogen peroxide. As a result, the upper layers of the soil are devoid of organic matter. So most strategies for microbe hunting involve digging down to depths where life or organic matter would be shielded from the oxidizing agent as well as from searingly high levels of ultraviolet light.

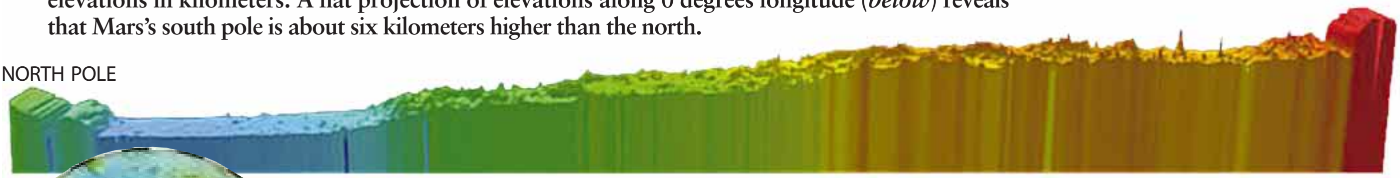
Upcoming probes will be equipped with robotic assemblies that can bore several centimeters into rocks or dig a few meters down into the soil. But barring any discoveries at those shallow depths, researchers will have to bring up samples from hundreds of meters below the surface, maybe even one or two kilometers down, before they can declare Mars dead or alive. Drilling for samples at such depths "most likely will require humans," says Charles Elachi, director of the Space and Earth Sciences Program at the Jet Propulsion Laboratory in Pasadena, Calif.

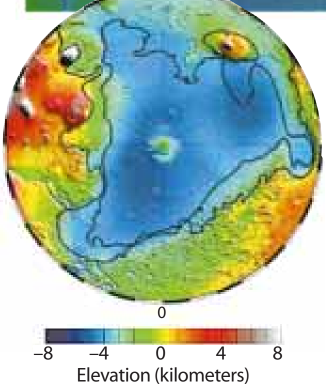
Few if any researchers argue that a human mission to Mars would not advance planetary science. The points of contention, predictably, have to do with the cost-effectiveness of human missions in comparison with robotic ones. The problem is that so little is known about several key factors that any analysis must depend on some largely arbitrary assumptions.

Then, too, it is difficult to predict the capabilities of robots even five or 10 years from now. Today the kind of robotic technology that can be delivered to another planet under NASA's "cheaper, faster, better" paradigm is not really up to the demands of a game of croquet, let alone those of fossil hunting in a frigid, unstructured environment. The kind of rover system that NASA has demonstrated on Mars is pitifully limited: the small Sojourner rover delivered by Pathfinder traveled just 106 meters around the landing site before Pathfinder stopped relaying its communications. And the best mobile-robot controllers are not even an intellectual match for a cockroach.

Telepresence, in which robotlike rovers would have sensors and manipulators that stand in for the eyes, ears and limbs of human operators on Earth, initially seems like an alluring option. Unfortunately, the round-trip time lag for communication with Mars is up to 40 minutes long. "You can't get telepresence," Spudis says. "At best, you

VAST OCEAN may have covered Mars's north pole to an average depth of several hundred meters. Black lines in the image (*bottom left*) indicate possible shorelines, and the color-coded scale shows elevations in kilometers. A flat projection of elevations along 0 degrees longitude (*below*) reveals that Mars's south pole is about six kilometers higher than the north.





get something like supervised telerobotics, and I don't think that would be good enough" to do serious scientific fieldwork.

One fact everyone agrees on is that human space missions are costly. Tallies of the cost of a human mission to Mars range from $20 billion—based on a scenario conceived by exploration advocate Zubrin [see "The Mars Direct Plan," on page 52]—to about $55 billion, NASA's current estimate. (For comparison, Congress appropriated $24 billion to pay for the U.S.'s role in the recent conflict in Kosovo.)

Although a human mission would be more expensive, it would also be more cost-effective, Zubrin insists. He concedes that sending astronauts to collect geologic samples and bring them to Earth would cost about 10 times more than sending robots. But by his calculations the human mission would return 100 times more material gathered from an area 10,000 times larger.

On the other hand, Arden L. Albee, a former chief scientist at JPL and the project scientist for the Global Surveyor mission, cites a 1986 study by NASA's Solar System Exploration Committee that determined that a robotic mission could have accomplished all the geologic sampling carried out on the moon during Apollo 15. In one day during that mission, astronauts David R. Scott and James B. Irwin drove a rover 11.2 kilometers, collecting samples at five stations. They picked up 45 rocks, 17 loose soil samples and eight firmly packed soil "cores." A robotic rover could perform much the same work, the study found, but it would take 155 days to do so. For much of that time the rover would be stationary while human experts on Earth were deliberating over its next move. Actual sampling would occupy 70 days, during which time the rover would be in motion for only 31 hours. "If you weigh [the benefits] against the actual cost, it becomes difficult to justify sending a man," says Albee, now dean of graduate studies at the California Institute of Technology.

Cooperation on Mars

With its enormous territory, astounding geologic features and inhospitable climate, the Red Planet will surely be conquered only by a combination of people and machines. NASA's Lee, for example, is leading a project at the Haughton impact crater on Devon Island in the Canadian Arctic. In the remote, frigid desert of the world's largest uninhabited island, he and his colleagues are studying the region's uncanny similarities to Mars and working out procedures and techniques that may be used by future explorers of the planet.

In their hunt for meaningful and representative samples, Lee and his co-workers have covered hundreds of kilometers and climbed to countless outcroppings. "There's no standard outcropping," he reports. "Few of the ones we've been to could have been accessed by a nonspecialized rover.

"Exploration and discovery is an extremely iterative process," he continues. "It is only with human adaptability and mobility that you can hope to go through that iterative process in a reasonable amount of time."

Still, Lee ventures that "nobody in their right mind should have a vision of humans alone on Mars." Semiautonomous machines, he explains, will be needed to do work that is too tedious or dangerous for people, such as performing aerial surveys and reconnaissance, creating supply depots, caches and shelters for long field trips, and transporting and curating the huge quantities of samples that geologists will gather.

Steven W. Squyres, the principal investigator of the project to build rovers for the sample-return missions to Mars, also envisions complementary roles for people and robots. His views coalesced some 15 years ago while he was participating in a project to study the geology, sedimentology, biology and chemistry of several Antarctic lakes. The environment under the ice was frigid, hostile and remote, like that of Mars. To gather data, the research team used both remotely operated vehicles (ROVs) and scuba equipment.

"The most effective way was to put the ROV down first, to answer the first-order questions," Squyres reports. "Then, when you figured out what you really wanted to do, you put the human down." He adds that the first-order questions in a search for life under the surface of Mars would be: "Where do you drill and about how deep? What's the Martian crust like? Is there subsurface water and, if so, where is it?" Squyres, a professor of astronomy at Cornell University, notes that more robotic missions to Mars are needed to answer those questions.

Although some scientists passionately argue scientific rationales for sending people to the Red Planet, there will probably have to be other imperatives as well. Nationalism—historically the most reliable motivator of grand exploration—is far from a sure thing, if for no other reason than that the project may be more than any one country is willing to undertake alone.

It is possible that a group of industrial nations, perhaps including a more politically and economically stable Russia, will seek to glorify themselves by going to Mars. And as business becomes increasingly global, space exploration may benefit from a new kind of nationalism. To distinguish themselves on the world's stage, international corporations may contribute capital or technology in exchange for the publicity value of being associated with a Mars mission or for the new technologies, broadcast rights or other potentially lucrative spin-offs.

After all, endeavors ranging from the Olympics to the recent global circumnavigation by balloon all benefited from heavy corporate sponsorship. A $55-billion event would dwarf those undertakings. But there may come a time when it will seem like a small price to pay to leave an indelible mark on history. SA

HOW TO GO TO MARS

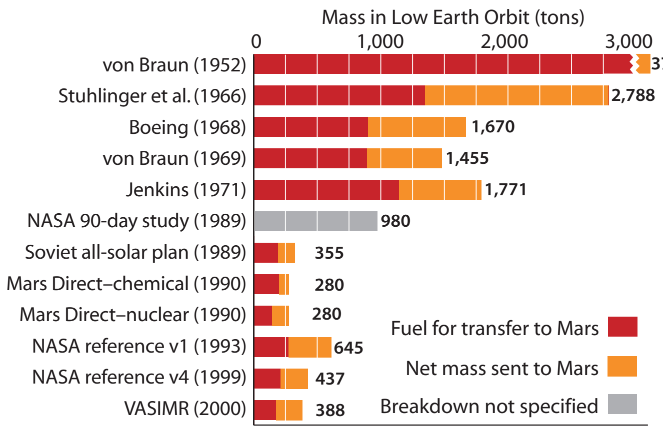
Staff writers George Musser *and* Mark Alpert *make sense of the myriad ideas for a human mission*

Going to Mars would be daunting. The planet never comes closer than 80 million kilometers to ours; a round-trip would take years. But scientists and engineers say they have solutions to the main technological challenges that a human mission would entail. The biggest obstacle is simply the enormous cost.

Cost estimates for a Mars mission boil down to one crucial number: the mass of the spacecraft. Lighter spacecraft need less fuel, which is the greatest single expense of a spaceflight. The history of Mars mission planning is largely an effort to minimize weight without unduly compromising safety or science. In 1952 rocket pioneer Wernher von Braun envisioned an armada of spaceships propelled by conventional chemical rockets and weighing 37,200 tons on departure. Just to haul such a fleet into Earth orbit would cost hundreds of billions of dollars. Since then, planners have wrung economies by using more efficient nuclear or electromagnetic rockets, scaling back the number of astronauts or the level of redundancy, and manufacturing fuel on Mars itself [*see chart at right*].

Today the barest-bone mission is the Mars Direct plan, with an estimated price tag of $20 billion in start-up costs, spread out over a decade, plus $2 billion per mission [see "The Mars Direct Plan," on page 52]. The National Aeronautics and Space Administration's own plan, the "design reference mission," has adopted many of the ideas of Mars Direct but costs roughly twice as much, in return for extra safety measures and a larger crew (six rather than four).

In its most recent version, NASA's plan [*see illustration on opposite page*] calls for three spacecraft: an unmanned cargo lander, which delivers an ascent vehicle and propellant plant to the Martian surface; an unoccupied habitat lander, which goes into Martian orbit; and a crew transfer vehicle (CTV), which, if the first two arrive successfully, sets out when Mars and Earth come back into alignment, 26 months after the



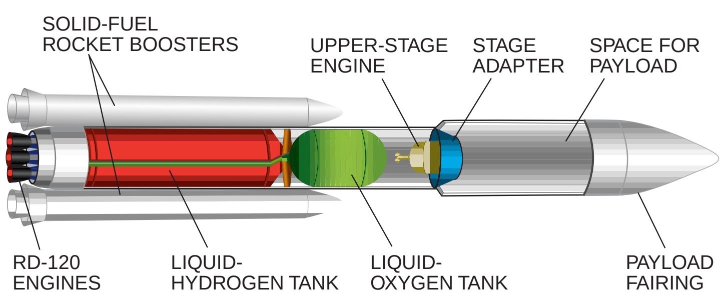
WEIGHT of proposed Mars missions on departure from Earth orbit—a proxy for cost—has slowly come down. Each weight estimate includes both crew and cargo flights for one team of astronauts.

EDWARD BELL

LAUNCH AND ASSEMBLY

In all the proposals for sending humans to Mars, the crucial first step is launching the spacecraft into a low Earth orbit (200 to 500 kilometers up). The basic problem is that any manned craft using present-day propulsion technologies will need a huge supply of propellant to get to Mars and hence will be extremely heavy: at least 130 metric tons and possibly twice that much. No launch vehicle now in use can lift that much mass into orbit. The space shuttle and heavy-lift rockets such as the Titan 4B have maximum payloads under 25 tons. Moreover, with launch costs currently as high as $20 million per ton, boosting a Mars spacecraft would be prohibitively expensive.

Aerospace companies are developing more cost-efficient rockets (such as the Delta 4) and reusable launch vehicles (such as VentureStar), but none could lift a 130-ton payload. The Apollo-era Saturn 5 could do the job, and so could the Energia booster developed by the former Soviet Union, but reviving production of either rocket would be impractical. So in all likelihood the Mars craft would have to be launched in stages and then assembled in orbit, preferably through docking maneuvers that could be controlled from the ground. (Assembling the craft at the International Space Station would be inefficient because the station's orbit has an inclination of 51.6 degrees; from the launch facilities at Cape



MAGNUM ROCKET is a relatively inexpensive option for launching the spacecraft that would carry the first astronauts to Mars. Using the same launchpads and solid-fuel boosters as the space shuttle, the Magnum could lift 80 tons into Earth orbit.

SARAH L. DONELSON

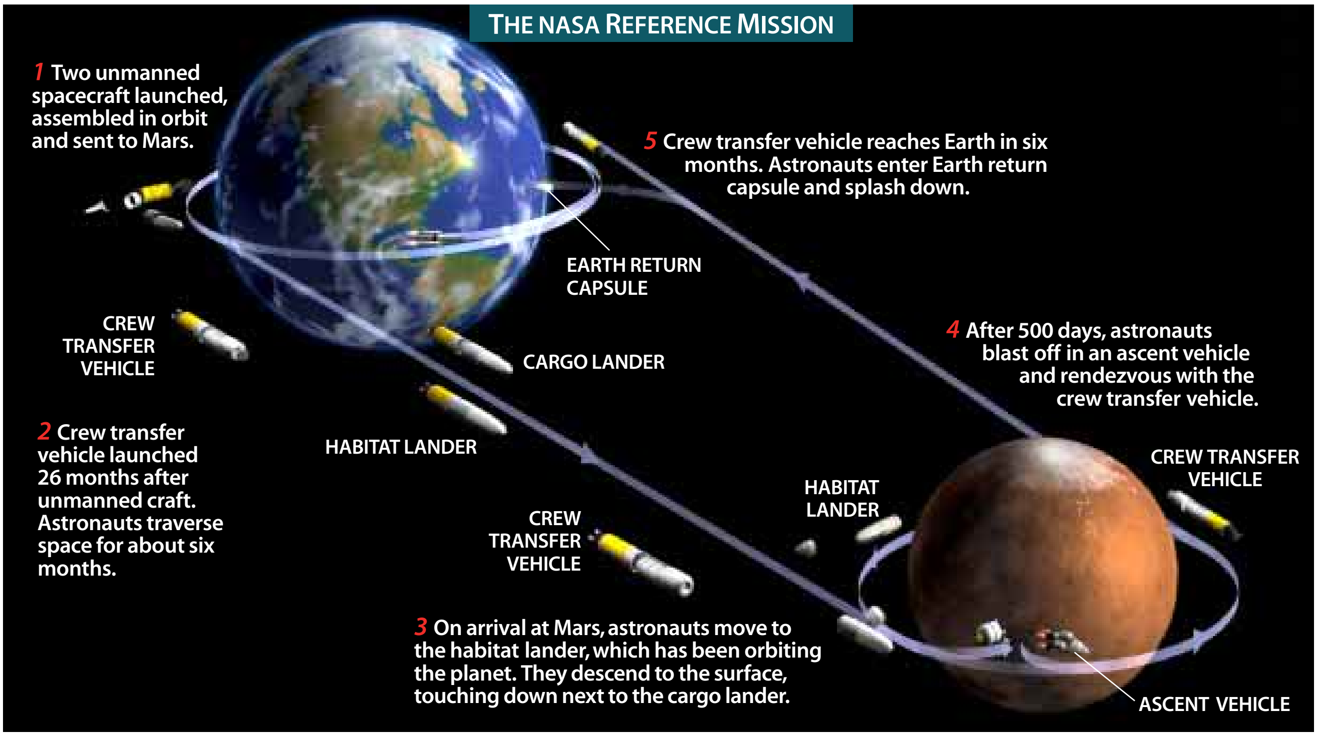
first launches. The CTV carries the astronauts to Mars and meets up with the habitat lander. The astronauts change ships, descend to the surface, stay for 500 days and return in the ascent vehicle. The CTV, which has been waiting in orbit, brings them home. Every 26 months, another trio of spacecraft sallies forth, eventually building up the infrastructure for a permanent settlement.

The estimated costs of these plans are cheaper than those of the International Space Station or the Apollo program. Still, NASA does not have a sterling reputation for adhering to cost estimates. For this reason, many Mars enthusiasts in organizations such as the Mars Society and the National Space Society have been casting about for new ways to run a space program.

The most fully developed plan is the work of ThinkMars, a group of students from the Massachusetts Institute of Technology and Harvard Business School. They propose setting up a for-profit corporation to manage the Mars project, contracting out the various tasks to private companies and NASA research centers. The U.S. and other governments would, in effect, buy seats or cargo space on the Mars ship at a reduced price. The difference would be made up by selling promotional opportunities and media rights and by licensing technological spin-offs.

Researchers have shown that a human mission is technically feasible. Now the enthusiasts need to win over the taxpayers, politicians and business leaders who would have to foot the bill.

We would like to thank the many scientists and engineers who have helped us map out the various technologies.

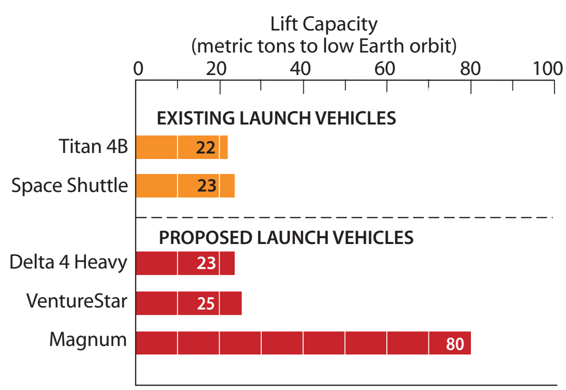


ALFRED T. KAMAJIAN

Canaveral, Fla., it is easiest to boost payloads into an orbit with a 28.5-degree inclination.) The space shuttle could transfer the crew to the Mars craft once it was completed.

To simplify the assembly, the number of launches and orbital rendezvous would have to be minimized. Engineers at the NASA Marshall Space Flight Center in Huntsville, Ala., have designed a rocket, called the Magnum, that could boost about 80 tons into orbit, enabling the deployment of a 130-ton Mars craft with only two liftoffs (for a comparison with other launch vehicles, see the chart below). The Magnum is designed to use the same launchpads and solid-fuel boosters as the space shuttle. The shuttle's boosters would be attached to a new two-stage rocket powered by three Russian-designed RD-120 engines. The Magnum could carry a 28-meter-long payload, and the skin of the rocket's upper stage could also serve as the Mars craft's heat shield.

Because the Magnum would use existing boosters and launch facilities, its costs would be relatively low: about $2 billion for development and $2 million per ton for each launch, which is a 10-fold improvement over the shuttle's costs. Furthermore, it may be possible to build an even more powerful launch vehicle from space shuttle components, as proposed by astronautical engineer Robert Zubrin. Called Ares, it would use a high-thrust upper-stage engine to put the manned spacecraft directly on a trajectory to Mars.



CURRENT LAUNCH VEHICLES cannot meet the needs of a human mission to Mars. Boosting a 130-ton Mars craft into Earth orbit would require six launches of the Titan 4B, space shuttle, Delta 4 Heavy or VentureStar—but only two of the Magnum.

SARAH L. DONELSON

PROPULSION SYSTEM

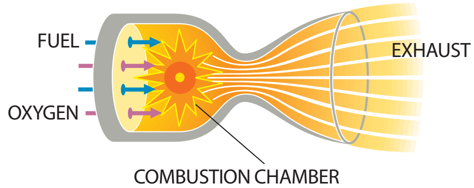
How can you propel a manned spacecraft from Earth orbit to Mars? Planners are considering several options, each with its own advantages and drawbacks. The basic trade-off is between the rocket's thrust and its fuel efficiency. High-thrust systems are the hares: they accelerate faster but generally consume more fuel. Low-thrust systems are the tortoises: they take longer to speed up but save on fuel. Both could be used in different phases of a single mission. High-thrust rockets can convey astronauts quickly, whereas low-thrust devices can handle slower shipments of freight or unoccupied vessels.

LEGEND FOR ILLUSTRATIONS
- PROPELLANT
- ELECTRIC CURRENT
- MAGNETIC FIELD
- OXYGEN

CHEMICAL

Nearly all spacecraft launched to date have relied on chemical rocket engines, which typically burn hydrogen and oxygen and use the expanding gases to provide thrust. It is a proven technology and produces more thrust than most other approaches, but less efficiently. Chemical rockets would require prodigious amounts of fuel to propel a manned spacecraft to Mars. One design calls for a 233-ton craft that would start the voyage with 166 tons of liquid hydrogen and oxygen. Its seven RL-10 engines (a venerable design used on many U.S. rockets) would be arranged in three propulsion stages. The first stage would boost the craft to a high elliptical orbit around Earth, the second would put the craft on a trajectory to Mars, and the third would propel the craft back to Earth at the end of the mission. Each stage would fire for a matter of minutes and then be discarded.

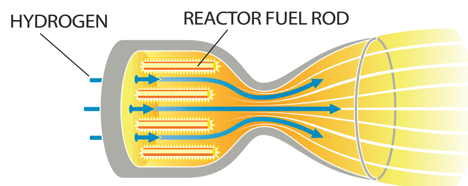
Thrust: 110,000 newtons
Exhaust speed: 4.5 kilometers per second
Sample burn time: 21 minutes
Sample fuel ratio: 55 percent



CHRISTOPH BLUMRICH

NUCLEAR THERMAL

The U.S. government built and ground-tested nuclear thermal rockets in the Rover/NERVA program of the 1960s. These engines provide thrust by streaming liquid hydrogen through a solid-core nuclear reactor; the hydrogen is heated to more than 2,500 degrees Celsius and escapes through the rocket nozzle at high speed. Nuclear propulsion delivers twice as much momentum per kilogram of fuel as the best chemical rockets, and the reactors can also be used to generate electricity for the spacecraft. A 170-ton manned vehicle containing three nuclear rockets and about 90 tons of liquid hydrogen could reach Mars in six or seven months. The big obstacle, however, is public opposition to putting a nuclear reactor in space—a problem for many other propulsion systems, too. NASA has not funded research into spaceborne reactors for nearly a decade.



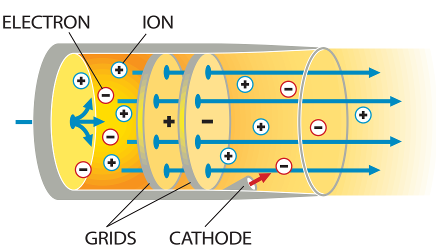
Thrust: 67,000 newtons
Exhaust speed: 9 kilometers per second
Sample burn time: 27 minutes
Sample fuel ratio: 32 percent

CHRISTOPH BLUMRICH

ION

First developed in the 1950s, ion propulsion is one of a number of technologies that use electrical fields rather than heat to eject the propellant. The gaseous fuel, such as cesium or xenon, flows into a chamber and is ionized by an electron gun similar to those in television screens and computer monitors. The voltage on a pair of metal grids extracts the positively charged ions so that they shoot through the grid and out into space. Meanwhile a cathode at the rear of the engine dumps electrons into the ion beam so that the spacecraft does not build up a negative charge. Just over a year ago the Deep Space 1 probe conducted the first interplanetary test of such a system. It consumed 2.5 kilowatts of solar power and produced a small but steady 0.1 newton of thrust. Unfortunately, the grids—which accelerate the particles but also get in their way—may not scale up to the megawatt levels needed for manned Mars missions. Also, a large ion drive might need to draw its power from nuclear reactors; solar panels capable of more than about 100 kilowatts would probably be unwieldy.

Thrust: 30 newtons
Exhaust speed: 30 kilometers per second
Sample burn time: 79 days
Sample fuel ratio: 22 percent

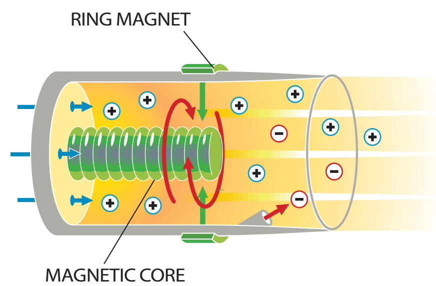


CHRISTOPH BLUMRICH; SOURCE: JAMES S. SOVEY *NASA Glenn Research Center*

HALL EFFECT

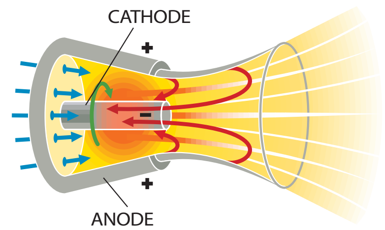
Like ion drives, Hall-effect thrusters use an electrical field to catapult positively charged particles (generally xenon). The difference is in how the thruster creates the field. A ring of magnets first generates a radial magnetic field, which causes electrons to circle around the ring. Their motion in turn creates an axial electrical field. The beauty of the system is that it requires no grids, which should make it easier to scale up than ion drives. The efficiency is lower but could be raised by adding a second thruster stage. Hall-effect thrusters have flown on Russian satellites since the early 1970s, and recently the technology has won converts in the U.S. The latest version, a joint U.S.-Russian project, consumes about 5 kilowatts and generates 0.2 newton of thrust.

Thrust: 30 newtons
Exhaust speed: 15 kilometers per second
Sample burn time: 90 days
Sample fuel ratio: 38 percent



CHRISTOPH BLUMRICH; SOURCE: JAMES S. SOVEY *NASA Glenn Research Center*

MAGNETOPLASMADYNAMIC

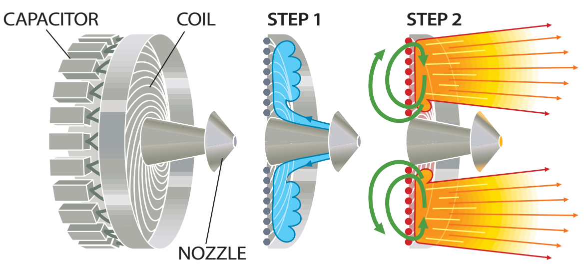


MPD rockets accelerate charged particles using magnetic rather than electrical fields. The device consists of a channel formed by an anode, with a rod-shaped cathode running down the middle. A voltage between the two electrodes ionizes the propellant, allowing a strong electric current to flow radially through the gas and down the cathode. The current in the cathode generates a circular magnetic field, which interacts with the current in the gas to accelerate particles in a direction perpendicular to both—that is, axially. The fuel can be argon, lithium or hydrogen, in increasing order of efficiency. After decades of intermittent interest, NASA resumed work on MPDs last year. Following up efforts at Princeton University and at institutions in Russia, Japan and Germany, the agency has built a 1-megawatt prototype in which the current comes in 2-millisecond pulses.

Thrust: 100 newtons
Exhaust speed: 20 to 100 kilometers per second
Sample burn time: 21 to 25 days
Sample fuel ratio: 6.7 to 31 percent

CHRISTOPH BLUMRICH; SOURCE: MICHAEL R. LAPOINTE *NASA Glenn Research Center*

PULSED INDUCTIVE THRUSTER

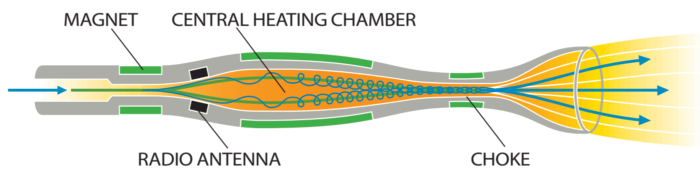


PIT is another technology that NASA is reexamining. The device relies on a rapid sequence of events that, like the MPD, sets up perpendicular electrical and magnetic fields. It begins when a nozzle releases a puff of gas (usually argon), which spreads out across the face of a flat coil of wire about 1 meter across. Then a bank of capacitors discharges a pulse of current, lasting about 10 microseconds, into the coil. The radial magnetic field generated by the pulse induces a circular electrical field in the gas, ionizing it and causing the particles to revolve in exactly the opposite direction as the original pulse of current. Because their motion is perpendicular to the magnetic field, they are pushed out into space. Unlike other electromagnetic drives, PIT requires no electrodes, which tend to wear out, and its power can be scaled up simply by increasing the pulse rate. In a 1-megawatt system the pulses would occur 200 times a second.

Thrust: 20 newtons
Exhaust speed: 50 kilometers per second
Sample burn time: 110 days
Sample fuel ratio: 14 percent

CHRISTOPH BLUMRICH; SOURCE: ROBERT VONDRA *TRW*, RALPH H. LOVBERG *University of California, San Diego* AND C. LEE DAILEY

VASIMR



The Variable Specific Impulse Magnetoplasma Rocket bridges the gap between high- and low-thrust systems. The propellant, generally hydrogen, is first ionized by radio waves and then guided into a central chamber threaded with magnetic fields. There the particles spiral around the magnetic-field lines with a certain natural frequency. By bombarding the particles with radio waves of the same frequency, the system heats them to 10 million degrees. A magnetic nozzle converts the spiraling motion into axial motion, producing thrust. By regulating the manner of heating and adjusting a magnetic choke, the pilot can control the exhaust rate. The mechanism is analogous to a car gearshift. Closing down the choke puts the rocket into high gear: it reduces the number of particles exiting (hence the thrust) but keeps their temperature high (hence the exhaust speed). Opening up corresponds to low gear: high thrust but low efficiency. A spacecraft would use low gear and an afterburner to climb out of Earth orbit and then shift up for the interplanetary cruise. NASA plans a test flight of a 10-kilowatt device in 2004; Mars missions would need 10 megawatts.

	Low gear	High gear
Thrust:	1,200 newtons	40 newtons
Exhaust speed:	10 km per second	300 km per second
Sample burn time:	2.1 days	53 days
Sample fuel ratio:	46 percent	2.4 percent

CHRISTOPH BLUMRICH; SOURCE: FRANKLIN CHANG-DIAZ *NASA Johnson Space Center*

SOLAR SAILS

A staple of science fiction, solar sails take the trade-off between thrust and efficiency to an extreme. They are pushed along by the gentle pressure of sunlight—feeble but free. To deliver 25 tons from Earth to Mars within a year, a sail would have to be at least 4 square kilometers in size. Its material must be no denser than about 1 gram per square meter. Carbon fibers are now nearly that wispy. The next challenge will be deploying such a large but fragile structure. In 1993 the Russian Space Regatta Consortium unfurled the 300-square-meter Znamya space mirror, but in a second test last year it got tangled. NASA recently funded an analogous idea for a magnetic "sail" to catch the solar wind (charged particles streaming from the sun) rather than sunlight.

Thrust: 9 newtons per square kilometer (at Earth's distance from sun)
Exhaust speed: not applicable
Sample burn time: 58 days

ROCKETRY TERMS

Thrust: the force that a rocket engine of this type could provide on a Mars mission, measured in newtons (equal to about a quarter of a pound of force).

Exhaust speed: a measure of fuel efficiency.

Sample burn time: how long the rocket must fire to accelerate a 25-ton payload from low Earth orbit to escape velocity. The time is inversely related to the thrust.

Sample fuel ratio: fraction of the total spacecraft mass taken up by propellant (in the above scenario). The amount of fuel is exponentially related to the exhaust speed.

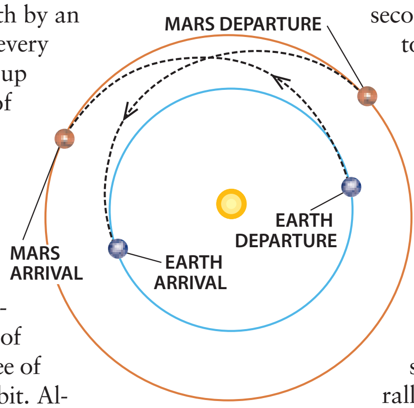
WHICH ROUTE TO TAKE?

CONJUNCTION CLASS

For high-thrust rockets, the most fuel-efficient way to get to Mars is called a Hohmann transfer. It is an ellipse that just grazes the orbits of both Earth and Mars, thereby making the most use of the planets' own orbital motion. The spacecraft blasts off when Mars is ahead of Earth by an angle of about 45 degrees (which happens every 26 months). It glides outward and catches up with Mars on exactly the opposite side of the sun from Earth's original position. Such a planetary configuration is known to astronomers as a conjunction. To return, the astronauts wait until Mars is about 75 degrees ahead of Earth, launch onto an inward arc and let Earth catch up with them.

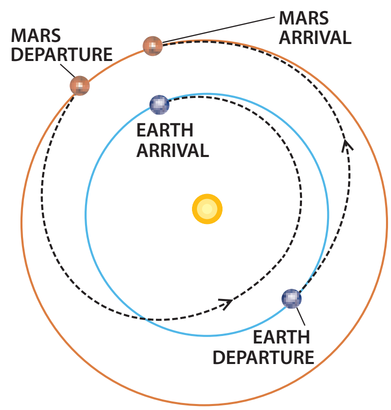
Each leg requires two bursts of acceleration. From Earth's surface, a velocity boost of about 11.5 kilometers per second breaks free of the planet's pull and enters the transfer orbit. Alternatively, starting from low Earth orbit, where the ship is already moving rapidly, the engines must impart about 3.5 kilometers per second. (From lunar orbit the impulse would be even smaller, which is one reason that the moon featured in earlier mission plans. But most current proposals skip it as an unnecessary and costly detour.) At Mars, retrorockets or aerobraking must slow the ship by about 2 kilometers per second to enter orbit or 5.5 kilometers per second to land. The return leg reverses the sequence.

The whole trip typically takes just over two and a half years: 260 days for each leg and 460 days on Mars. In practice, because the planetary orbits are elliptical and inclined, the optimal trajectory can be somewhat shorter or longer. Leading plans, such as Mars Direct and NASA's reference mission, favor conjunction-class missions but quicken the journey by burning modest amounts of extra fuel. Careful planning can also ensure that the ship will circle back to Earth naturally if the engines fail (a strategy similar to that used by *Apollo 13*).



OPPOSITION CLASS

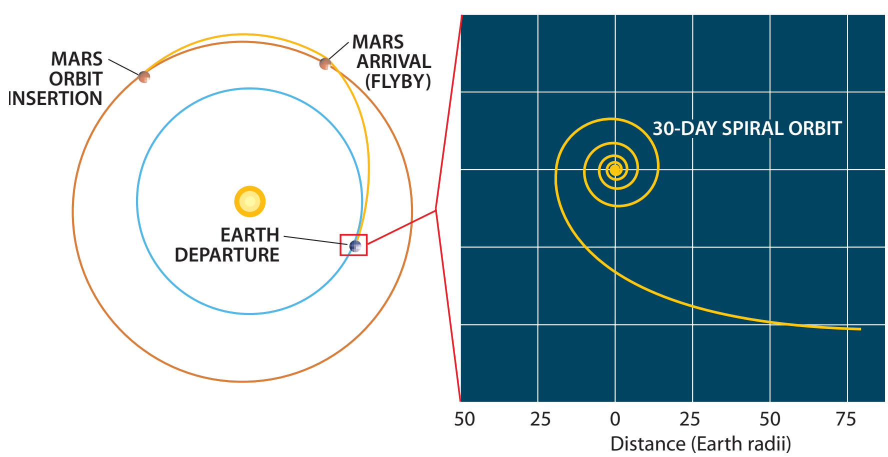
To keep the trip short, NASA planners traditionally considered opposition-class trajectories, so called because Earth makes its closest approach to Mars—a configuration known to astronomers as an opposition—at some point in the mission choreography. These trajectories involve an extra burst of acceleration, administered en route. A typical trip takes one and a half years: 220 days getting there, 30 days on Mars and 290 days coming back. The return swoops toward the sun, perhaps swinging by Venus, and approaches Earth from behind. The sequence can be flipped so that the outbound leg is the longer one. Although such trajectories have fallen into disfavor—it seems a long trip for such a short stay—they could be adapted for ultrapowerful nuclear rockets or "cycler" schemes in which the ship shuttles back and forth between the planets without stopping.



LOW THRUST

Low-thrust rockets such as ion drive save fuel but are too weak to pull free of Earth's gravity in one go. They must slowly expand their orbits, spiraling outward like a car switchbacking up a mountain. Reaching escape velocity could take up to a year, which is a long time to expose the crew to the Van Allen radiation belts that surround Earth. One idea is to use low-thrust rockets only for hauling freight. Another is to move a vacant ship to the point of escape, ferry astronauts up on a "space taxi" akin to the shuttle and then fire another rocket for the final push to Mars. The second rocket could either be high or low thrust. In one analysis of the latter possibility, a pulsed inductive thruster fires for 40 days, coasts for 85 days and fires for another 20 days or so on arrival at the Red Planet.

A VASIMR engine opens up other options. Staying in low gear (moderate thrust but low efficiency), it can spiral out of Earth orbit in 30 days. Spare propellant shields the astronauts from radiation. The interplanetary cruise takes another 85 days. For the first half, the rocket upshifts; at the midpoint it begins to brake by downshifting. On arrival at Mars, part of the ship detaches and lands while the rest—including the module for the return flight—flies past the planet, continues braking and enters orbit 131 days later.



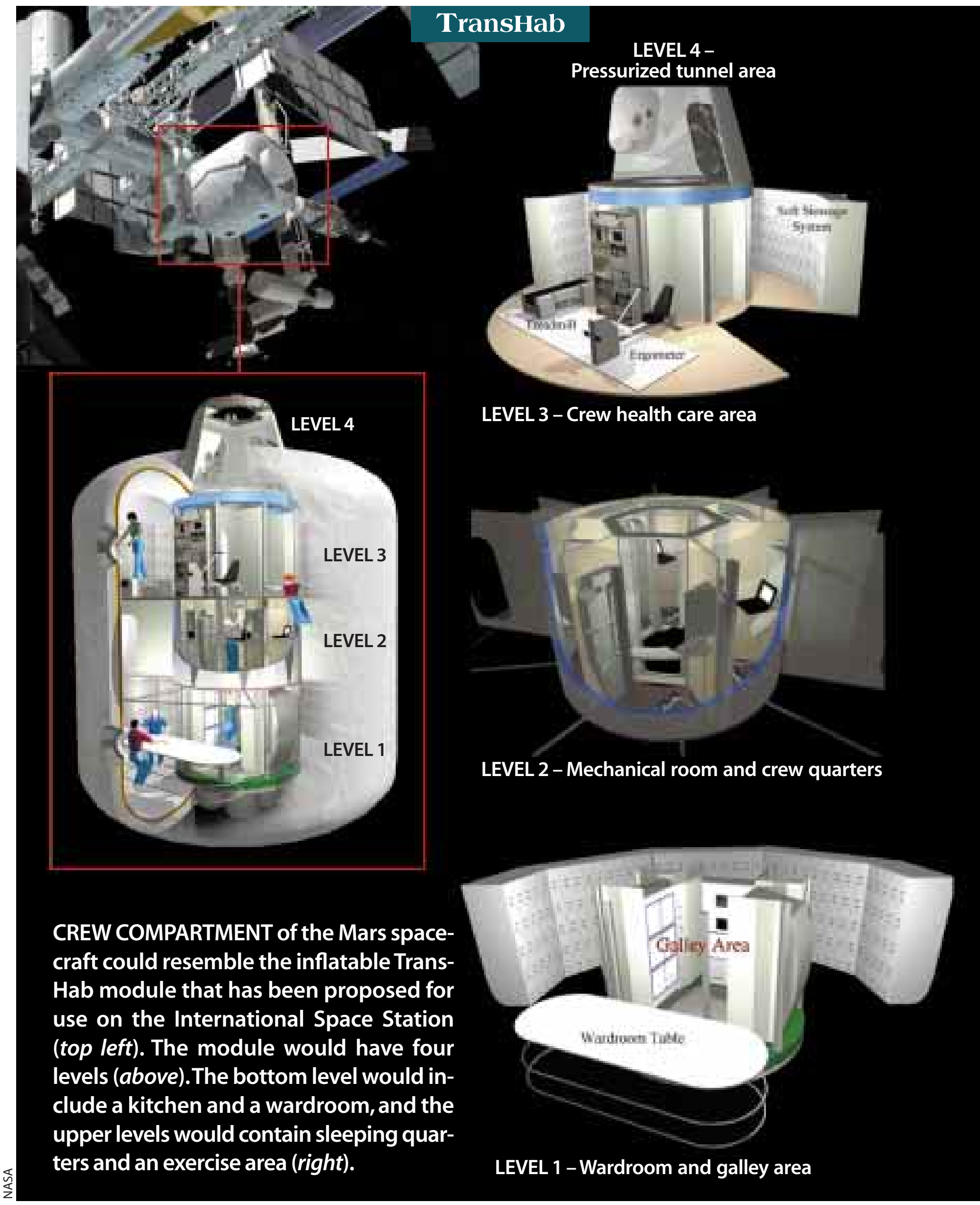
ILLUSTRATIONS BY EDWARD BELL

During the journey to Mars, nothing will be more essential to the crew's safety than the spacecraft's life-support systems. Researchers at the NASA Johnson Space Center in Houston have already begun an effort to improve the efficiency and reliability of current systems. Volunteer crews have spent up to three months in a closed chamber designed to test new technologies for recycling air and water. In addition to physical and chemical methods, the experiments included demonstrations of biological regeneration—for example, processing the crew's solid wastes into fertilizer for growing wheat, which provided the volunteers with oxygen and fresh bread.

Scientists are also studying how to minimize the health effects from prolonged exposure to zero gravity. Astronauts who have spent several months in Earth orbit have lost significant amounts of bone mass, among other health problems [see "Weightlessness and the Human Body," by Ronald J. White; SCIENTIFIC AMERICAN, September 1998]. One way to stave off atrophy would be to slowly rotate the Mars spacecraft during its interplanetary cruise. In several plans, a tether or truss connects the crew capsule to a counterweight, such as a used rocket stage. One rotation per minute around a 340-meter-long spin arm would simulate the 0.38-*g* force on the Red Planet's surface. Doubling the rate shortens the required spin arm by a factor of four but worsens the Coriolis force, which would sway the astronauts as they moved inside the spacecraft. Mission planners, however, are not enthusiastic about spinning the spacecraft during its flight, because it would complicate maneuvering and communications procedures. Medical researchers are also considering alternatives such as exercise regimens, dietary supplements and centrifuge chairs.

Another concern is radiation. The crew would be exposed to two types: cosmic rays, the high-energy ions that stream constantly through our galaxy, and solar flares, the intense streams of protons that are periodically ejected from the sun. Cosmic rays are more energetic than solar flare protons and thus more difficult to block. An astronaut in space would absorb a dose of 75 rems per year; on board a spacecraft, behind an aluminum wall six centimeters thick, the dose would be 20 percent lower. (Extra shielding does little good. Even astronauts on the Martian surface will receive this dose.) Radiation experts believe, however, that this annual dose would increase the probability of an astronaut dying from cancer within 30 years by only a few percentage points. Antioxidant pills might counteract some of this risk.

Solar flare radiation is more dangerous because it comes in unpredictable bursts, which could deliver 4,000 rems to the skin and 200 rems to internal organs in a single deadly dose. At least one such storm occurs near the peak of the 11-year-long solar cycle, and smaller yet potent storms erupt every couple of years. Astronauts in low Earth orbit are protected by the planet's magnetic field, which traps and deflects the incoming protons, but travelers en route to the moon and Mars forgo this safety. Fortunately, the particles can be easily blocked. The best shields are made of hydrogen-rich materials such as polyethylene or water; heavier atoms are not as effective, because the proton collisions can dislodge the atoms' neutrons, triggering a dangerous cascade of radiation. A 10-centimeter layer of water reduces the dose to 20 rems. Mission planners have proposed creating a solar-flare storm shelter on the Mars craft simply by storing the crew's water in bladders surrounding their sleeping area. Satellites observing the sun could warn the astronauts of an impending flare.



CREW COMPARTMENT of the Mars spacecraft could resemble the inflatable TransHab module that has been proposed for use on the International Space Station (*top left*). The module would have four levels (*above*). The bottom level would include a kitchen and a wardroom, and the upper levels would contain sleeping quarters and an exercise area (*right*).

DESCENT AND ASCENT

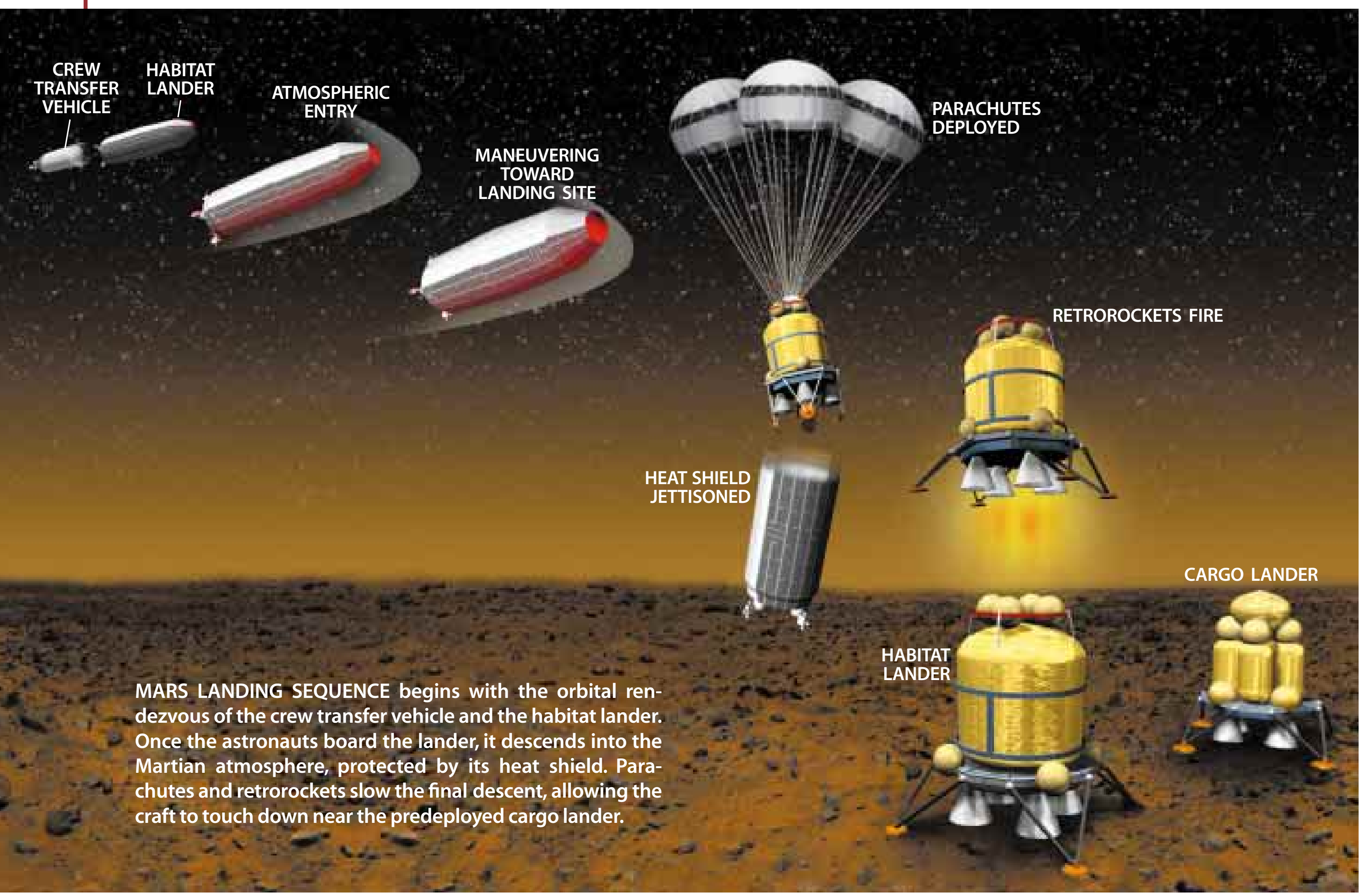
Landing a manned spacecraft on Mars will be significantly more difficult than landing the Apollo lunar modules on the moon. Mars, unlike the moon, has an atmosphere, and its gravity is twice as strong as the moon's. Furthermore, the Mars lander would be much more massive than the lunar modules because it would carry the habitat in which the astronauts would live during their 500 days on the surface.

Only three robotic vehicles have successfully landed on the Red Planet: Vikings 1 and 2 in 1976 and Mars Pathfinder in 1997. All three employed heat shields, parachutes and retrorockets to slow their descent. (Pathfinder also used air bags to cushion its landing.) A manned lander would follow the same basic sequence, but its geometry would be different [*see illustration below*]. The robotic craft sat on saucer-shaped heat shields and plunged uncontrolled through the Martian atmosphere, like a child skidding down a ski slope on a garbage-can lid. A manned craft, though, would need precise guidance during the descent, because it would have to land very close to the unmanned cargo vehicle that would have been sent to Mars earlier.

NASA's current plans call for a bullet-shaped lander wrapped in an outer shell that serves as the heat shield. According to the plan, the lander is sent to Mars unmanned, in advance of the crew. It goes into orbit by aerobraking against the Red Planet's atmosphere. The lander remains in orbit until the astronauts arrive in the crew transfer vehicle. After the astronauts board the lander, it descends much like the space shuttle, with its nose tilted upward. By rolling the spacecraft to the left or right, the pilot can steer it toward the landing site. Parachutes slow its descent, and then the retrorockets fire, enabling the pilot to set the craft down at exactly the right spot.

At the end of 500 days the astronauts board an ascent vehicle that blasts off the surface to an orbital rendezvous with the crew transfer vehicle, which then brings the astronauts back to Earth. On the first human mission to Mars, a fully fueled ascent vehicle would be connected to the habitat lander; on subsequent missions, however, the ascent vehicles would be predeployed and would use rocket fuel manufactured on the Red Planet. A propellant production unit about the size of a large automobile could combine liquid hydrogen brought from Earth with carbon dioxide from the Martian atmosphere. A series of chemical reactions would yield liquid-methane and liquid-oxygen propellant, as well as extra water and breathable air for the crew. The production techniques will be tested on the Mars Surveyor robotic landers currently scheduled to be launched in 2001 and 2003. The plans for Surveyor 2003 include the test-firing of a small rocket engine using methane and oxygen made on Mars.

DON FOLEY



MARS LANDING SEQUENCE begins with the orbital rendezvous of the crew transfer vehicle and the habitat lander. Once the astronauts board the lander, it descends into the Martian atmosphere, protected by its heat shield. Parachutes and retrorockets slow the final descent, allowing the craft to touch down near the predeployed cargo lander.

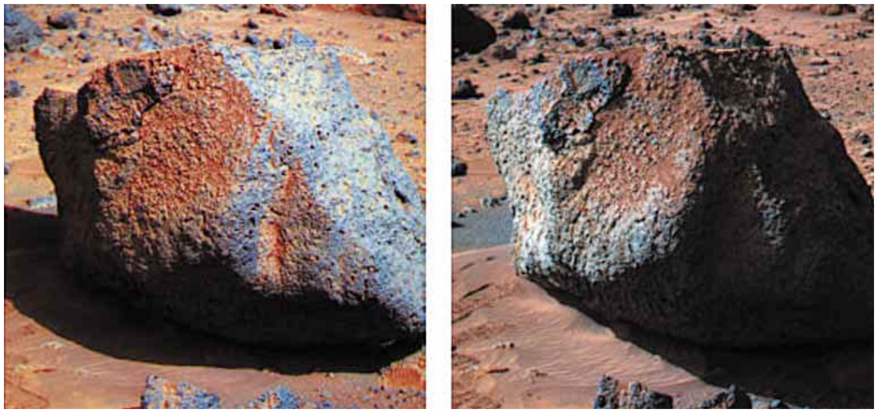
WHAT WILL IT BE LIKE?

As soon as astronauts disembark, they will know they are in an alien world; the weaker gravity will be obvious in the very act of walking. Taking a step is like swinging a pendulum, which occurs at a tempo related to the strength of gravity. Consequently, people will tend to walk about 60 percent as fast as on Earth and burn half as many calories doing so. A speed that would be a casual stroll here is best handled as a run on Mars.

In the thin atmosphere—the equivalent of Earth's at an altitude of about 35 kilometers—temperature and pressure fluctuate widely and quickly, but weather patterns are generally uniform from place to place. Although the wind can gust to 100 kilometers per hour, the force it exerts is low. Astronauts may see fog, frost and wispy blue clouds in the early morning. The sky changes in color depending on when and where one looks. At noon and toward the horizon, dust scattering makes it red. The rising and setting sun is blue; elsewhere the sky is butterscotch. The lighting plays tricks on the eye. Because of the varying proportion of direct sunlight and indirect sky glow, the coloring of rocks looks different depending on the time of day [*see illustration above*].

Mars is boringly flat. The famous Twin Peaks at the Mars Pathfinder site are just 50 meters high yet clearly visible a kilometer away. Even Olympus Mons, the largest mountain in the solar system, generally has a grade of only a few percent. The topography gets more interesting on the rim of Valles Marineris, which is thought to resemble the Canyonlands in Utah.

Because of the flatness, astronauts will be able to see that Mars is smaller than Earth: the distance to the horizon is proportional to the square root of a planet's radius. Two people 170 centimeters tall (about 5 feet 8 inches) could see each other up to seven kilometers away. On Earth you seldom notice the theoretical horizon (in this case, 2.5 kilometers farther) because topography intrudes. The horizon is also the limit of direct radio communications on Mars, which lacks an ionosphere. Astronauts will need relay satellites.



NASA/JET PROPULSION LABORATORY

YOGI, a rock much photographed by the Mars Pathfinder lander in 1997, looks different in the morning (*left*) than in the afternoon (*right*) because of the vagaries of Martian light.

DUST

Tiny particles may be the biggest problem for humans on Mars. Because the Red Planet utterly lacks liquid water, which mops up fine particulates on Earth, it is covered in dust with an average grain size of about two microns—comparable to cigarette smoke. The dust will gum up space suits, scratch helmet visors, cause electrical shorts, sandblast instruments and clog motors. On the moon, which is similarly dusty, suits lasted only two days before they began to leak. In addition, Viking lander analyses suggest that particles are coated with corrosive chemicals such as hydrogen peroxide. Although their concentrations are low, these toxins could slowly wear away rubber seals. NASA plans more detailed studies on upcoming landers.

If even a small fraction of the dust particles are quartz, as Mars Pathfinder results hint, they could pose a major health threat if inhaled: silicosis, an incurable lung condition that kills several hundred miners and construction workers in the U.S. every year. To keep their habitat dust-free, astronauts will need to clean off thoroughly before entering. That will not be easy. Being magnetized and electrically charged, the dust sticks to everything, and water will be in short supply. Astronauts might scrub with dry-ice snow condensed out of the atmosphere. They could also wear two-layer space suits, the outer layer of which would be left in a special airlock outside the main habitat.

Another issue is electric power. On Mars Pathfinder, the output of the solar panels fell 1 percent every three days as powder accumulated on them. A dust storm would darken the skies and halve power generation. For these reasons, a mission might need a 100-kilowatt nuclear reactor.

PLANETARY PROTECTION

Microbes will inevitably accompany astronauts to Mars, complicating the search for native life. Conversely, any Martian bugs will be able to hitch a ride back to Earth. The organisms probably would not cause disease in humans or other species—most scientists think they would simply be too different from terrestrial life-forms—but the risk of a global disaster is not zero. Although NASA is developing a bioisolation system for robotic sample-return missions, there is no equivalent way to decontaminate an astronaut. The quarantine procedures during the Apollo program were cumbersome, controversial—and leaky. And quarantines lead to horrible dilemmas. If the astronauts get sick, are they to be prevented from returning to Earth on the off-chance they have picked up an alien plague? It would be better not to have to make that decision. A 1992 National Research Council report concluded that the existence of extant or dormant life on Mars should be resolved before astronauts are sent. At the very least, astronauts will need to know in advance which parts of the planet are safe to explore and what precautions they should take elsewhere to avoid direct contact with any possible forms of Martian life. SA

1

THE MARS DIRECT PLAN

A leading advocate of manned missions to Mars, Robert Zubrin, outlines his relatively inexpensive plan to send astronauts to the Red Planet within a decade

JPL/CALTECH/NASA

"Space is there, and we are going to climb it." These words from President John F. Kennedy in 1962 set forth the goal of sending an American to the moon within the decade. But for most of the 30 years since the Apollo moon landing, the U.S. space program has lacked a coherent vision of what its next target should be. The answer is simple: the human exploration and settlement of Mars.

This goal is not beyond our reach. No giant spaceship built with exotic equipment is required. Indeed, all the technologies needed for sending humans to Mars are available today. We can reach the Red Planet with relatively small spacecraft launched directly to Mars by booster rockets embodying the same technology that carried astronauts to the moon more than a quarter of a century ago. The key to success lies with the same strategy that served the earliest explorers of our own planet: travel light and live off the land. The first piloted mission to Mars could reach the planet within a decade. Here is how the proposed plan—what I call the Mars Direct project—would work.

At a not too distant date—perhaps as soon as 2005—a single, heavy-lift booster rocket with a capability equal to that of the Saturn 5 rockets from the Apollo era is launched from Cape Canaveral, Fla. When the ship is high enough in Earth's atmosphere, the upper stage of the rocket detaches from the spent booster, fires its engine and throws a 45-metric-ton, unmanned payload on a trajectory to Mars.

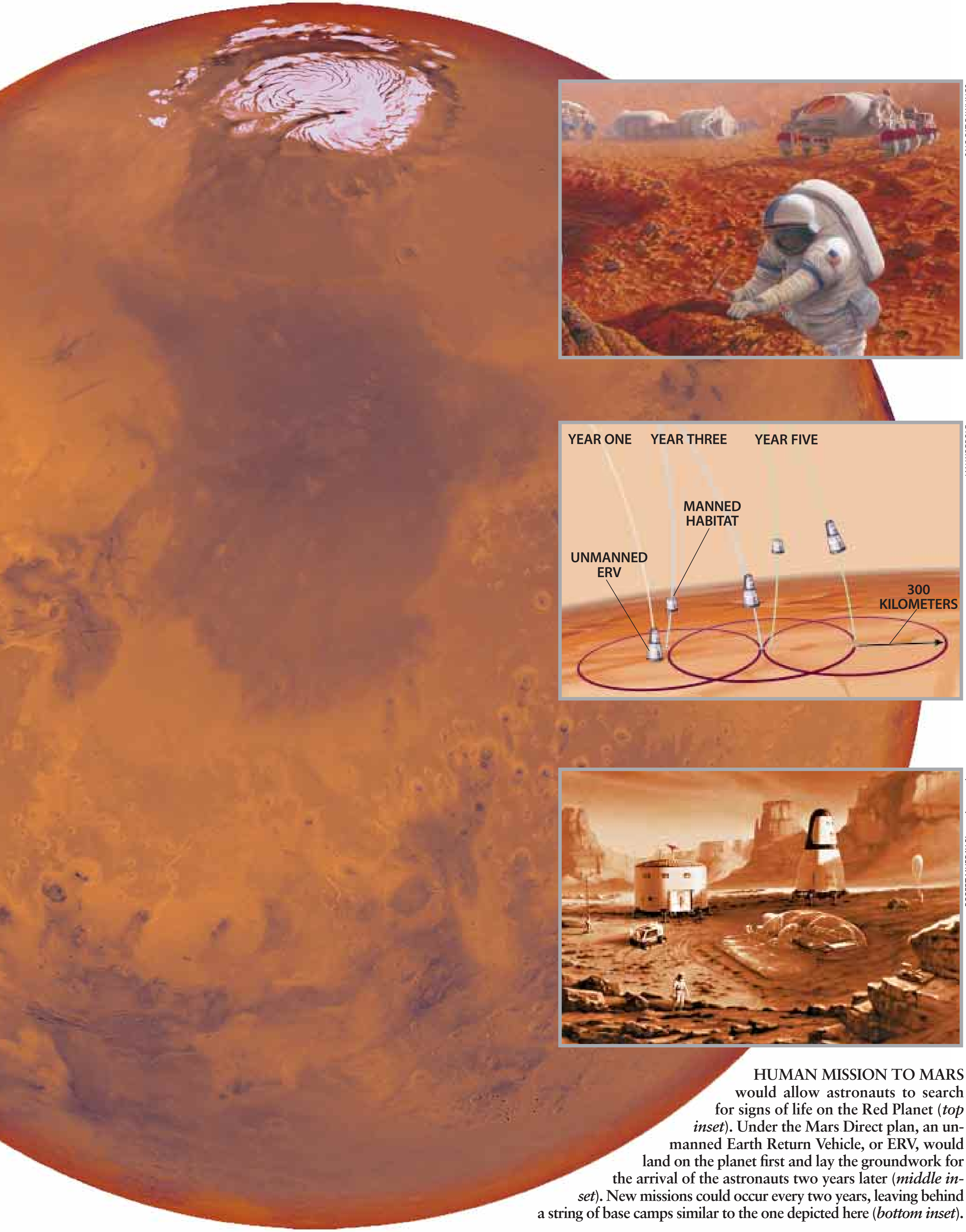
This payload is the Earth Return Vehicle, or ERV, which, as the name implies, is built to bring astronauts back to Earth from Mars. But on this voyage no humans are on board; instead the ERV carries six tons of liquid-hydrogen cargo, a set of compressors, an automated chemical-processing unit, a few modestly sized scientific rovers, and a small 100-kilowatt nuclear reactor mounted on the back of a larger rover powered by a mixture of methane and oxygen. The ERV's own methane-oxygen tanks, which will be used during the return trip, are unfueled.

Arriving at Mars eight months after takeoff, the ERV slows itself down with the help of friction between its heat shield and the planet's atmosphere—a technique known as aerobraking. The vehicle eases into orbit around Mars and then lands on the surface using a parachute and retrorockets. Once the ship has touched down, scientists back at mission control on Earth telerobotically drive the large rover off the ERV and move it a few hundred meters away. Mission control then deploys the nuclear reactor, which will provide power for the compressors and the chemical-processing unit.

Inside this unit, the hydrogen brought from Earth reacts with the Martian atmosphere—which is 95 percent carbon dioxide (CO_2)—to produce water and methane (CH_4). This process, called methanation, eliminates the need for long-term storage of cryogenic liquid-hydrogen fuel, a difficult task. The methane is liquefied and stored, and the water molecules are electrolyzed—broken apart into hydrogen and oxygen. The oxygen is then reserved for later use; the hydrogen is recycled through the chemical-processing unit to generate more water and methane.

Ultimately, these two reactions, methanation and electrolysis, provide 48 tons of oxygen and 24 tons of methane, both of which will eventually be burned as rocket propellant for the astronauts' return voyage. To ensure that the mixture of methane and oxygen will burn efficiently, an additional 36 tons of oxygen must be generated by breaking apart the CO_2 in the Martian atmosphere. The entire process takes 10 months, at the end of which a total of 108 tons of methane-oxygen propellant has been generated—18 times more propellant for the return trip than the original feedstock needed to produce it.

The journey home will require 96 tons of propellant, leaving an extra 12 tons for the operation of the rovers. Additional stockpiles of oxygen can also be produced, both for breathing and for conversion into water by combining the oxygen with the hydrogen brought from Earth. The ability to produce oxygen and water on Mars greatly reduces the amount of life-supporting supplies that must be hauled from Earth.

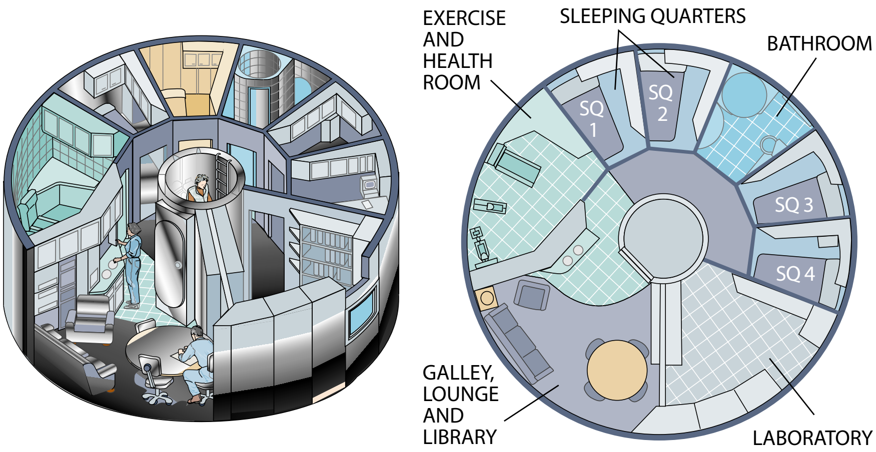


SAIC; PAT RAWLINGS

IAN WORPOLE

ROBERT MURRAY *Pioneer Astronautics*

HUMAN MISSION TO MARS would allow astronauts to search for signs of life on the Red Planet (*top inset*). Under the Mars Direct plan, an unmanned Earth Return Vehicle, or ERV, would land on the planet first and lay the groundwork for the arrival of the astronauts two years later (*middle inset*). New missions could occur every two years, leaving behind a string of base camps similar to the one depicted here (*bottom inset*).



IAN WORPOLE

HOME SWEET HOME in interplanetary space and on Mars might look like this. The upper deck of the habitat, shown here, would have sleeping quarters for four people as well as a laboratory, library, galley and gym. A solar-flare storm shelter would be located in the center. The lower deck (*not shown*) would serve as a garage, workshop and storage area. During the trip to Mars, a tether system could produce artificial gravity.

With this inaugural site on Mars operating successfully, two more boosters lift off from Cape Canaveral in 2007 and again hurl their payloads toward Mars. One of these is an unmanned ERV just like the one launched in 2005. The other, however, consists of a manned vessel with a crew of four men and women with provisions to last three years. The ship also brings along a pressurized methane-oxygen-powered ground rover that will allow the astronauts to conduct long-distance explorations in a shirtsleeve environment.

The Astronauts Arrive

During the trip, artificial gravity as strong as that found on Mars can be produced by first extending a tether between the inhabited module and the burned-out booster rocket's upper stage; the entire assembly is then allowed to spin at a rate of, say, one revolution per minute. Such a system would eliminate any concerns over the health effects of zero gravity on the astronauts. The crew's exposure to radiation will also be acceptable. Solar flare radiation, consisting of protons with energies of about one million electron volts, can be shielded by 12 centimeters of water or provisions, and there will be enough materials on board the ship to build an adequate pantry storm shelter for use in such an event. The residual cosmic-ray dose, about 50 rems for the entire two-and-a-half-year mission, represents a statistical cancer risk of about 1 percent, roughly the same as the risk from smoking for the same amount of time.

On arrival at Mars, the manned craft drops the tether to the booster, aerobrakes and then lands at the 2005 site. Beacons at the original location should enable the ship to touch down at just the right spot, but if the landing is off course by tens or even hundreds of kilometers, the astronauts can still drive to the correct location in their rover. And in the unlikely event that the ship sets down thousands of kilometers away, the second ERV that was launched with the manned vessel can serve as a backup system. If that, too, should fail, the extra rations on the manned craft ensure that the crew can survive until a third ERV and additional supplies can be sent in 2009.

But with current technology, the chances of a misguided landing are small. So assuming the astronauts reach the 2005 location as planned, the second ERV touches down several hundred kilometers away. This new ERV, like its predecessor, starts making propellant, this time for the 2009 mission, which in turn will fly out with an additional ERV to open up a third Mars site.

Thus, under the Mars Direct plan, the U.S. and its international partners would launch two heavy-lift booster rockets every other year: one to dispatch a team of four people to inhabit Mars and the other to prepare a new site for the next mission. The average launch rate of one a year is only about 15 percent of the rate at which the U.S. currently launches space shuttles. In effect, the live-off-the-land strategy used by the Mars Direct plan removes the prospect of a manned mission to Mars from the realm of megaspacecraft fantasy and renders it a task comparable in difficulty to the Apollo missions to the moon.

The men and women sent to Mars will stay on the surface for one and a half years, taking advantage of the ground vehicles to conduct extensive exploration of the surface. With a 12-ton stockpile of fuel for these trucks, the astronauts can travel more than 24,000 kilometers during their stay, giving them the kind of mobility necessary to conduct a serious search for evidence of past or present life—an investigation that is key to revealing whether life is a phenomenon unique to Earth or commonplace throughout the universe.

Because no one will be left in orbit, the crew will benefit from the natural gravity and protection against radiation offered by the Martian environment. As a result, there is no need for a quick return to Earth, a complication that has plagued conventional mission plans that consist of an orbiting mother ship and small landing parties sent to the surface. At the conclusion of their stay, the Mars astronauts will return by direct flight in the ERV. As the series of missions progresses, a string of small bases will be

Continued on page 55

Consumable Requirements for Mars Direct Mission with Crew of Four

	Daily need per person (kilograms)	Percent recycled	Total mass for 200-day one-way flight (kilograms)	Total for 600-day stay on surface (kilograms)
Oxygen	1.0	80	160	0
Dry food	0.5	0	400	1,200
Whole food	1.0	0	800	2,400
Potable water	4.0	80	0	0
Wash water	26.0	90	2,080	0
Total	**32.5**	**87**	**3,440**	**3,600**

JOHNNY JOHNSON

Mass Allocations for Mars Direct Mission

ERV Component	Metric Tons	Habitat Component	Metric Tons
ERV cabin structure	3.0	Habitat structure	5.0
Life-support system	1.0	Life-support system	3.0
Consumables	3.4	Consumables	7.0
Solar array (5 kilowatts of electricity)	1.0	Solar array (5 kilowatts of electricity)	1.0
Reaction control system	0.5	Reaction control system	0.5
Communications and information management	0.1	Communications and information management	0.2
Furniture and interior	0.5	Furniture and interior	1.0
Space suits (4)	0.4	Space suits (4)	0.4
Spares and margin (16 percent)	1.6	Spares and margin (16 percent)	3.5
Aeroshell	1.8	Pressurized rover	1.4
Rover	0.5	Open rovers (2)	0.8
Hydrogen feedstock	6.3	Lab equipment	0.5
ERV propulsion stages	4.5	Field science equipment	0.5
Propellant production plant	0.5	Crew	0.4
Nuclear reactor (100 kilowatts of electricity)	3.5		
ERV total mass	**28.6**	**Habitat total mass**	**25.2**

EARTH RETURN VEHICLE blasts off from the surface of Mars with a crew of four on board (*right*). The payloads of the ERV and the manned habitat are detailed in the table above.

Continued from page 54
left behind on the planet, opening broad stretches of Mars to continued human exploration and, eventually, habitation.

In 1990, when my colleague David A. Baker and I (we were then both at Martin-Marietta, which is now part of Lockheed Martin) first put forward the basic Mars Direct plan, the National Aeronautics and Space Administration viewed it as too radical for serious consideration. But since then, with encouragement from Michael Griffin, NASA's former associate administrator for exploration, as well as from the current head of NASA, Daniel S. Goldin, the group in charge of designing human missions to Mars at the NASA Johnson Space Center decided to take another look at our idea.

The Mars Society

In 1994 researchers there produced a cost estimate for a program based on an expanded version of the Mars Direct plan that had been scaled up by about a factor of two. Their result: $50 billion. Notably, in 1989 this same group had assigned a $400-billion price tag to the traditional, cumbersome approach to a manned mission based on orbital assembly of megaspacecraft. I believe that with further discipline in the design of the mission, the cost could be brought down to the $20- to $30-billion range. Spent over 10 years, this amount would constitute an annual expenditure of about 20 percent of NASA's budget, or around 1 percent of the U.S. military's budget. It is a small price to pay for a new world.

To mobilize public support for an expanded Mars effort—including robotic as well as human exploration—and to initiate privately funded missions, the Mars Society was formed in 1998. As its first private project, the society is building a Mars simulation base at the Haughton meteorite impact crater on Devon Island in the Canadian Arctic. Because of its geologic and climatic similarities to the Red Planet, this area has been of interest to NASA scientists for some time. The society's Mars Arctic Research Station, or MARS, will support a greatly expanded study of this environment and will provide a location for field-testing human exploration tactics and prototype equipment, including habitation modules, ground-mobility systems, photovoltaic systems and specialized drilling rigs. The current plan is to have the Devon Island MARS base operational by the summer of 2000. This should be possible on a budget of about $1 million.

We hope that the credibility earned through this project will enable the society to expand its financial resources. It could then help fund robotic missions to Mars and, eventually, human expeditions, perhaps on a cost-sharing basis with NASA or other government agencies. But it is clear that the fastest way to send humans to Mars is to show the government why it should invest in this endeavor. The society has therefore launched an educational campaign directed toward politicians and other power brokers.

Someday millions of people will live on Mars. What language will they speak? What values and traditions will they cherish as they move from there to the solar system and beyond? When they look back on our time, will any of our other actions compare in importance with what we do now to bring their society into being? Today we have the opportunity to be the parents, the founders, the shapers of a new branch of the human family. By so doing, we will put our stamp on the future. It is a privilege beyond reckoning. SA

This article updates a version that appeared in the Spring 1999 issue of Scientific American Presents.

ROBERT ZUBRIN *is president of the Mars Society and founder of Pioneer Astronautics, which does research and development on space exploration. He is the author of* The Case for Mars: The Plan to Settle the Red Planet and Why We Must *(Simon & Schuster, 1996) and* Entering Space: Creating a Space-Faring Civilization *(Tarcher-Putnam, 1999).*

2 TO MARS BY WAY OF ITS MOONS

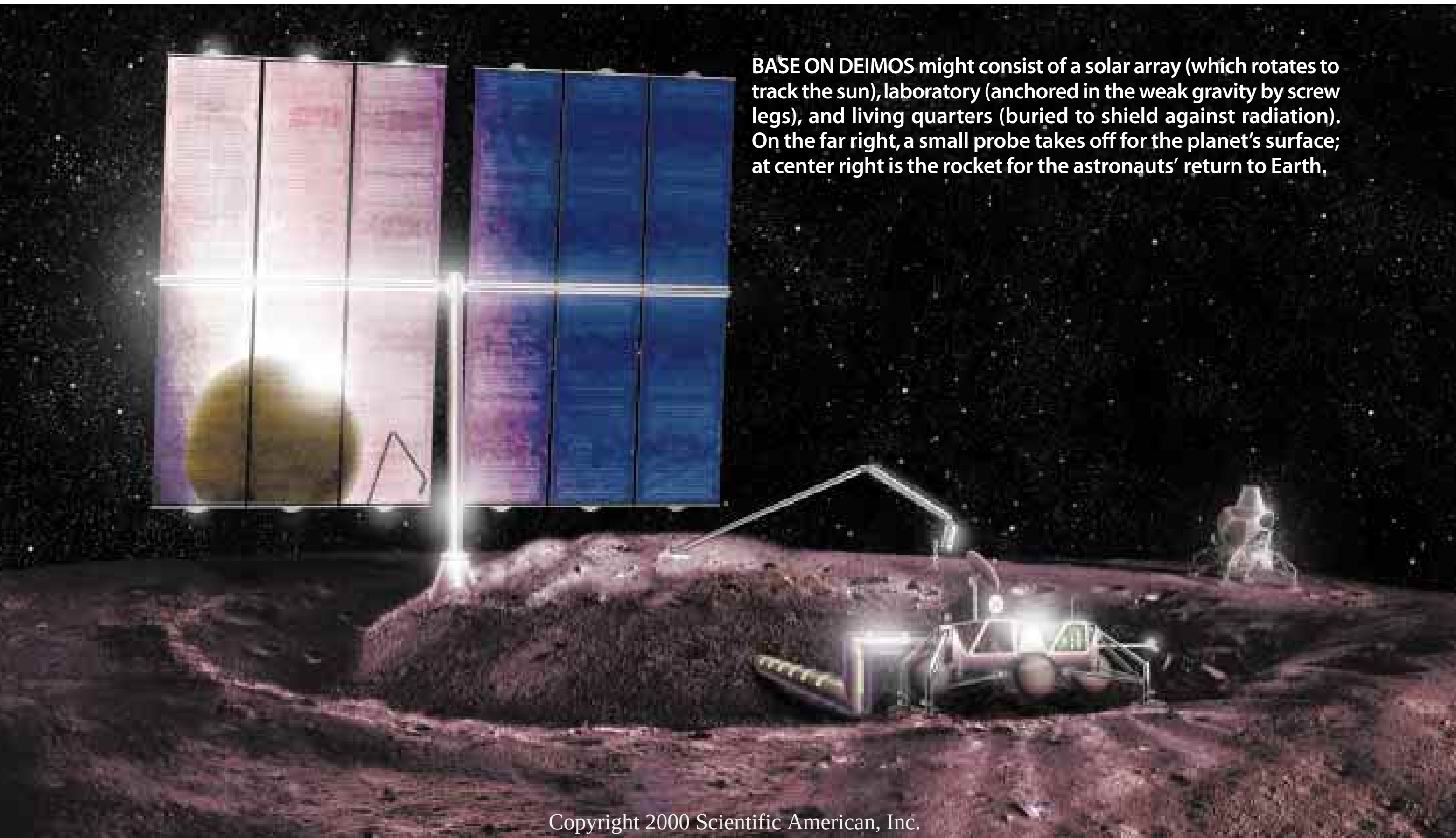
Phobos and Deimos would make ideal staging areas, argues veteran space scientist S. Fred Singer

Three decades after the first Apollo landing on the moon, the debate between proponents of manned and unmanned space missions has not changed a great deal. But many space scientists who work with robotic satellites, including me, have gradually moved from opposing human spaceflight to a more moderate position. In special situations, we now realize, sending people into space is not just an expensive stunt but can be more cost-effective than sending robots. Mars exploration is one of those cases.

The basic advantage of astronauts is that they can explore Mars in real time, free of communications delays and capable of following up interesting results with new experiments. Robots, even after decades of research to make them completely autonomous, cannot manage without people in the loop. But the question arises: Where should the astronauts be? The obvious answer—on the surface of Mars—is not necessarily the most efficient. At the first "Case for Mars" conference in 1981, one of the more provocative conclusions was that the Martian moons, Phobos and Deimos, could serve as comparatively inexpensive beachheads.

Most current mission scenarios involve a pair of spacecraft. The first positions propellants and other heavy components, such as spare modules and reentry vehicles, on or near Mars. Because the journey time is not crucial, it can use electric propulsion and gravity-assist procedures to reduce the cost. The story is rather different for the second spacecraft, which transports the astronauts. It must traverse Earth's radiation belts rapidly, and to save on supplies, the transit time to Mars should be as short as possible. In the near term, chemical rockets seem to be the only feasible option.

The various mission plans part ways when it comes to deciding what should happen once the crew ship and the freight ship link up at the Red Planet. In order of increasing difficulty and expense, six possible scenarios are: a Mars flyby analogous to the early Apollo missions, with immediate return to Earth; a Mars orbiter, permitting a longer stay near the planet; a Phobos-Deimos (Ph-D) mission, involving a transfer to a circular, equatorial orbit, with a landing and base on a Martian moon, preferably

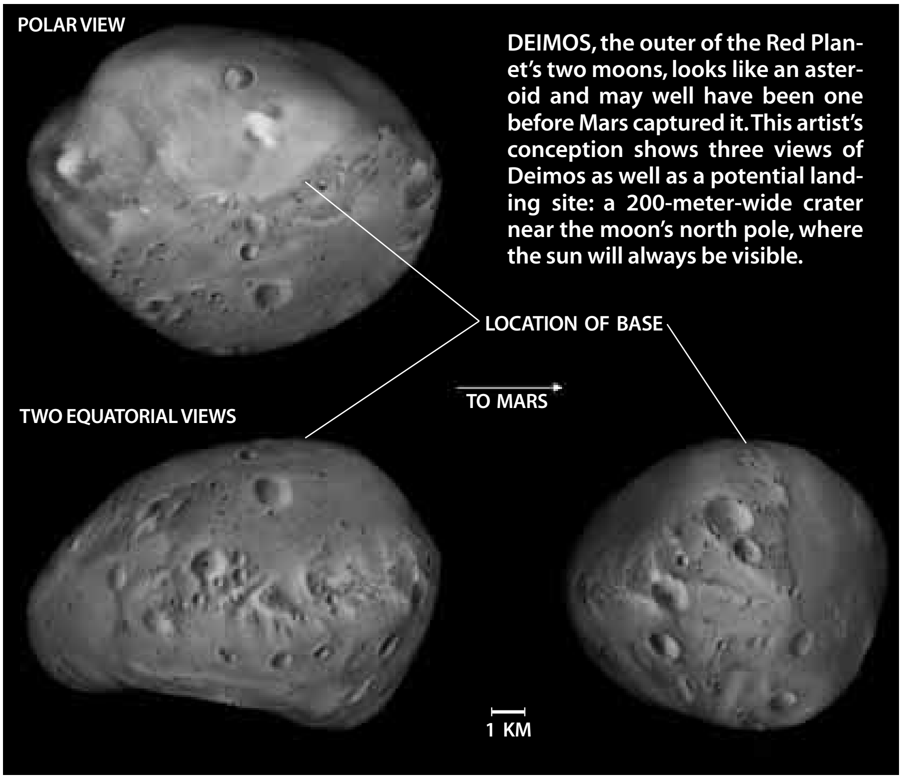


BASE ON DEIMOS might consist of a solar array (which rotates to track the sun), laboratory (anchored in the weak gravity by screw legs), and living quarters (buried to shield against radiation). On the far right, a small probe takes off for the planet's surface; at center right is the rocket for the astronauts' return to Earth.

Deimos; a hybrid mission (Ph-D-plus) that adds a brief sortie to the Martian surface; a full-scale Martian landing, with a longer stay on the surface and a complete program of research; and finally, an extended stay on Mars, during which astronauts erect permanent structures and commence continuous habitation of the planet.

The trick will be to make sure the first manned mission is ambitious—the adventure is, after all, part of the attraction—but not too ambitious, lest it not win funding. The Ph-D and Ph-D-plus missions offer a compelling balance of cost and benefit and would provide the greatest return for science.

Deimos would offer an excellent base for the study of Mars. From there the astronauts could deploy and control atmospheric probes, subsurface penetrators and rover vehicles all over the Martian surface. The moon's near-synchronous orbit permits direct contact with a rover for about 40 hours at a time. Phobos, being closer to the planet, orbits faster and therefore lacks this particular advantage. But astronauts on either moon could analyze returned samples without fear of contaminating Earth with any Martian life-forms.



DEIMOS, the outer of the Red Planet's two moons, looks like an asteroid and may well have been one before Mars captured it. This artist's conception shows three views of Deimos as well as a potential landing site: a 200-meter-wide crater near the moon's north pole, where the sun will always be visible.

B. E. JOHNSON; PETER C. THOMAS; CALVIN HAMILTON; A. TAYFUN ONER

The ready availability of a vacuum would make it easier to operate laboratory instruments such as mass spectrometers and electron microscopes. By relocating the spacecraft to different locations on Deimos—an easy task in the minuscule gravity—astronauts could protect themselves from solar storms and meteor streams. Besides, the moons are fascinating bodies in their own right; direct sampling would investigate their mysterious origins [see "Phobos and Deimos," by Joseph Veverka; SCIENTIFIC AMERICAN, February 1977].

B. E. JOHNSON

In comparison, an operating base on the surface of Mars would suffer many handicaps. Rovers deployed elsewhere on the planet would still have to be operated by remote control, which would require a satellite communications system to relay the commands. Returning samples from distant locations to the base would be more difficult. Heavy backup batteries or nuclear generators would be needed to power the base at night or during dust storms.

Most of the advantages of a lander mission, in terms of both science and adventure, could be captured by a sortie from the moons to the surface. A small shuttle craft would suffice, rather than a full-blown landing vehicle—thus reducing the total cost of the mission. Coming from an established base in orbit, the astronauts would have more flexibility in the selection of a landing site, whereas the crew of a large Mars lander would need to play it safe, choosing a site from which it would be easy to launch the return trip to Earth.

In the more distant future, the moons could serve as way stations for descent to or ascent from the surface via tethers. Scientists on Deimos could safely direct large-scale climatological experiments, such as altering weather patterns or melting the polar caps—thereby testing techniques for terraforming Mars or mitigating climate change on Earth.

Although the costs and benefits of various mission scenarios are difficult to analyze at this early stage, I conducted a poll of Mars mission experts during a conference several years ago. The clear winner for the initial mission, showing the greatest net benefit, was the Ph-D-plus project. It offers the full spectrum of science more cheaply and quickly, and it would set the stage for an eventual base and colony on the surface. SA

S. FRED SINGER *is director of the Science and Environmental Policy Project in Fairfax, Va., and professor at George Mason University. A pioneer in the use of rockets (captured German V-2s) to investigate the upper atmosphere and near-Earth space, he was the first director of the National Weather Satellite Center. He devised the cosmic-ray method of dating meteorites and was among the first to study the origin and evolution of the Martian moons.*

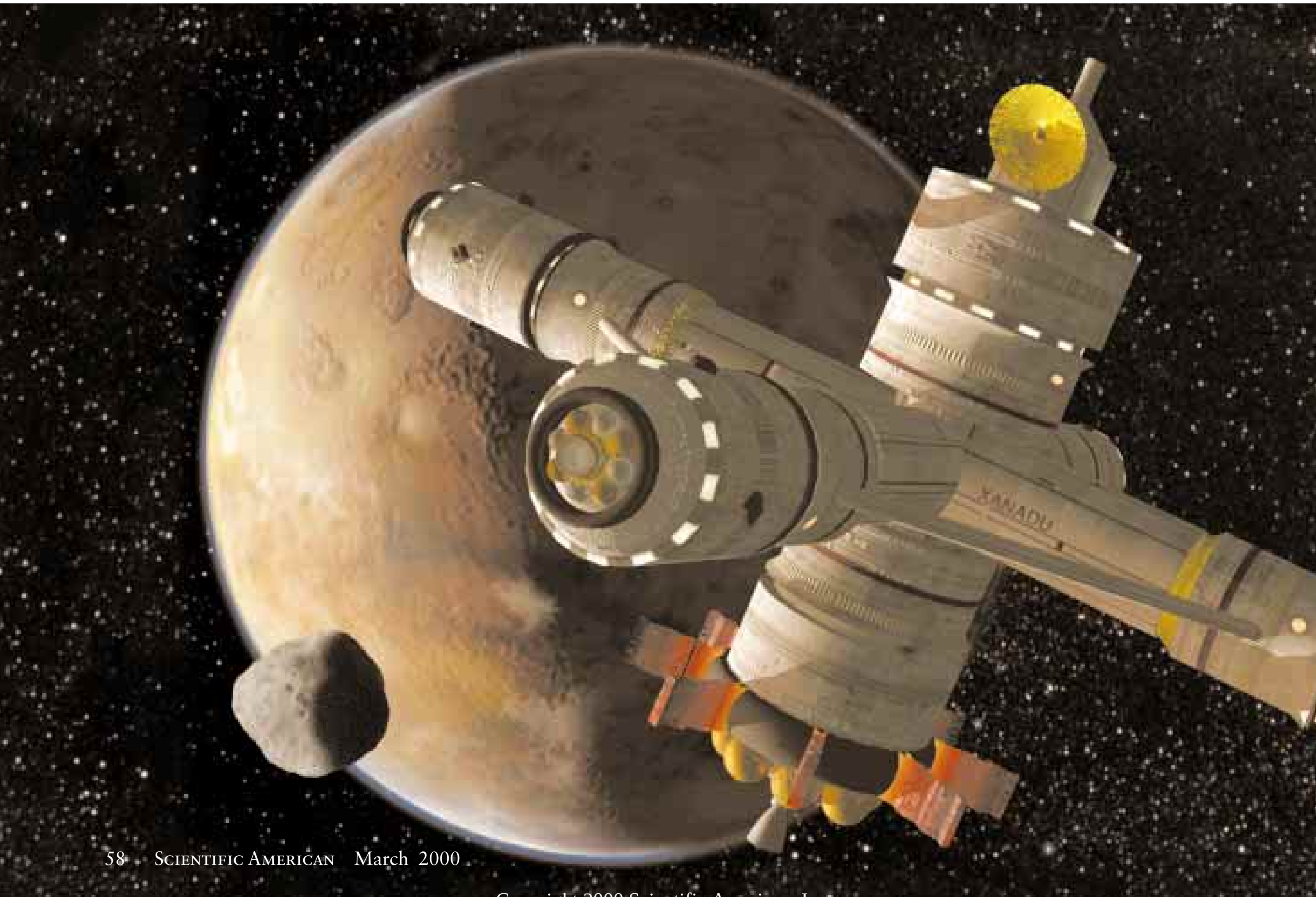
3 A BUS BETWEEN THE PLANETS

Gravity-assist trajectories between Earth and Mars would reduce the cost of shuttling human crews and their equipment, say James Oberg *and* Buzz Aldrin

Chemical rockets have served humankind well in its first, tentative steps into space. Having ridden atop them to the moon and back, one of us (Aldrin) can vouch for the technology's merits. Nevertheless, for trips beyond our nearest neighbor in space, chemical rockets alone leave much to be desired.

Even Mars, the next logical destination in space, would be a stretch for chemical rockets. To deliver a human crew to the planet would require so much fuel that essentially all scenarios for such a voyage involve producing, on the planet's surface, large amounts of fuel for the return trip. That requirement adds another element of risk and complexity to the proposed mission. Much more powerful plasma rockets, on the other hand, are still probably a decade away from use on a human-piloted spacecraft.

We think there is a middle ground: using chemical rockets and augmenting their modest propulsive power by taking creative advantage of gravity-assist maneuvers. In these excursions, mission planners send a spacecraft hurtling so close to a celestial body, typically a planet, that the body's gravitational field changes the spacecraft's velocity. The scheme is commonly used to boost the speed of a probe headed toward the solar system's outer planets, which would otherwise be all but unreachable. Mission controllers began using gravity assists in the 1970s on such missions as Mariner 10 to Mercury, which got an



assist from the Venusian gravitational field; Pioneer 11 to Saturn, which flew by Jupiter; and Voyager 1, catapulted by Jupiter's prodigious gravitational field and now hurtling through interstellar space at 62,000 kilometers per hour. Even though there are no sizable celestial bodies between Earth and Mars, a mission between the two planets can still be executed so as to benefit significantly from their gravity.

Boing!

A gravity-assist maneuver can be likened to a rubber ball bouncing off a wall. In this analogy, the spacecraft is like the rubber ball, and the planet is like the wall. As the ball bounces off the wall, the bounce-off velocity will be higher or lower if the wall is moving toward or away from the ball as they meet. The mathematical relation is described by a fundamental principle of Newtonian physics: conservation of momentum. The change in the ball's momentum is balanced by an inverse change in the wall's momentum.

In a gravity assist, the spacecraft "collides" elastically with the planet's gravitational field. If the planet is moving into the arc of the spacecraft's trajectory as the craft flies by the planet, the "rebound" speed of the vehicle will be higher than its approach speed. As with the ball bouncing off the wall, momentum is conserved: the planet's momentum changes as much as the spacecraft's. Because of the immense difference in their masses, though, the planet's velocity change is not significant.

CASTLE IN ORBIT around Mars might feature four docking ports, at the ends of the crossed arms, to receive robotic resupply vehicles and planetbound "taxis." Food and supplies would be stored in the arms, one of which might have an artificially lit greenhouse. In the central shaft the living quarters would include a heavily shielded solar-flare storm shelter. If it were nuclear-powered, the craft would also have radiators to dissipate engine heat (*bottom*).

DON DIXON

The more massive the planet, the more sharply it can alter the spacecraft's trajectory. Jupiter, the most massive planet in the solar system by far, can effect a change as great as 160 degrees in a vehicle's direction relative to the planet. Not only can mission controllers change the spacecraft's speed and direction within the orbital plane, they can also put the craft in a new orbital plane quite different from that of the planet's orbit around the sun.

How can gravity assist help transport people to Mars? The answer is that it would be used to make critical adjustments to the trajectories of "cycler" spacecraft. These would use the gravity of Earth and Mars as the primary shaper of their trajectories as they cruised back and forth repeatedly, like buses on a scheduled route, shuttling crews and supplies between the two planets. Typically the cycler would not have to be decelerated into orbit around Mars, and it would never have to blast off the planet's surface for the return to Earth. The basic concept goes back more than three decades but continues to produce novel mission strategies, ones that we believe merit more attention than they generally receive in discussions of human missions to Mars.

The gravity-assist cycler approach is attractive because it would minimize the need for propulsive maneuvers. Because of the massive life-support equipment that would be required to sustain humans on an interplanetary voyage, huge quantities of rocket fuel would be required for each such maneuver [see "How to Go to Mars," on page 44].

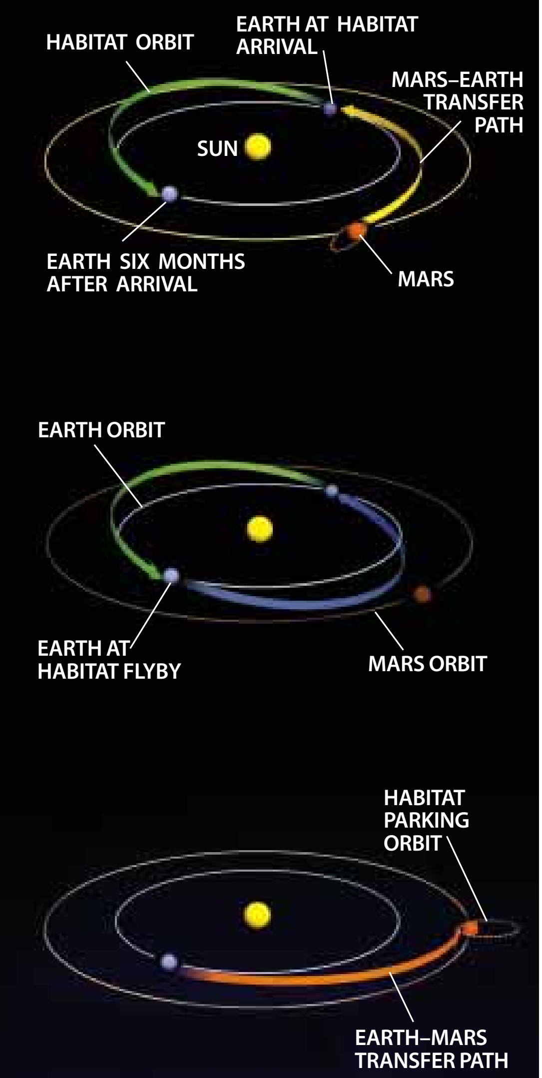
Castles in the Firmament

The cycler concept goes back to the early 1980s. Alan L. Friedlander and John C. Niehoff, both then with Science Applications International, described a system in which several long-lived space habitats (which they called castles) would be placed in solar orbits that would periodically approach Earth and Mars. Human crews would occupy these castles during the interplanetary cruise, which would last two or more years. Then, during the encounters with Mars or Earth, the travelers would make use of more spartan vehicles ("taxis") to go back and forth between a castle and a planet. The castles would be resupplied using propulsion technologies, such as ion drive, that are highly efficient but too slow for human passengers. The trip on board the taxi between a castle and a planet would take about a week or less.

As originally conceived, the castles would orbit the sun in such a way that they would encounter Earth about once every five years and Mars every 3.75 years. In a second proposal the habitats would encounter Earth every three years and Mars every 7.5 years. Neither of these orbits would have been significantly modified by the planetary encounters. Thus, gravity assist was not a factor in these early concepts.

In 1985 Aldrin proposed a cycling habitat orbit that would make crucial use of gravity assist during each Earth flyby. These castles would also circle the sun, but the strategy would speed up the interplanetary transit time by exploiting orbits whose farthest point from the star (or aphelion) would be well beyond Mars. A major advantage of this scheme is that the habitats would encounter each planet every 2.7 years, and the planet-to-planet transit time would be as little as six months. A drawback would be that periodic propulsion maneuvers would be needed to keep the cycling habitat in this advantageous orbit. Because these maneuvers would not be time-critical, however, they could be performed by high-efficiency, low-thrust propulsion systems.

Moreover, one of the most critical maneuvers would be accomplished largely by gravity assist. The interval separating encounters between the habitat and Mars would not be an exact, whole-number multiple of a Martian year. So the planet would be in a different place, relative to the solar system, each time the habitat was about to make its approach. For this reason, the orbit of the habitat would have to be adjusted each time so that it would encounter the planet. In technical terms, mission controllers would have to rotate the habitat orbit's line of apsides (the line from its perihelion—closest point to the sun—to its aphelion) enough so that the trajec-



CYCLING TRAJECTORY would carry the habitat from Mars to Earth (*yellow, top*). Then, orbiting the sun, the craft would periodically reencounter Earth (*green* and *blue, top* and *middle*), where it would use Earth's gravity to tweak its trajectory. After returning to Mars, it would settle into an elongated "parking" orbit (*bottom*).

SLIM FILMS

tory would coincide with the position of Mars at the next planned encounter. Aldrin's insight was that this shift could be accomplished mainly by gravity assist as the habitat swung by Earth.

Because of its elongated orbit, the habitat would encounter Earth and, especially, Mars at relatively high velocities. Those high speeds would be problematic if it were the massive habitat that would have to be slowed down for reentry. But it would never need to slow down, because passengers would use the taxis to go to and from the planets.

Those advantages notwithstanding, it is difficult to compare the costs of the cycler strategy with those of more traditional approaches to Mars exploration. Clearly, a great deal of infrastructure would have to be built and orbited to carry out the cycler mission. Once up and orbiting, however, that infrastructure could be used to send dozens, if not hundreds, of people to Mars. Calculating how many passengers would be necessary to break even, though, is extremely difficult because of uncertainties about how many habitats would be required, how much it would cost to build, launch, supply and maintain them, and how much it would cost to carry out missions with one-shot rockets.

Improved Cyclers

Aldrin has continued refining his ideas about cycling habitats and Mars exploration. In his latest conception the habitats would follow trajectories that would encounter the planets at lower velocities, allowing more time and flexibility for trips between the habitat and the planets. Instead of a simple, alternating Earth-Mars-Earth-Mars encounter sequence, this latest scheme would exploit creative celestial mechanics to add "dwell time" at both Mars and Earth.

In this plan the single Earth swingby would become a multiple Mars-Earth-Earth-Earth-Earth-Mars sequence of encounters [*see illustration at left*]. During the Earth portion of the trajectory, the habitat would remain in an Earth-like orbit around the sun, but every six months it would fly by Earth, using the planet's gravitational field to help adjust the orbit for the next encounter. Also, the Mars swingby would have a hesitation period during which the habitat would be waiting for Earth to come into position for the return leg. The trajectory repeats itself once every 52 months, during which time Earth and Mars come into conjunction with each other twice (two synodic periods).

To accomplish the biannual Earth flyby maneuvers, controllers would use Earth's gravity to shift the spacecraft's orbital plane around the sun into one inclined more than 10 degrees to that of Earth's but with the same orbital period as Earth (one year). This cycler strategy uses three such back-to-back maneuvers (or one six-month encounter followed by or preceded by a 12-month reencounter), followed by a gravity assist onto the Mars-bound leg. NASA now plans to use the Earth-Earth six-month reencounter trajectory for the Mars Sample Return mission scheduled for 2005 and for the CONTOUR Discovery science mission.

At Mars, introducing a dwell time presents many challenges. The planet's mass cannot induce even a 10-degree bend in a spacecraft's trajectory under approach velocities typical of cycling orbits. So it is likely that controllers would have to use a Martian gravity assist, plus perhaps a small propulsive maneuver, to turn the spacecraft toward the inner solar system. The vehicle would then encounter Venus and exploit that planet's Earth-like gravity to aim itself back for another Mars encounter.

Dennis V. Byrnes of the Jet Propulsion Laboratory in Pasadena, Calif., recently analyzed similar trajectory options. Byrnes, who is deputy manager of the Navigation and Mission Design Section at JPL, verified the feasibility of a cycling system based on three habitats following a trajectory that covered three synodic periods (about 78 months) with five Earth flybys, each a year apart, between Mars encounters. Such a system would offer an opportunity to travel from Earth to Mars, or vice versa, every 26 months.

Analyses such as Byrnes's underscore the fact that space scientists have just scratched the surface in their studies of the suitability of cycling in human interplanetary travel. As they continue refining their ideas through a series of successively better mission designs, these specialists are making it more likely that humankind will someday rely on this remarkably flexible and robust concept to reach the Red Planet—not once, but over and over again. SA

JAMES OBERG *and* BUZZ ALDRIN *have been collaborating on orbital strategies for Mars exploration since they met at the first "Case for Mars" conference in Boulder, Colo., in 1981. Oberg, an aerospace writer and consultant, was an engineer at the NASA Johnson Space Center in Houston from 1975 to 1997. Aldrin, who was the second man to walk on the moon, retired from NASA's astronaut corps in 1970 to return to the U.S. Air Force, where he commanded the test-pilot school at Edwards Air Force Base. He is now an aerospace consultant based in Laguna Beach, Calif.*

STAYING SANE IN SPACE

Is the "right stuff" enough? asks staff writer Sarah Simpson

Andy Thomas knew he was in for a rough ride the moment he floated into the entrance module of the Mir space station. "It was like going down into a dark mine shaft, pulling myself along a bungee cord between bags of equipment," the Australian-born astronaut recalls. The crawlway eventually opened into a compartment the size of a Winnebago, where coffee stains dotted the ceiling and walls in areas not already strewn with metal boxes, books and tangled hoses: home to Thomas and two cosmonauts for the next five months of 1998.

That experience was a weekend getaway compared to a round-trip Mars mission, during which astronauts would be cooped up in a capsule for up to eight months at a time and isolated from the rest of the world for two and a half years. Seeing the same few faces day after day, enduring the ills and disorientation of weightlessness, never having a moment alone—marriages and families fall apart over much less. Going to Mars should be one of humanity's greatest adventures, but it could turn into a humiliating fiasco unless mission planners devise ways to keep the space explorers from driving one another crazy.

"On a 10-day shuttle mission you can gut your way through it," Thomas says. But he and others argue that novelty and willpower aren't enough on longer missions. Just as engineers take care not to ask too much of the hardware—building in safety margins and multiple backup systems—they need to have realistic expectations of the users. "To assume that people with the 'right stuff' and the right training can deal with anything is risky," says David F. Dinges, director of the unit for experimental psychiatry at the University of Pennsylvania School of Medicine. "The people we'll send will be special, but they're not gods."

A look at past missions illustrates what can go wrong. The stress of overwork led to rebellion on the U.S. space station Skylab during the third and final crew rotation, which began in November 1973. The three men had fallen increasingly behind schedule and took a day off against ground controllers' instructions. The Mir space station also was the site of tension, according to reports from astronauts and cosmonauts who shared time there. Language and cultural differences amplified the stress: Americans complained about autocratic Russian leadership; Russians bemoaned the egos of some of their visitors.

These tales of agitation come as no surprise to people who have experienced similar confinement in nuclear submarines, offshore oil-drilling platforms and remote stations in Antarctica. Behavioral scientist Jack Stuster, who has performed studies for NASA, cites the story of a diesel mechanic at a small U.S. Navy outpost in Antarctica who became so crippled with depression that he neglected the facility's only generator. The man's condition could have doomed the entire crew if it hadn't been for the medic who helped him recover.

Interpersonal conflict tops the list of problems reported in the diaries of personnel at remote posts that Stuster and others have studied. Predictably, matters that might seem trivial at home, such as feelings of exclusion from a clique or even the exasperation of hearing a bunkmate's jokes time and again, can bloat and blister in tight quarters. Such annoyances have compromised mission goals only rarely, but during a Mars transit a dysfunctional crew could spell disaster.

NASA, following up work by the European and Russian space agencies, is now gearing up a major effort to learn how better to watch for these problems among astronauts. With NASA's support the National Space Biomedical Research Institute plans to spend about $3 million to investigate the psychology and behavior of isolated groups. The goal is to formulate objective ways to recognize failing performance, says Dinges, the team's associate leader. Previous studies relied on astronauts' own reports, which sometimes gloss over crucial issues. "With trained professionals, they may say they're fine even when they're incapacitated," Dinges says.

These issues may seem obvious, but it is remarkable how many people overestimate their ability to cope or simply fail to prepare. Some of the first six American astronauts who boarded Mir didn't bring enough to fill their free time, and the result was cabin fever and flaring tempers. Thomas says he vowed not to repeat that mistake. He packed pencils and paper and made sketching his new hobby. "It's a psychological escape when you can't get away physically," he explains.


NASA

COOPED-UP ASTRONAUTS, such as this team on board the space shuttle *Atlantis* in January 1997, might not look so cheerful during a half-year journey to Mars.

Thomas is now leading the development of a new NASA training program to make astronauts sensitive to the psychological challenges they will face in space. The initial two-day seminar took place last November and included two astronauts assigned for turns on the upcoming International Space Station. A second phase of training this winter confined a team of astronauts to an isolated spot in the Canadian wilderness for 10 days to complete team tasks.

Stuster insists that the right physical surroundings are also essential for long stints in space. "Humans are incredibly adaptable, but we don't want to subject them to austere conditions," he says. At NASA's new Habitability Design Center in Houston, four architects are helping a team of engineers dream up individual crew quarters for the International Space Station. Soundproof collapsible cubbies will attach to the station's inside wall, each outfitted with an aluminum desk and sleeping harness. Astronauts will be able to personalize their tiny havens with books and photographs held in place by Velcro straps and bungee cords. A similar setup could provide private escape for explorers bound for Mars [see "How to Go to Mars," on page 44].

Above all, most experts agree, crew selection is the key to mission success. Hints at a person's potential to endure may lie in their biographies. But it may not be clear how people will get along until they are given an opportunity to spend time together as a group. "There are some people who probably shouldn't go," says *Apollo 17* astronaut Harrison Schmitt. "If you want to test it, put them on a space station for 90 days." SA

INVADERS FROM HOLLYWOOD

Thanks to Pathfinder and other missions, science gets some respect in Tinseltown, as staff writer Philip Yam *finds after touchdown on a Vancouver set*

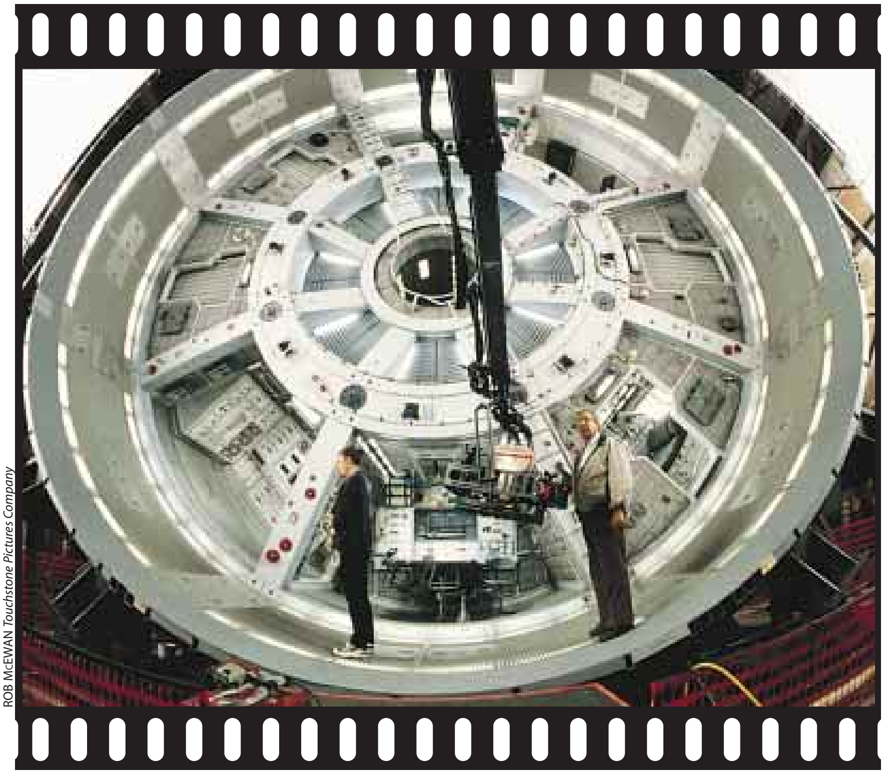
Sitting in the front row in a darkened room where filmmakers view "dailies"—raw footage from recent shoots—is a man you wouldn't associate with the glittering world of make-believe. Coming to this Vancouver studio in a down-to-earth green polo shirt, khakis and sneakers, Matthew P. Golombek could be confused with a young academic who was headed to his next lecture but stepped on the wrong bus. In fact, as project scientist for NASA's 1997 Pathfinder mission, he may be the closest thing Earth has to a resident Martian. Disney has called him to serve as a science consultant on its movie *Mission to Mars*, which opens this month. As the film rolls, showing actors Gary Sinise, Jerry O'Connell and Connie Nielsen as researchers on their way to the Red Planet, Golombek can't resist adding his two cents. "Hey, these scientists are good-looking," he quips. "That's not reality."

Scientific accuracy doesn't usually seem to be one of Hollywood's major concerns. Yet consultants have always been an integral part of science-fiction films. Even back in the genre's heyday of the 1950s, "in films we laugh at today, there were consultants to add verisimilitude," explains Vivian Sobchack, a film studies professor at the University of California at Los Angeles and author of the book *Screening Space: The American Science Fiction Film*. Moreover, she notes, directors often embedded short documentaries within their movies. For instance, *Them!*, the classic film about marauding mutant ants, contains a minidocumentary about the insects.

Modern special effects have made it easier than ever to put science into movies. They enable *Mission to Mars* to

ROB McEWAN *Touchstone Pictures Company*

MARS ON EARTH: The habitat module from *Mission to Mars* looks authentically weathered by dust storms. It took some 120,000 gallons of latex to paint the ground.



ROB McEWAN *Touchstone Pictures Company*

ROTATING LIVING QUARTERS in a spaceship would actually have to be much bigger if they were to simulate the gravity of either Earth or Mars.

give viewers a feel for what it might actually be like to travel to and survive on Mars—from zero gravity to withering dust storms—as well as of the main scientific reason for doing so, namely, looking for life. Golombek, along with NASA astronauts Story Musgrave and Kathryn Clark, read the script and discussed the technical reality with those responsible for different aspects of the movie.

Most eye-opening to a visitor is the 55-acre outdoor movie set at the Fraser Sand Dunes, just south of Vancouver. There set decorators trucked in tons of pebbles, coated the area with thousands of square yards of "shotcrete"—sprayable concrete—and blasted 120,000 gallons of environmentally friendly latex paint out of fire hoses to color the dunes Martian red. The landscape looks straight out of the famous Pathfinder photographs. "I'm so impressed by how they made it look real," Golombek says.

Of course, some dramatic license is to be expected in fiction. To begin with, in the movie, a rescue effort launches a few months after disaster strikes the first Martian landing. Realistically, no such rescue would be attempted, Golombek notes: Earth and Mars are in orbital alignment only once every 26 months. So barring a major advance in space propulsion, the Martian pioneers are on their own. For a real manned expedition, NASA might first send robotic missions to build up an infrastructure on or near Mars, Golombek says. Then, if an emergency arose, a crew might have the essential equipment readily available.

The film also features an unmanned orbiter swinging by Mars on its way to Saturn. That's not likely, Golombek remarks: considering Mars's small size, there's not much point in using its gravity to accelerate a probe. The astronauts make a tense space walk to the orbiter from their ship, which has been crippled by a micrometeorite impact. In reality, metal shields can protect against these objects. Once on board the orbiter, the astronauts descend to the surface—a very unlikely scenario, in that a robotic orbiter wouldn't be "man-rated," as Golombek puts it, and be able to land safely.

It can also be hard for filmmakers to re-create every new scientific detail. According to Golombek, the Martian surface isn't truly red; the best information so far suggests that the ground is probably more of a yellowish brown, although the palette varies geographically. Most people see the planet's color as red because, as far as primary colors go, red is the closest match.

Budget restraints lead to other compromises—in this case, forcing set makers to scale back on construction. The living quarters inside the rescue vehicle are part of a 50-foot-wide structure that spins to simulate Earth's gravity. But, Clark notes, given the rotational speed depicted in the film, the pendulum arm should be much longer, which would have made the whole structure impractically big for the studio. The wheel does, however, raise an interesting question: How does the human body respond to different g forces at the same time? The feet would feel one g but the head something less because it is slightly closer to the hub of rotation. Clark says there are no data yet on such effects.

For Golombek, the exaggerations do not detract from the real value of the film: to convey the sense of adventure in Mars exploration and, just maybe, to galvanize the public. The other Mars movie coming out this year, *Red Planet,* as well as two projects by director James Cameron, scheduled for 2001, undoubtedly make the same trade-offs. "You really have to forgive that stuff," Golombek remarks. Movies just wouldn't be as much fun if science were to have the last say: *The Angry Yellowish Brown Planet* just doesn't cut it. As Golombek concludes, "Hollywood does a much better job of talking about what NASA does than NASA does itself." SA

Further Information for Special Report on Mars

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The Tick-Tock of the Biological Clock

CYNTHIA TURNER

Biological clocks count off 24-hour intervals in most forms of life. Genetics has revealed that related molecular timepieces are at work in fruit flies, mice and humans

by Michael W. Young

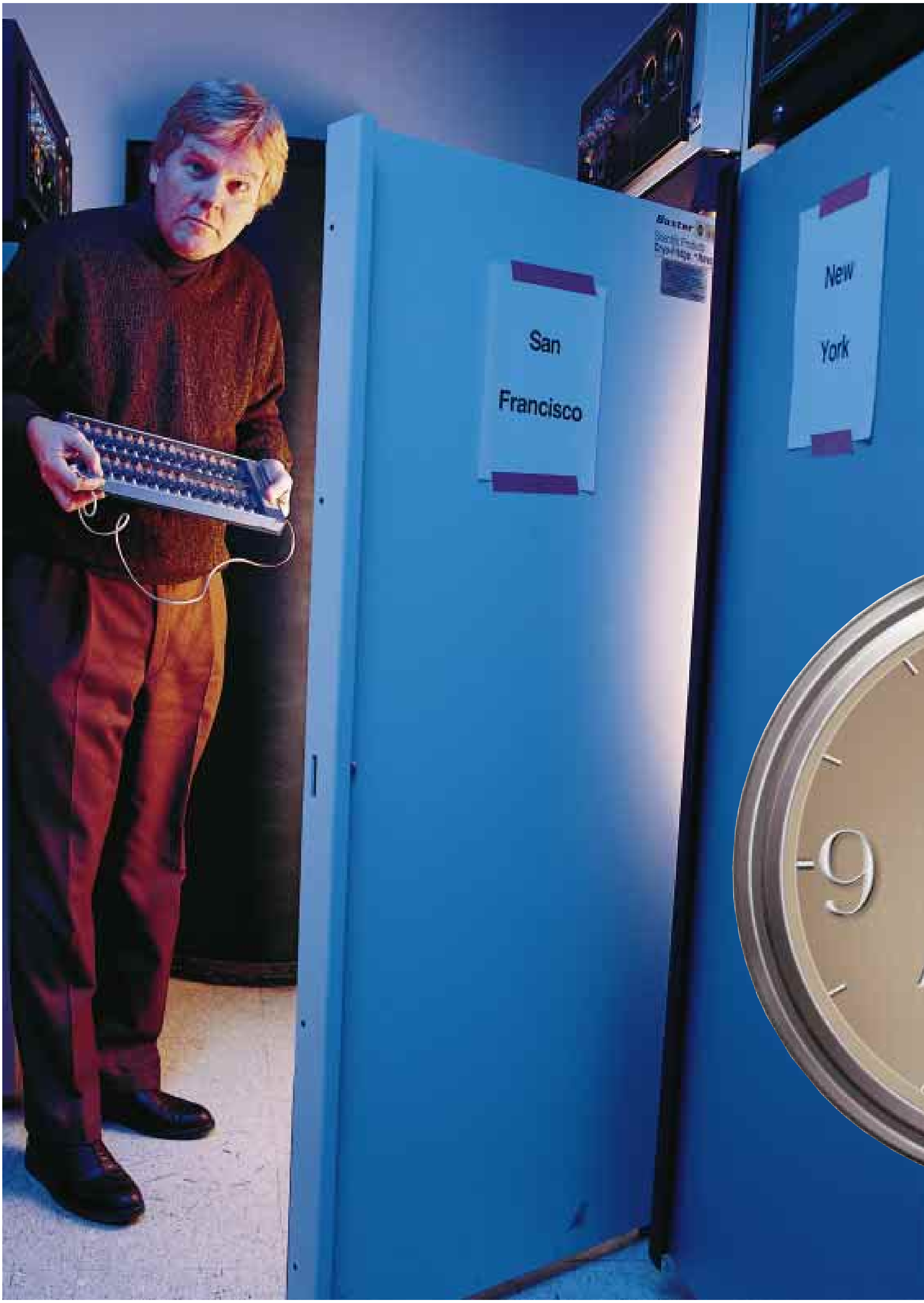
SAN FRANCISCO

PETER MURPHY

You have to fight the urge to fall asleep at 7:00 in the evening. You are ravenous at 3 P.M. but have no appetite when suppertime rolls around. You wake up at 4:00 in the morning and cannot get back to sleep. This scenario is familiar to many people who have flown from the East Coast of the U.S. to California, a trip that entails jumping a three-hour time difference. During a weeklong business trip or vacation, your body no sooner acclimatizes to the new schedule than it is time to return home again, where you must get used to the old routine once more.

Nearly every day my colleagues and I put a batch of *Drosophila* fruit flies through the jet lag of a simulated trip from New York to San Francisco or back. We have several refrigerator-size incubators in the laboratory: one labeled "New York" and another tagged "San Francisco." Lights inside these incubators go on and off as the sun rises and sets in those two cities. (For consistency, we schedule sunup at 6 A.M. and sundown at 6 P.M. for both locations.) The temperature in the two incubators is a constant, balmy 77 degrees Fahrenheit.

The flies take their simulated journey inside small glass tubes packed into special trays that monitor their movements with a narrow beam of infrared light. Each time a fly moves into the beam, it casts a shadow on a phototransistor in the tray, which is connected to a computer that records the activity. Going from New York to San Francisco time does not involve a five-hour flight for our flies: we simply disconnect a fly-



NEW
YORK

PETER MURPHY

GIVING FRUIT FLIES JET LAG is helping researchers such as the author (*above*) understand the molecular basis of the biological clocks of a variety of other organisms, including humans. The tiny flies are kept in small glass tubes (*photograph at left*) packed into trays equipped with sensors that record the insects' activity. When a tray from an incubator kept at New York time, where it is dark at 7:30 P.M., is moved to another incubator simulating San Francisco time, where it is three hours earlier and still light, the levels of key proteins in the flies' brains plunge.

THE BASICS

THE BIOLOGICAL CLOCK

THE AUTHOR ANSWERS SOME KEY QUESTIONS

Where is the biological clock? In mammals the master clock that dictates the day-night cycle of activity known as circadian rhythm resides in a part of the brain called the suprachiasmatic nucleus (SCN). But cells elsewhere also show clock activity.

What drives the clock? Within individual SCN cells, specialized clock genes are switched on and off by the proteins they encode in a feedback loop that has a 24-hour rhythm.

Is the biological clock dependent on the normal 24-hour cycle of light and darkness? No. The molecular rhythms of clock-gene activity are innate and self-sustaining. They persist in the absence of environmental cycles of day and night.

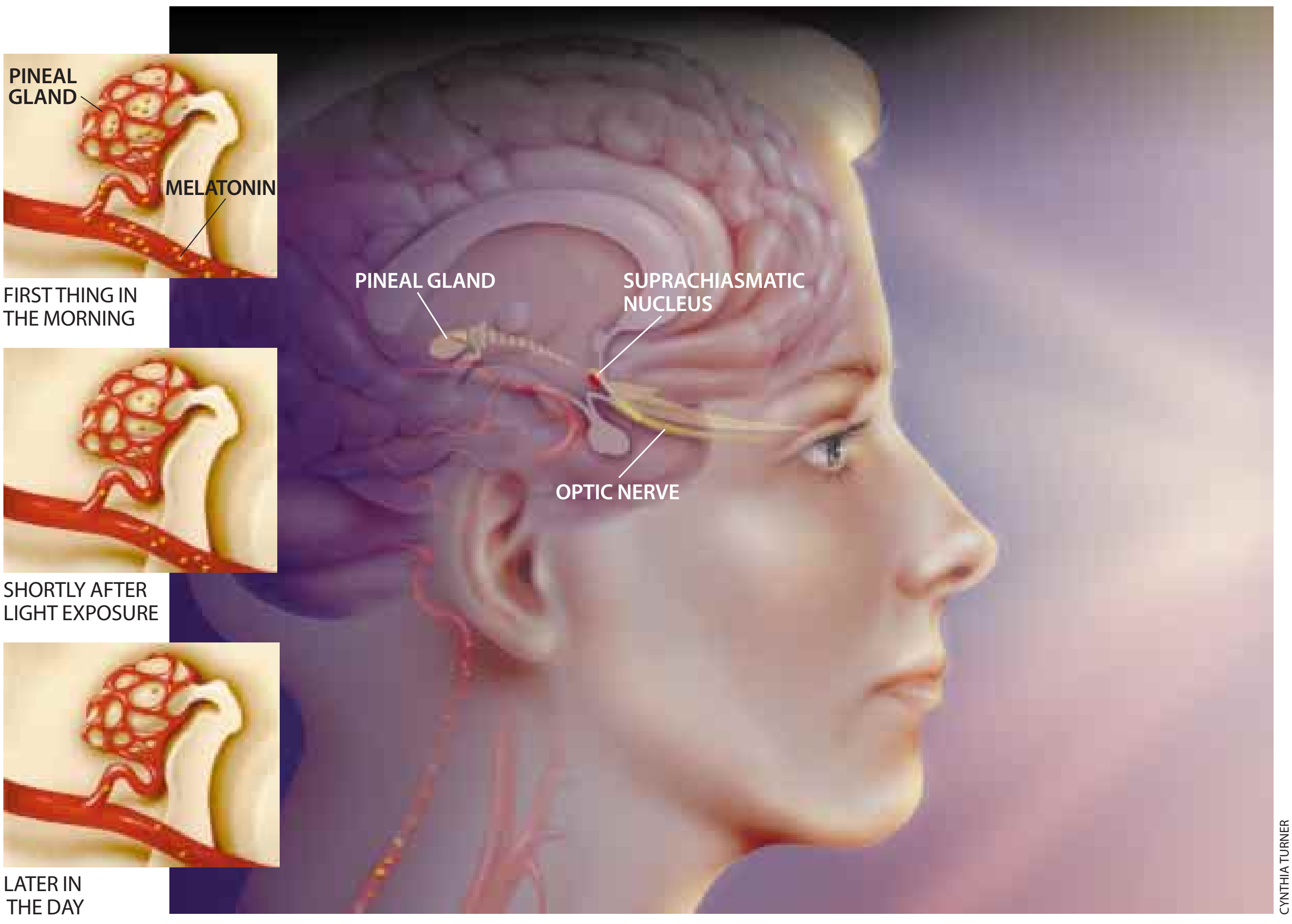
What role does light play in regulating and resetting the biological clock? Bright light absorbed by the retina during the day helps to synchronize the rhythms of activity of the clock genes to the prevailing environmental cycle. Exposure to bright light at night resets circadian rhythms by acutely changing the amount of some clock-gene products.

How does the molecular clock regulate an individual's day-night activity? The fluctuating proteins synthesized by clock genes control additional genetic pathways that connect the molecular clock to timed changes in an animal's physiology and behavior.

filled tray in one incubator, move it to the other one and plug it in.

We have used our transcontinental express to identify and study the functions of several genes that appear to be the very cogs and wheels in the works of the biological clock that controls the day-night cycles of a wide range of organisms that includes not only fruit flies but mice and humans as well. Identifying the genes allows us to determine the proteins they encode—proteins that might serve as targets for therapies for a wide range of disorders, from sleep disturbances to seasonal depression.

The main cog in the human biological clock is the suprachiasmatic nucleus (SCN), a group of nerve cells in a region at the base of the brain called the hypothalamus. When light hits the retinas of the eyes every morning, specialized nerves send signals to the SCN, which in turn controls the production cycle of a multitude of biologically active sub-



LIGHT HITTING THE EYE causes the pineal gland of the brain to taper its production of melatonin (*insets*), a hormone that appears to play a role in inducing sleep. The signal to reduce melatonin secretion is relayed from the retina, through the optic nerve, to a structure called the suprachiasmatic nucleus (SCN). The connection from the SCN to the pineal is indirect.

stances. The SCN stimulates a nearby brain region called the pineal gland, for instance. According to instructions from the SCN, the pineal rhythmically produces melatonin, the so-called sleep hormone that is now available in pill form in many health-food stores. As day progresses into evening, the pineal gradually begins to make more melatonin. When blood levels of the hormone rise, there is a modest decrease in body temperature and an increased tendency to sleep.

The Human Clock

Although light appears to "reset" the biological clock each day, the day-night, or circadian, rhythm continues to operate even in individuals who are deprived of light, indicating that the activity of the SCN is innate. In the early 1960s Jürgen Aschoff, then at the Max Planck Institute of Behavioral Physiology in Seewiesen, Germany, and his colleagues showed that volunteers who lived in an isolation bunker—with no natural light, clocks or other clues about time—nevertheless maintained a roughly normal sleep-wake cycle of 25 hours.

More recently Charles Czeisler, Richard E. Kronauer and their colleagues at Harvard University have determined that the human circadian rhythm is actually closer to 24 hours—24.18 hours, to be exact. The scientists studied 24 men and women (11 of whom were in their 20s and 13 of whom were in their 60s) who lived for more than three weeks in an environment with no time cues other than a weak cycle of light and dark that was artificially set at 28 hours and that gave the subjects their signals for bedtime.

They measured the participants' core body temperature, which normally falls at night, as well as blood concentrations of melatonin and of a stress hormone called cortisol that drops in the evening. The researchers observed that even though the subjects' days had been abnormally extended by four hours, their body temperature and melatonin and cortisol levels continued to function according to their own internal 24-hour circadian clock. What is more, age seemed to have no effect on the ticking of the clock: unlike the results of previous studies, which had suggested that aging disrupts circadian rhythms, the body-temperature and hormone fluctuations of the older subjects in the Harvard study were as regular as those of the younger group.

As informative as the bunker studies are, to investigate the genes that underlie the biological clock scientists had to turn to fruit flies. Flies are ideal for genetic studies because they have short life spans and are small, which means that researchers can breed and interbreed thousands of them in the laboratory until interesting mutations crop up. To speed up the mutation process, scientists usually expose flies to mutation-causing chemicals called mutagens.

The first fly mutants to show altered circadian rhythms were identified in the early 1970s by Ron Konopka and Seymour Benzer of the California Institute of Technology. These researchers fed a mutagen to a few fruit flies and then monitored the movement of 2,000 of the progeny, in part using a form of the same apparatus that we now use in our New York to San Francisco experiments. Most of the flies had a normal 24-hour circadian rhythm: the insects were active for roughly 12 hours a day and rested for the other 12 hours. But three of the flies had mutations that caused them to break the pattern. One had a 19-hour cycle, one had a 28-hour cycle, and the third fly appeared to have no circadian rhythm at all, resting and becoming active seemingly at random.

Time Flies

In 1986 my research group at the Rockefeller University and another led by Jeffrey Hall of Brandeis University and Michael Rosbash of the Howard Hughes Medical Institute at Brandeis found that the three mutant flies had three different alterations in a single gene named *period,* or *per,* which each of our teams had independently isolated two years earlier. Because different mutations in the same gene caused the three behaviors, we concluded that *per* is somehow actively involved both in producing cir-

CLOCKS EVERYWHERE

THEY ARE NOT JUST IN THE BRAIN

Most of the research on the biological clocks of animals has focused on the brain, but that is not the only organ that observes a day-night rhythm.

Jadwiga Giebultowicz of Oregon State University has identified PER and TIM proteins—key components of biological clocks—in the kidneylike malpighian tubules of fruit flies. She has also observed that the proteins are produced according to a circadian cycle, rising at night and falling during the day. The cycle persists even in decapitated flies, demonstrating that the malpighian cells are not merely responding to signals from the insects' brains.

In addition, Steve Kay's research group at the Scripps Research Institute in La Jolla, Calif., has uncovered evidence of biological clocks in the wings, legs, oral regions and antennae of fruit flies. By transferring genes that direct the production of fluorescent PER proteins into living flies, Kay and his colleagues have shown that each tissue carries an independent, photoreceptive clock. The clocks even continue to function and respond to light when each tissue is dissected from the insect.

HEAD OF A FRUIT FLY contains several biological clocks. Cells taken from the oral regions and antennae (*structures between eyes*) show the same response to cycles of light and darkness as those isolated from the brain.

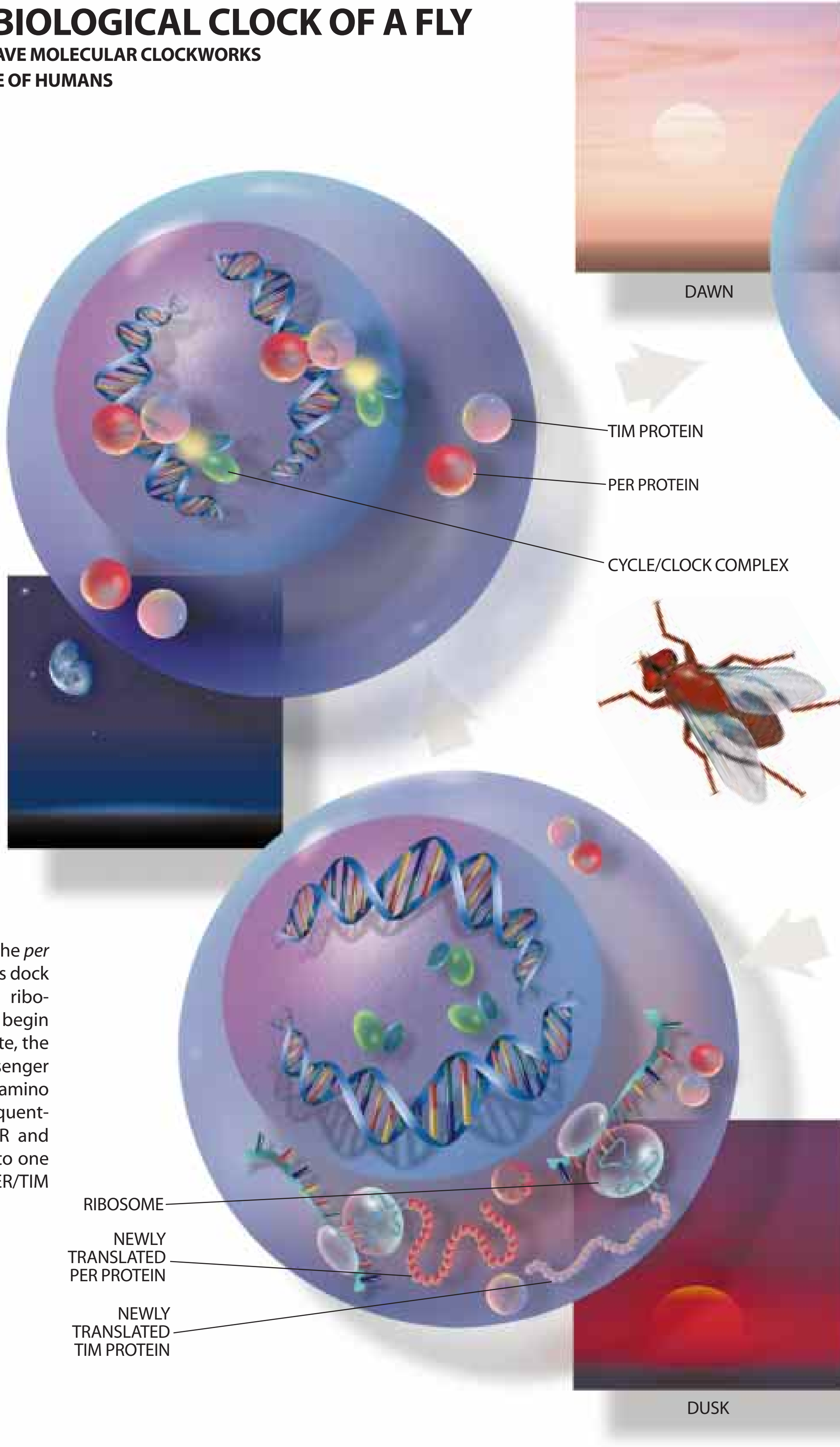
JUERGEN BERGER *Max Planck Institute/SPL/Photo Researchers, Inc.*

And the extracranial biological clocks are not restricted to fruit flies. Ueli Schibler of the University of Geneva showed in 1998 that the *per* genes of rat connective-tissue cells called fibroblasts are active according to a circadian cycle.

The diversity of the various cell types displaying circadian clock activity suggests that for many tissues correct timing is important enough to warrant keeping track of it locally. The findings might give new meaning to the term "body clock." *—M.W.Y.*

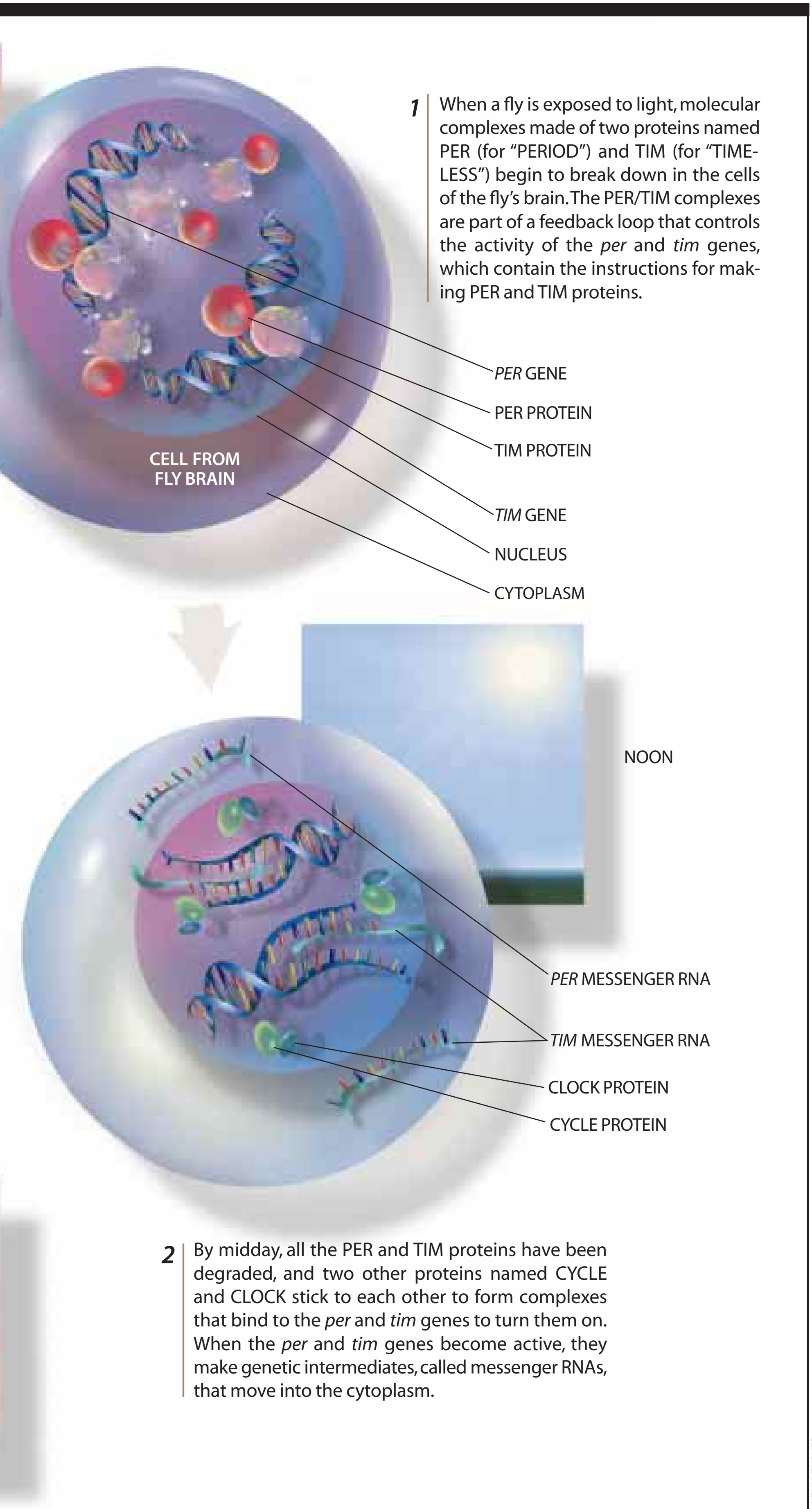
A DAY IN THE BIOLOGICAL CLOCK OF A FLY

CELLS FROM A FLY BRAIN HAVE MOLECULAR CLOCKWORKS CLOSELY RELATED TO THOSE OF HUMANS



4 During the night, the new PER/TIM complexes move into the nucleus, where they block the activity of CYCLE and CLOCK, essentially shutting down their own production. When the sun comes up the following day, the PER/TIM complexes break down, and the cycle starts anew.

3 Once in the cytoplasm, the *per* and *tim* messenger RNAs dock with structures called ribosomes. The ribosomes begin to "read out," or translate, the information in the messenger RNAs to make strings of amino acids. The strings subsequently fold into mature PER and TIM proteins that stick to one another to form new PER/TIM complexes at dusk.



1 When a fly is exposed to light, molecular complexes made of two proteins named PER (for "PERIOD") and TIM (for "TIMELESS") begin to break down in the cells of the fly's brain. The PER/TIM complexes are part of a feedback loop that controls the activity of the *per* and *tim* genes, which contain the instructions for making PER and TIM proteins.

2 By midday, all the PER and TIM proteins have been degraded, and two other proteins named CYCLE and CLOCK stick to each other to form complexes that bind to the *per* and *tim* genes to turn them on. When the *per* and *tim* genes become active, they make genetic intermediates, called messenger RNAs, that move into the cytoplasm.

CYNTHIA TURNER

cadian rhythm in flies and in setting the rhythm's pace.

After isolating *per,* we began to question whether the gene acted alone in controlling the day-night cycle. To find out, two postdoctoral fellows in my laboratory, Amita Sehgal and Jeffrey Price, screened more than 7,000 flies to see if they could identify other rhythm mutants. They finally found a fly that, like one of the *per* mutants, had no apparent circadian rhythm. The new mutation turned out to be on chromosome 2, whereas *per* had been mapped to the X chromosome. We knew this had to be a new gene, and we named it *timeless,* or *tim*.

But how did the new gene relate to *per*? Genes are made of DNA, which contains the instructions for making proteins. DNA never leaves the nucleus of the cell; its molecular recipes are read out in the form of messenger RNA, which leaves the nucleus and enters the cytoplasm, where proteins are made. We used the *tim* and *per* genes to make PER and TIM proteins in the laboratory. In collaboration with Charles Weitz of Harvard Medical School, we observed that when we mixed the two proteins, they stuck to each other, suggesting that they might interact within cells.

In a series of experiments, we found that the production of PER and TIM proteins involves a clocklike feedback loop [*see illustration at left*]. The *per* and *tim* genes are active until concentrations of their proteins become high enough that the two begin to bind to each other. When they do, they form complexes that enter the nucleus and shut down the genes that made them. After a few hours enzymes degrade the complexes, the genes start up again, and the cycle begins anew.

Moving the Hands of Time

Once we had found two genes that functioned in concert to make a molecular clock, we began to wonder how the clock could be reset. After all, our sleep-wake cycles fully adapt to travel across any number of time zones, even though the adjustment might take a couple of days or weeks.

That is when we began to shuttle trays of flies back and forth between the "New York" and "San Francisco" incubators. One of the first things we and others noticed was that whenever a fly was moved from a darkened incubator to one that was brightly lit to mimic day-

BODY CHANGES OVER 24-HOUR PERIOD

1:00 A.M.
- Pregnant women are most likely to go into labor.
- Immune cells called helper T lymphocytes are at their peak.

2:00 A.M.
- Levels of growth hormone are highest.

4:00 A.M.
- Asthma attacks are most likely to occur.

6:00 A.M.
- Onset of menstruation is most likely.
- Insulin levels in the bloodstream are lowest.
- Blood pressure and heart rate begin to rise.
- Levels of the stress hormone cortisol increase.
- Melatonin levels begin to fall.

7:00 A.M.
- Hay fever symptoms are worst.

8:00 A.M.
- Risk for heart attack and stroke is highest.
- Symptoms of rheumatoid arthritis are worst.
- Helper T lymphocytes are at their lowest daytime level.

Noon
- Level of hemoglobin in the blood is at its peak.

3:00 P.M.
- Grip strength, respiratory rate and reflex sensitivity are highest.

4:00 P.M.
- Body temperature, pulse rate and blood pressure peak.

6:00 P.M.
- Urinary flow is highest.

9:00 P.M.
- Pain threshold is lowest.

11:00 P.M.
- Allergic responses are most likely.

ADAPTED FROM *SEARCH*, SPRING 1998

light, the TIM proteins in the fly's brain disappeared—in a matter of minutes.

Even more interestingly, we noted that the direction the flies "traveled" affected the levels of their TIM proteins. If we removed flies from "New York" at 8 P.M. local time, when it was dark, and put them into "San Francisco," where it was still light at 5 P.M. local time, their TIM levels plunged. But an hour later, when the lights went off in "San Francisco," TIM began to reaccumulate. Evidently the flies' molecular clocks were initially stopped by the transfer, but after a delay they resumed ticking in the pattern of the new time zone.

In contrast, flies moved at 4 A.M. from "San Francisco" experienced a premature sunrise when they were placed in "New York," where it was 7 A.M. This move also caused TIM levels to drop, but this time the protein did not begin to build up again because the molecular clock was advanced by the time-zone switch.

We learned more about the mechanism behind the different molecular responses by examining the timing of the production of *tim* RNA. Levels of *tim* RNA are highest at about 8 P.M. local time and lowest between 6 A.M. and 8 A.M. A fly moving at 8 P.M. from "New York" to "San Francisco" is producing maximum levels of *tim* RNA, so protein lost by exposure to light in "San Francisco" is easily replaced after sunset in the new location. A fly traveling at 4 A.M. from "San Francisco" to "New York," however, was making very little *tim* RNA before departure. What the fly experiences as a premature sunrise eliminates TIM and allows the next cycle of production to begin with an earlier schedule.

Not Just Bugs

Giving flies jet lag has turned out to have direct implications for understanding circadian rhythm in mammals, including humans. In 1997 researchers led by Hajime Tei of the University of Tokyo and Hitoshi Okamura of Kobe University in Japan—and, independently, Cheng Chi Lee of Baylor College of Medicine—isolated the mouse and human equivalents of *per.* Another flurry of work, this time involving many laboratories, turned up mouse and human forms of *tim* in 1998. And the genes were active in the suprachiasmatic nucleus.

Studies involving mice also helped to answer a key question: What turns on the activity of the *per* and *tim* genes in the first place? In 1997 Joseph Takahashi of the Howard Hughes Medical Institute at Northwestern University and his colleagues isolated a gene they called *Clock* that when mutated yielded mice with no discernible circadian rhythm. The gene encodes a transcription factor, a protein that in this case binds to DNA and allows it to be read out as messenger RNA.

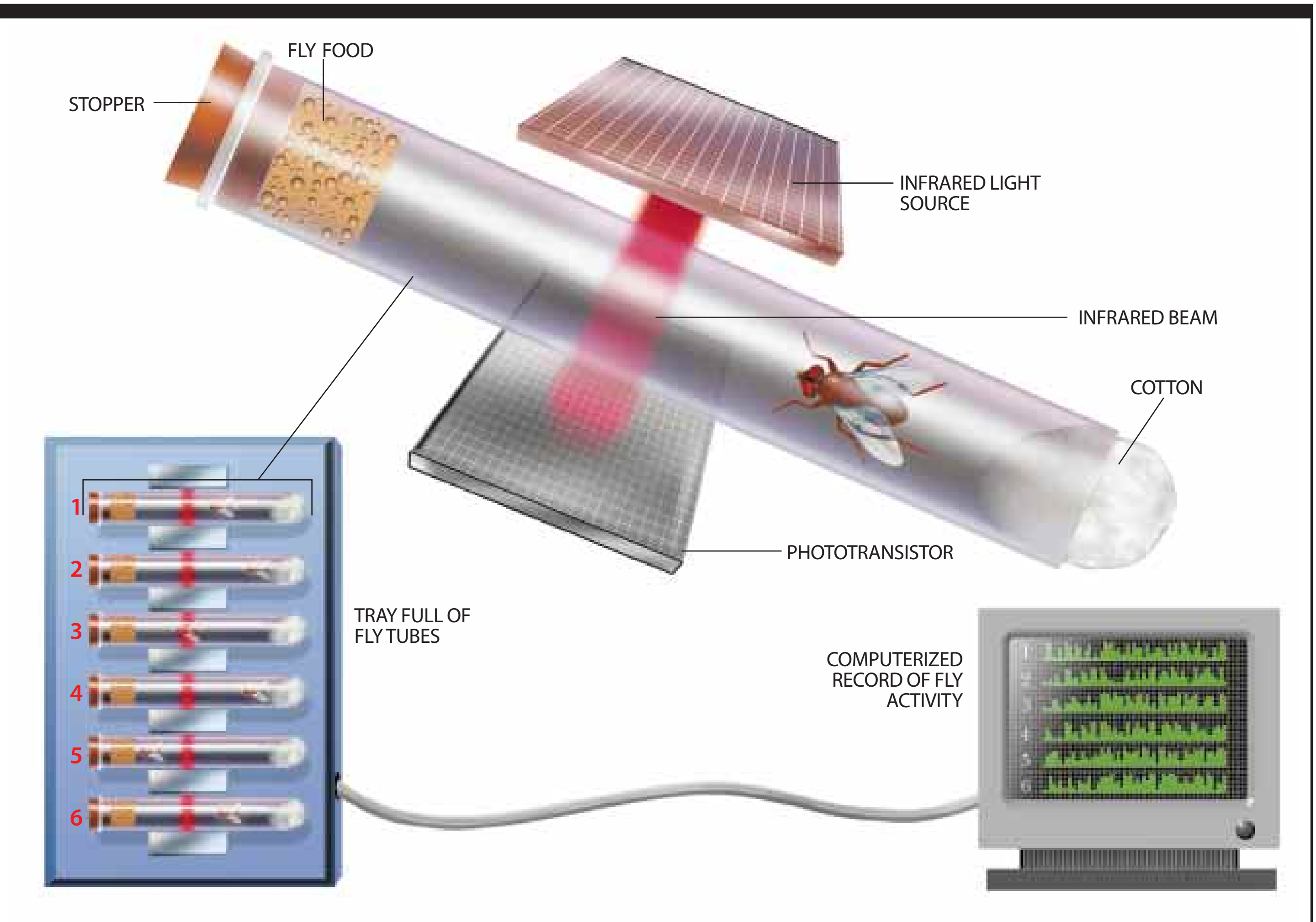
Shortly thereafter a fly version of the mouse *Clock* gene was isolated, and various research teams began to introduce combinations of the *per, tim* and *Clock* genes into mammalian and fruit fly cells. These experiments revealed that the CLOCK protein targets the *per* gene in mice and both the *per* and *tim* genes in flies. The system had come full circle: in flies, whose clocks are the best understood, the CLOCK protein—in combination with a protein encoded by a gene called *cycle*—binds to and activates the *per* and *tim* genes, but only if no PER and TIM proteins are present in the nucleus. These four genes and their proteins

MONITORING THE CIRCADIAN RHYTHMS OF FLIES

AN APPARATUS TO TRACK FLY ACTIVITY

To identify genes that play a role in the day-night activity cycle of flies, researchers expose fruit flies to mutation-causing chemicals that affect the genes of their offspring. When they become adults, each of the offspring is placed into a small glass tube. The tubes have fly food at one end and cotton at the other end to let in air.

The fly tubes are placed into special trays equipped with infrared lights and detectors. Fruit flies normally rest at night and are active during the day. The trays, which are connected to a computer, monitor each fly's movements by recording how many times it passes through an infrared beam. Analyzing thousands of mutant flies in this manner eventually yields some with abnormal circadian rhythms. —*M.W.Y.*



constitute the heart of the biological clock in flies, and with some modifications they appear to form a mechanism governing circadian rhythms throughout the animal kingdom, from fish to frogs, mice to humans.

Recently Steve Reppert's group at Harvard and Justin Blau in my laboratory have begun to explore the specific signals connecting the mouse and fruit fly biological clocks to the timing of various behaviors, hormone fluctuations and other functions. It seems that some output genes are turned on by a direct interaction with the CLOCK protein. PER and TIM block the ability of CLOCK to turn on these genes at the same time as they are producing the oscillations of the central feedback loop—setting up extended patterns of cycling gene activity.

An exciting prospect for the future involves the recovery of an entire system of clock-regulated genes in organisms such as fruit flies and mice. It is likely that previously uncharacterized gene products with intriguing effects on behavior will be discovered within these networks. Perhaps one of these, or a component of the molecular clock itself, will become a favored target for drugs to relieve jet lag, the side effects of shift work, or sleep disorders and related depressive illnesses. Adjusting to a trip from New York to San Francisco might one day be much easier. SA

The Author

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Further Information

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MOLECULAR BASES FOR CIRCADIAN CLOCKS. Jay C. Dunlap in *Cell,* Vol. 96, No. 2, pages 271–290; January 22, 1999.

TIME, LOVE, MEMORY: A GREAT BIOLOGIST AND HIS QUEST FOR THE ORIGINS OF BEHAVIOR. J. Weiner. Alfred Knopf, 1999.

A tutorial on biological clocks—including ideas for home and classroom activities—can be found on the National Science Foundation's Science and Technology Center for Biological Timing's site at http://cbt4pc.bio.virginia.edu/tutorial/TUTORIALMAIN.html on the World Wide Web.

SWARM SMARTS

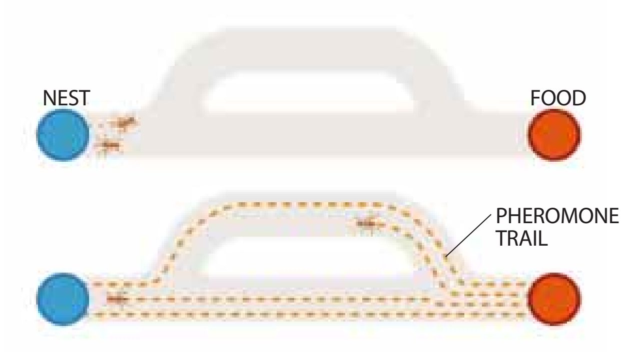
by Eric Bonabeau and Guy Théraulaz

JAMES GARY

Using ants and other social insects as models, computer scientists have created software agents that cooperate to solve complex problems, such as the rerouting of traffic in a busy telecom network

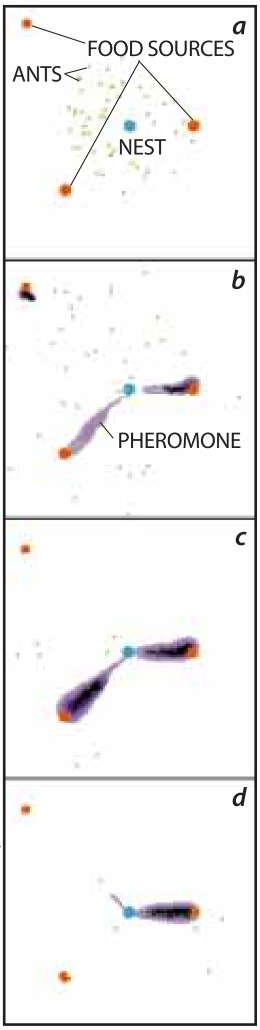
Insects that live in colonies—ants, bees, wasps, termites—have long fascinated everyone from naturalists to artists. Maurice Maeterlinck, the Belgian poet, once wrote, “What is it that governs here? What is it that issues orders, foresees the future, elaborates plans and preserves equilibrium?” These, indeed, are puzzling questions.

Each insect in a colony seems to have its own agenda, and yet the group as a whole appears to be highly organized. Apparently the seamless integration of all individual activities does not require any supervision. In fact, scientists who study the behavior of social insects have found that



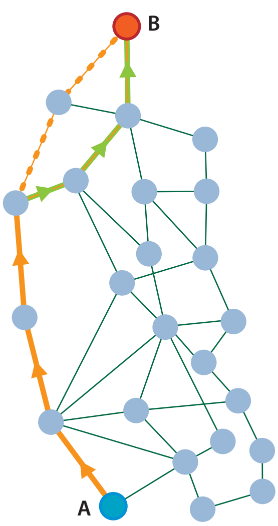
BRYAN CHRISTIE

PHEROMONE TRAILS enable ants to forage efficiently. Two ants leave the nest at the same time (*top*), each taking a different path and marking it with pheromone. The ant that took the shorter path returns first (*bottom*). Because this trail is now marked with twice as much pheromone, it will attract other ants more than the longer route will.



SIMULATION DONE IN STARLOGO, COURTESY OF MITCH RESNICK *MIT Media Lab*

DIFFERENT FOOD SOURCES are raided sequentially because of pheromone evaporation. In this computer simulation, three identical sources of food are located at unequal distances from a nest. After foraging randomly (*a*), the ants begin to raid the food sources that are closest (*b, c*). As those supplies dwindle, the concentration of pheromone along their trails decreases through evaporation (*d*). The ants will then exploit the farther source.



BRYAN CHRISTIE

NETWORK TRAFFIC can be rerouted on the fly with software agents that mimic ants. A transmission that needs to travel from A to B must go through a number of intermediate nodes. If a portion of the shortest path (*orange*) between the two locations is congested, the system must redirect the transmission through an alternative (*green*). Software agents can perform this rerouting automatically in a manner that is similar to how ants raid different food sources (*illustration above*). In the analogy, a congested path is like a depleted food source.

cooperation at the colony level is largely self-organized: in numerous situations the coordination arises from interactions among individuals. Although these interactions might be simple (one ant merely following the trail left by another), together they can solve difficult problems (finding the shortest route among countless possible paths to a food source). This collective behavior that emerges from a group of social insects has been dubbed "swarm intelligence."

Recently a growing community of researchers has been devising new ways of applying swarm intelligence to diverse tasks. The foraging of ants has led to a novel method for rerouting network traffic in busy telecommunications systems. The cooperative interaction of ants working to transport a large food item may lead to more effective algorithms for robots. The way in which insects cluster their colony's dead and sort their larvae can aid in analyzing banking data. And the division of labor among honeybees could help streamline assembly lines in factories.

Virtual Foraging

One of the early studies of swarm intelligence investigated the foraging behavior of ants. Jean-Louis Deneubourg of the Free University of Brussels and his colleagues showed that the ant "highways" often seen in nature (and in people's kitchens) result from individual ants exuding pheromone, a chemical substance, that attracts other ants. Deneubourg, a pioneer in the field, also demonstrated that this process of laying a trail of pheromone that others can follow was a good strategy for finding the shortest path between a nest and a food source.

In experiments with the Argentine ant *Linepithema humile,* Deneubourg constructed a bridge with two branches, one twice as long as the other, that separated a nest from a food source. Within just a few minutes the colony usually selected the shorter branch. Deneubourg found that the ants lay and follow trails of pheromone as they forage. The first ants returning to the nest from the food source are those that have taken the shorter path in both directions, from the nest to the food and back. Because this route is the first to be doubly marked with pheromone, nestmates are attracted to it.

If, however, the shorter branch is presented to the colony after the longer branch, the ants will not take it because the longer branch has already been marked with pheromone. But computer scientists can overcome this problem in an artificial system by introducing pheromone decay: when the chemical evaporates quickly, longer paths will have trouble maintaining stable pheromone trails. The software ants can then select a shorter branch even if it is discovered belatedly. This property is highly desirable in that it prevents the system from converging on mediocre solutions. (In *L. humile,* the pheromone concentrations do decay but at a very slow rate.)

In a computer simulation of pheromone evaporation [*see illustration at left*], researchers presented identical food sources to an artificial colony at different distances from the nest. At first the virtual ants explored their environment randomly. Then they established trails that connected all of the food sources to the nest. Next they maintained only the trails of the sources closest to the nest, leading to the exploitation of those supplies. With the depletion of that food, the software ants began to raid the farther sources.

Extending this ant model, Marco Dorigo, a computer scientist at the Free University of Brussells, and his colleagues have devised a way to solve the famous "traveling salesman prob-

Traveling Sales Ants

In the traveling salesman problem, a person must find the shortest route by which to visit a given number of cities, each exactly once. The classic problem is devilishly difficult: for just 15 cities [*see top illustration below*] there are billions of route possibilities.

Recently researchers have begun to experiment with antlike agents to derive a solution. The approach relies on the artificial ants laying and following the equivalent of pheromone trails [*see illustrations on opposite page*].

Envision a colony of such ants, each independently hopping from city to city, favoring nearby locations but otherwise traveling randomly. After completing a tour of all the cities, an ant goes back to the links it used and deposits pheromone. The amount of the chemical is inversely proportional to the overall length of the tour: the shorter the distance, the more pheromone each of the links receives. Thus, after all the ants have completed their tours and spread their pheromone, the links that belonged to the highest number of short tours will be richest with the chemical. Because the pheromone evaporates, links in long routes will eventually contain significantly less of the substance than those in short tours will.

The colony of artificial ants is then released to travel over the cities again, but this time they are guided by the earlier pheromone trails (high-concentration links are favored) as well as by the intercity distances (nearby locations have priority), which the ants can obtain by consulting a table storing those numbers. In general, the two criteria—pheromone strength and intercity distance—are weighted roughly equally.

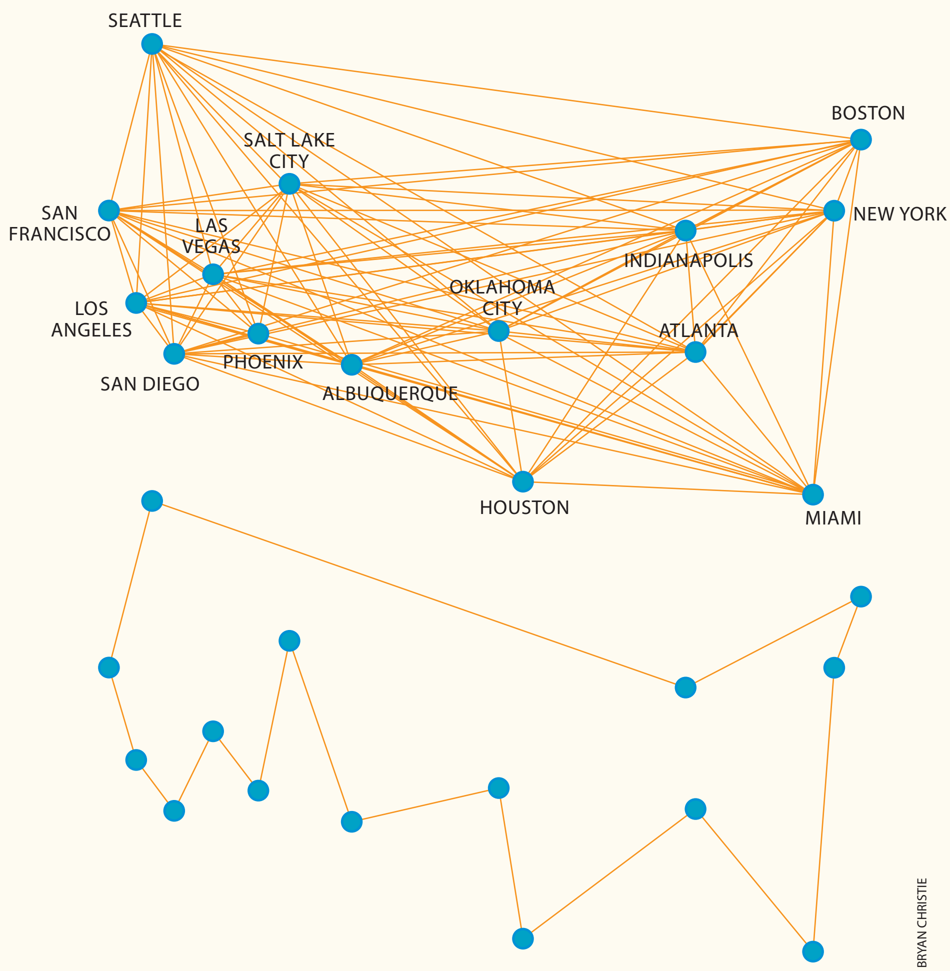
Marco Dorigo of the Free University of Brussels and his colleagues have implemented this ant-based system in software. Of course, the methodology assumes that the favored links, when taken together, will lead to an overall short route. Dorigo has found that after repeating the process (tour completion followed by pheromone reinforcement and evaporation) numerous times, the artificial ants are indeed able to obtain progressively shorter tours, such as that shown in the bottom illustration below.

Nevertheless, a difficulty arises when many routes happen to use a link that, as it turns out, is not part of a short tour. (In fact, such a link might belong to many, many long routes.) Dorigo discovered that although this popular link might bias the search for several iterations, a better connection will eventually replace it. This optimization is a consequence of the subtle interplay between reinforcement and evaporation, which ensures that only the better links survive. Specifically, at some point an alternative connection that is part of a short route would be selected by chance and would become reinforced more than the popular link, which would then lose its attractiveness to the artificial ants as its pheromone evaporated.

Another problem occurs when a short route contains a very long link that initially is less likely to be used. But Dorigo has shown that even though the connection might be a slow starter, once it has been selected it will quickly become reinforced more than other, competing links.

It is important to note that this ant-based method is effective for finding short routes but not necessarily the shortest one. Nevertheless, such near-optimal solutions are often more than adequate, particularly because obtaining the best route can require an unwieldy amount of computation. In fact, determining the exact solution quickly becomes intractable as the number of cities increases.

In addition, Dorigo's system has one advantage: its inherent flexibility. Because the artificial ants are continuously exploring different paths, the pheromone trails provide backup plans. So, whenever one of the links breaks down (bad weather between Houston and Atlanta, for instance), a pool of alternatives already exists. —*E.B.* and *G.T.*



BRYAN CHRISTIE

lem" [*see box on preceding page*]. The problem calls for finding the shortest route that goes through a given number of cities exactly once. This test is appealing because it is easy to formulate and yet extremely difficult to solve. It is "NP-complete": the solution requires a number of computational steps that grows faster than the number of cities raised to any finite power (NP stands for nondeterministic polynomial). For such problems, people usually try to find an answer that is good enough but not necessarily the best (that is, a route that is sufficiently short but perhaps not the shortest). Dorigo has shown that he can obtain near-optimal routes by using artificial ants that are tweaked so that the concentration of pheromone they deposit varies with the overall distances they have traveled.

Similar approaches have been successful in a number of other optimization tasks. For instance, artificial ants provide the best solution to the classic quadratic assignment problem, in which the manufacture of a number of goods must be assigned to different factories so as to minimize the total distance over which the items need to be transported between facilities. In a related application, David Gregg of Unilever in the U.K. and Vincent Darley of Bios Group in Santa Fe, N.M., report that they have developed an ant-based method for decreasing the time it takes to perform a given amount of work in a large Unilever plant. The system must efficiently schedule various storage tanks, chemical mixers, packing lines and other equipment.

In addition to solving optimization problems that are basically static, or nonvarying, antlike agents can also cope with glitches and dynamic environments—for example, a factory where a machine breaks down. By maintaining pheromone trails and continuously exploring new paths, the ants serendipitously set up a backup plan and thus are prepared to respond to changes in their environment. This property, which may explain the ecological success of real ants, is crucial for many applications.

Consider the dynamic unpredictability of a telephone network. A phone call from A to B generally has to go through a number of intermediate nodes, or switching stations, requiring a mechanism to tell the call where it should hop next to establish the A-to-B connection. Obviously the algorithm for this process should avoid congested areas to minimize delays, and backup routes become especially valuable when conditions change dramatically. Bad weather at an airport or a phone-in competition on TV will lead to transient local surges of network traffic, requiring on-the-fly rerouting of calls through less busy parts of the system.

To handle such conditions, Ruud Schoonderwoerd and Janet Bruten of Hewlett-Packard's research laboratories in Bristol, England, and Owen Holland of the University of the West of England have invented a routing technique in which antlike agents deposit bits of information, or "virtual pheromone," at the network nodes to reinforce paths through uncongested areas. Meanwhile an evaporation mechanism adjusts the node information to disfavor paths that go through busy areas.

Specifically, each node keeps a routing table that tells phone calls where to go next depending on their destinations. Antlike agents continually adjust the table entries, or scores, to reflect the current network conditions. If an agent experi-

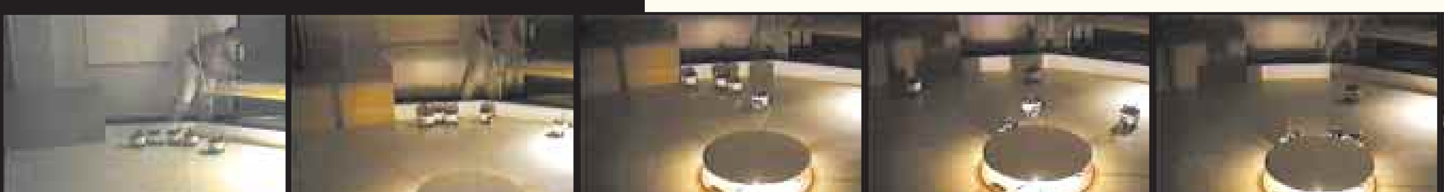
Cooperative Transport in Ants and Robots

In some ant species, nestmates are recruited to help when a single ant cannot retrieve a large prey. Then, during an initial period that can last up to several minutes, the ants change their positions and alignments around the object until they are able to move the prey toward their nest.

Using mechanical robots, C. Ronald Kube and Hong Zhang of the University of Alberta have reproduced this behavior. The

MARK MOFFETT *Minden Pictures*

ANTS WORK TOGETHER to fold a large leaf (*left*). Such teamwork has inspired scientists to program robots without the use of complex software. In an experiment at the University of Alberta (*below*), the robots must push an illuminated circular box toward a light. Even though each robot (*right*) does not communicate with the others and acts independently by following a small set of simple instructions, together the group is able to accomplish its goal.



ences a long delay because it went through a highly congested portion of the network, it will add just a tiny amount of "pheromone" to the table entries that would send calls to that overloaded area. In mathematical terms, the scores for the corresponding nodes would be increased just slightly. On the other hand, if the agent went quickly from one node to another, it would reinforce the use of that path by leaving a lot of "pheromone"—that is, by increasing the appropriate scores substantially. The calculations are such that even though a busy path may by definition have many agents traveling on it, their cumulative "pheromone" will be less than that of an uncongested path with fewer agents.

The system removes obsolete solutions by applying a mathematical form of evaporation: all of the table entries are decreased regularly by a small amount. This process and the way in which the antlike agents increase the scores are designed to work in tandem so that busy routes experience more evaporation than reinforcement, whereas uncongested routes undergo just the opposite.

Any balance between evaporation and reinforcement can be disrupted easily. When a previously good route becomes congested, agents that follow it are delayed, and evaporation overcomes reinforcement. Soon the route is abandoned, and the agents discover (or rediscover) alternatives and exploit them. The benefits are twofold: when phone calls are rerouted through the better parts of a network, the process not only allows the calls to get through expeditiously but also enables the congested areas to recover from the overload.

Several companies are exploring this approach for handling the traffic on their networks. France Télécom and British Telecommunications have taken an early lead in applying ant-based routing methods to their systems. In the U.S., MCI Worldcom has been investigating artificial ants not only for managing the company's telephone network but also for other tasks such as customer billing. The ultimate application, though, may be on the Internet, where traffic is particularly unpredictable.

To handle the demanding conditions of the Net, Dorigo and his colleague Gianni Di Caro of the Free University of Brussels have increased the sophistication of the ant agents by taking into account several other factors, including the overall time it takes information to get from its origin to its destination. (The approach for phone networks considers just the time it takes to go from one node to another, and the traffic in the reverse direction is assumed to be the same.) Simulation results indicate that Dorigo and Di Caro's system outperforms all other routing methods in terms of both maximizing throughput and minimizing delays. In fact, extensive tests suggest that the ant-based method is superior to Open Shortest Path First, the protocol that the Internet currently uses, in which nodes must continually inform one another of the status of the links to which they are connected.

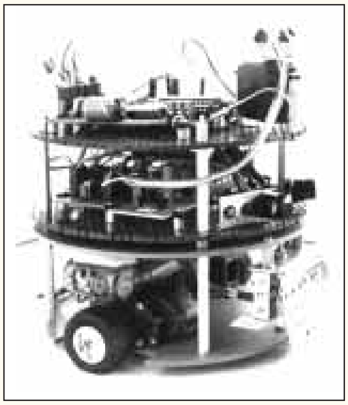
A Swarm of Applications

Other behaviors of social insects have inspired a variety of research efforts. Computer scientists are studying insect swarms to devise different techniques for controlling a group of robots. One application being investigated is cooperative transport [*see box below*]. Using such approaches, engineers could design relatively simple and cheap robots that would work together to perform increasingly sophisticated tasks. In another project, a model that was initially introduced to explain how ants cluster their dead and sort their

task for their robotic army was to push a box toward a goal, and each individual was programmed with very simple instructions: find the box, make contact with it, position yourself so that the box is between you and the goal, then push the box toward the goal.

Although the robots were intentionally programmed very crudely, the similarity between their behavior and that of a swarm of ants is striking. (The videotaped experiments can be viewed at http://www.cs.ualberta.ca/~kube/ on the World Wide Web.) At first, the robots move randomly, trying to find the box. After locating it they begin pushing, but if they are unsuccessful in moving it they change their positions and alignments. Even temporary setbacks are evident, as when the box is moved in a direction away from the goal. The robots make continual adjustments when they lose contact with the box, when they block one another or when the box rotates. Eventually the robots, despite their limited capabilities, are successful in delivering the box to the goal.

Obviously, individuals trying to push an object can find far more efficient ways to work together. But because of the extreme simplicity of this ant-based approach—for one thing, the robots do not need to communicate with one another—it is promising for miniaturization and low-cost applications. —*E.B.* and *G.T.*



ROBOTICS RESEARCH LABORATORY, UNIVERSITY OF ALBERTA

ROBOTICS RESEARCH LABORATORY, UNIVERSITY OF ALBERTA

From Cemeteries to Databases

In some ant species, such as *Messor sancta,* workers pile up their colony's dead to clean their nests. The illustration at the right shows the dynamics of such cemetery organization. If the corpses are randomly distributed at the beginning of the experiment, the workers will form clusters within a few hours.

Jean-Louis Deneubourg of the Free University of Brussels and his colleagues have proposed a simple explanation: small groups of items grow by attracting workers to deposit more items, and this positive feedback leads to the formation of larger and larger bunches. Scientists, however, still do not know the exact details of the individual behavior that implements the feedback mechanism.

Another phenomenon can be explained in a similar way. The workers of the ant *Leptothorax unifasciatus* sort the colony's brood systematically. Eggs and microlarvae are placed at the center of an area, the largest larvae at the periphery, and pupae and prepupae in between. One explanation of this behavior is that ants pick up and drop items according to the number of similar surrounding objects. For example, if an ant finds a large larva surrounded by eggs, it will most likely pick up the larval "misfit." And that ant will probably deposit its load in a region containing other large larvae.

By studying such brood sorting, Erik Lumer of University College London and Baldo Faieta of Interval Research in Palo Alto, Calif., have developed a method for exploring a large database. Imagine that a bank wants to determine which of its customers is most likely to repay a loan. The problem is that many of the customers have never borrowed money from any financial institution.

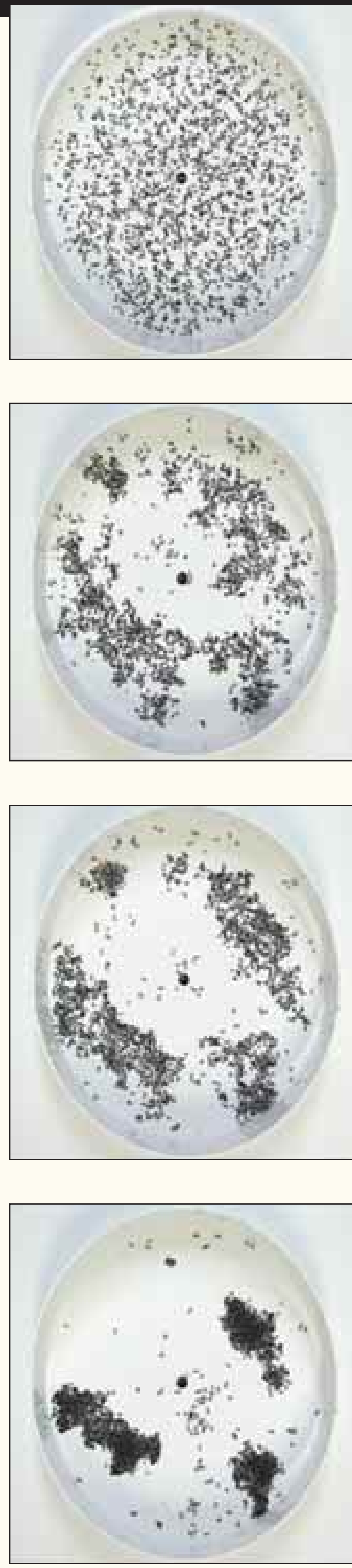
But the bank has a large database of customer profiles with attributes such as age, gender, marital status, residential status, banking services used by the customer and so on. If the bank had a way to visualize clusters of people with similar characteristics, loan officers might be able to predict more accurately whether a particular person would repay a loan. If, for example, a mortgage applicant belonged to a group dominated by defaulters, that person might not be a good credit risk.

Because clusters are generally visualized best in two dimensions (higher dimensions make the data difficult for humans to interpret), Lumer and Faieta represent each customer as a point in a plane. So each client is like a brood item, and software ants can move the clients around, picking them up and depositing them according to the surrounding items. The distance between two customers indicates how similar they are. For the single attribute of age, for instance, shorter distances depict smaller age differences. The artificial ants make their sorting decisions by considering all the different customer characteristics simultaneously. And depending on the bank's objectives, the software could mathematically weigh some of the attributes more heavily than others.

Through this kind of analysis, one cluster might contain people who are about 20 years old and single, most of them living with their parents and whose most popular banking service is interest checking. Another grouping may consist of people who are about 57, female, married or widowed, and homeowners with no mortgage.

Of course, banks and insurance companies have already used similar types of cluster analyses. But the ant-based approach enables the data to be visualized easily, and it boasts one intriguing feature: the number of clusters emerges automatically from the data, whereas conventional methods usually assume a predefined number of groups into which the data are then fit. Thus, antlike sorting has been effective in discovering interesting commonalities that might otherwise have remained hidden.

—*E.B.* and *G.T.*



ERIC BONABEAU AND GUY THÉRAULAZ

WORKER ANTS cluster their dead to clean their nest. At the outset of this experiment, 1,500 corpses are located randomly (*top*). After 26 hours, the workers have formed three piles (*bottom*). This behavior and the way in which ants sort their larvae has led to a new type of computer program for analyzing banking data.

larvae has become the basis of a new approach for analyzing financial data [*see box at left*]. And research investigating the flexible way in which honeybees assign tasks could lead to a more efficient method for scheduling jobs in a factory [*see box at right*].

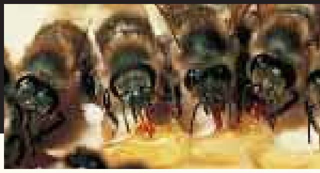
Additional examples abound. Applying knowledge of how wasps construct their nests, Dan Petrovich of the Air Force Institute of Technology in Dayton, Ohio, has designed a swarm of tiny mobile satellites that would assemble themselves into a larger, predefined structure. H. Van Dyke Parunak of the Environmental Research Institute of Michigan in Ann Arbor is deploying a variety of insectlike software agents to solve manufacturing problems—for example, scheduling a complex network of suppliers to a factory. Paul B. Kantor of Rutgers University has developed a swarm-intelligence approach for finding information over the World Wide Web and in other large networks. Web surfers looking for interesting sites can, if they belong to a "colony" of users, access information in the form of digital pheromones (essentially, ratings) left by fellow members in previous searches.

Indeed, the potential of swarm intelligence is enormous. It offers an alternative way of designing systems that have traditionally required centralized control and extensive preprogramming. It instead boasts autonomy and self-sufficiency, relying on direct or indirect interactions among simple individual agents. Such operations could lead to systems that can adapt quickly to rapidly fluctuating conditions.

But the field is in its infancy. Because researchers lack a detailed understanding of the inner workings of insect swarms, identifying the rules by which individuals in those swarms interact has been a huge challenge, and without such information computer scientists have had trouble developing the appropriate software. In addition, although swarm-intelligence approaches have been effective at performing a number of optimization and control tasks, the systems developed have been inherently reactive and lack the necessary overview to solve problems that require in-depth reasoning techniques. Furthermore, one criticism of the field is that the use of autonomous insectlike agents will lead to unpredictable behavior in the computers they inhabit. This characteristic may actually turn out to be a strength, though, in that it could allow such systems to adapt to solve new, unforeseen problems—a flexibility that traditional software typically lacks.

Many futurists predict that chips will soon be embedded into thousands of mundane objects, from envelopes to trash cans to heads of lettuce. Enabling all these pieces of silicon to communicate with one another in a meaningful way will require novel approaches. As high-technology author Kevin Kelly puts it, "Dumb parts, properly connected into a swarm, yield smart results." The trick, of course, is in the proper connection of all the parts. SA

Busy as a Bee



HANS PFLETSCHINGER *Peter Arnold, Inc.*

PAUL A. SOUDERS *Corbis*

HONEYBEES (*top*) perform tasks based on the hive's needs. By studying the way in which these jobs are assigned, scientists hope to develop better ways to program the equipment in an automated factory (*bottom*).

In a honeybee colony, individuals specialize in certain tasks, depending on their age. Older bees, for example, tend to be the foragers for the hive. But the allocation of tasks is not rigid: when food is scarce, younger nurse bees will forage, too.

Using such a biological system as a model, we have worked with Michael Campos of Northwestern University to devise a technique for scheduling paint booths in a truck factory. In the facility the booths must paint trucks coming out of an assembly line, and each booth is like an artificial bee specializing in one color. The booths can change their colors if needed, but doing so is time-consuming and costly.

Because scientists have yet to understand exactly how honeybees regulate their division of labor, we made the following assumption: an individual performs the tasks for which it is specialized unless it perceives an important need to perform another function. Thus, a booth with red paint will continue to handle orders of that color unless an urgent job requires a white truck and the other booths, particularly those specializing in white, have much longer queues.

Although this basic rule sounds simplistic, in practice it is very effective. In fact, a honeybeelike system enables the paint booths to determine their own schedules with higher efficiency—specifically, fewer color changes—than a centralized computer can provide. And the method is adept at responding to changes in consumer demand. If the number of trucks that need to be painted blue surges unexpectedly, other booths can quickly forgo their specialty colors to accommodate the unassigned vehicles. Furthermore, the system copes easily with glitches. When a paint booth breaks down, other stations compensate swiftly by immediately divvying up the additional load. —*E.B.* and *G.T.*

The Authors

ERIC BONABEAU and GUY THÉRAULAZ study the behaviors of social insects and their application in the design of complex systems. Bonabeau is chief scientist at EuroBios in Paris. He received a Ph.D. in theoretical physics and advanced degrees in computer science and applied mathematics from the University of Paris XI (Paris-Sud). Théraulaz is a research associate at the Laboratory of Ethology and Animal Psychology of CNRS at Paul Sabatier University in Toulouse, France. He received a Ph.D. in neuroscience and ethology from the University of Provence.

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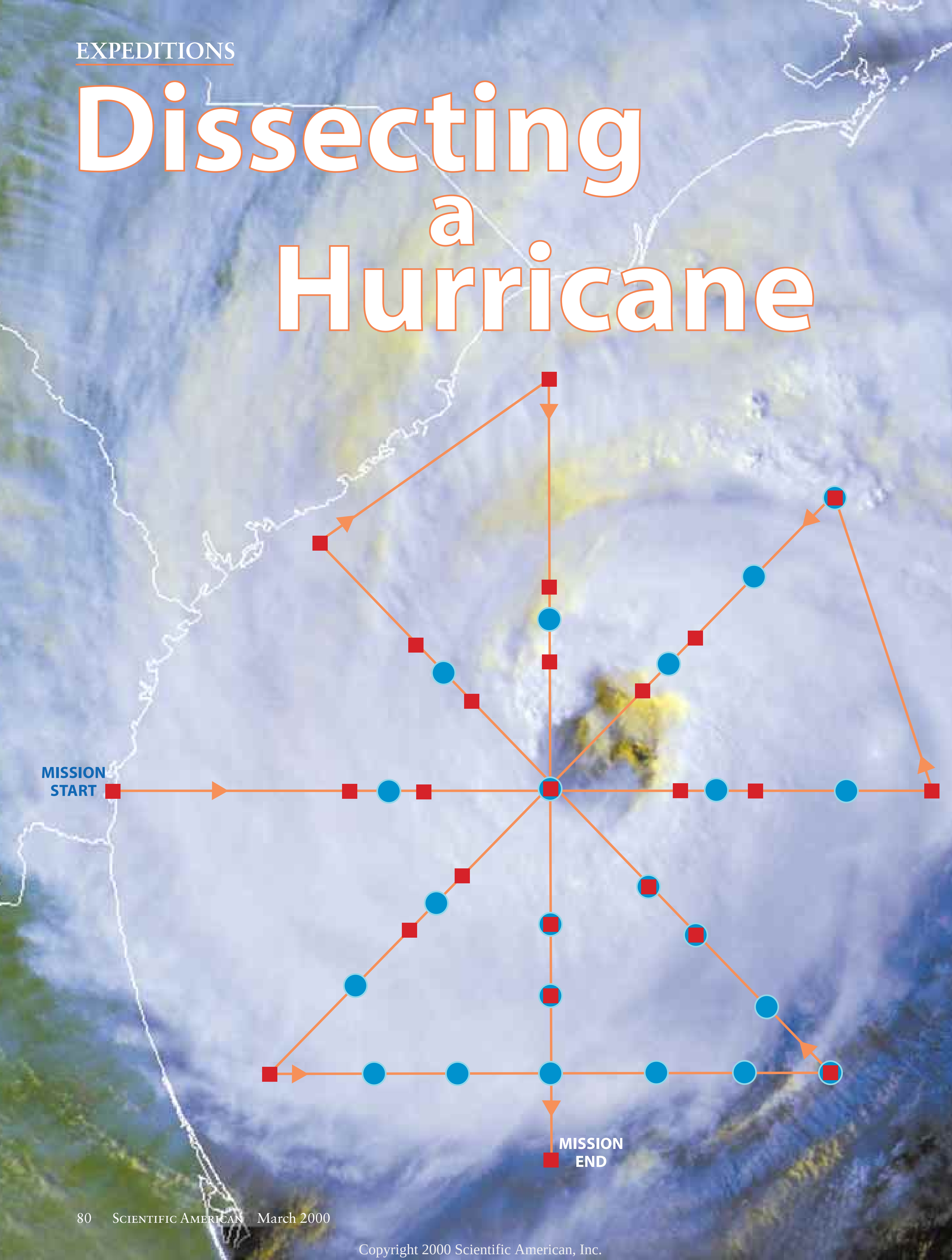
Dissecting a Hurricane



Flying into the raging tumult of Dennis, scientists suspected that the storm might transform into a monster—if they were lucky

by Tim Beardsley, *staff writer*
Photographs by Andrew Itkoff, Silver Image

MacDILL AIR FORCE BASE, FLORIDA, AUGUST 29, 1999, 1:52 P.M.: Safety lectures are over and everyone is strapped into our four-engine WP3D turboprop plane, known affectionately as *Miss Piggy*. The aircraft, jammed with computers, four different radars and a variety of other instruments, is at last surging down the runway. The past few hours have been a metaphorical whirlwind: quickly arranged travel, a 6 A.M. flight from Baltimore, then briefing sessions with the flight crew interspersed with hurried explanations from Frank D. Marks, the lead scientist on the flight.

Our destination is a real whirlwind: Hurricane Dennis, now swirling 290 kilometers east of Jacksonville, Fla., powering 145-kilometer-per-hour winds and menacing the Carolinas. On land fearful vacationers and residents on North Carolina's barrier islands are boarding up windows, throwing bags into cars and fleeing the coming storm. But Marks and his fellow scientists from the National Oceanic and Atmospheric Administration regard Dennis with hope rather than dread. If our flight through its curved arms goes as planned, this storm will shed light on a central mystery about hurricanes and typhoons: whether it is the ocean below or the winds above that wield more power in determining whether a storm will swell to greater fury or unwind into a harmless region of low pressure.

Marks is among those pushing the idea that the ocean controls how hurricanes evolve by either adding or removing energy in the form of heat. Today's forecasting models, in contrast, treat the ocean as a passive bystander.

These models have conspicuously failed to predict when storms will intensify. Hurricane Andrew startled forecasters in 1992 when it intensified abruptly while passing over the warm waters of the Gulf Stream; it later killed 15 people and destroyed property worth $25 billion in southern Florida. In 1995 in the Gulf of Mexico, Hurricane Opal transformed overnight—after the 11 P.M. television news assured Gulf Coast residents that they had little to fear—from a Category 2 to a Category 4 terror capable of extreme devastation. Opal, too, had just passed over an eddy of deep warm water. Although the storm ebbed somewhat before coming ashore, it caused more than 28 deaths altogether. And earlier in 1999 Hurricane Bret followed what now seemed to be an emerging pattern, escalating from Category 2 to 4 after passing over warm water. Fortunately, it made landfall over unpopulated farmland in Texas.

If Marks and his colleagues are right, by analyzing in detail the heart of a hurricane they should be able to tease apart the web of factors that drive the storms to live, grow and die. The scientists will need to learn the temperature of the sea at different depths during the hurricane's passage. They will also want to know as much as possible about its winds and waves.

Dennis, now a strong Category 2 hurricane, has the same ominous potential for rapid intensification as Andrew and Opal did. When Hurricane Bonnie crossed the Gulf Stream in 1998—without intensifying—Marks had been frustrated by a lack of instruments to study it. But as he watched Dennis's course in late August, he recognized an opportunity. Equipment was available, and by good fortune Eric D'Asaro of the University of Washington had just dropped three high-tech floats in an east-west line across Dennis's path. The floats move up and down, monitoring temperature and salinity in the so-called mixed layer between the sea surface and about 200 meters' depth. These data could complement observations made from *Miss Piggy*. Marks scrambled his air team to launch a detailed examination of Dennis, which is what brought us to the jetway.

Our group will scan the storm from the inside out, penetrate it with falling probes, take its temperature and clock its winds. Over the past few days NOAA's

PLANNED TRACK of a research mission into Hurricane Dennis on August 29, 1999, sliced the storm every which way to measure how winds and waves interact. The National Oceanic and Atmospheric Administration sent its WP3D research aircraft *Miss Piggy* on the demanding expedition because Dennis threatened to intensify dangerously. The actual route deviated somewhat from that planned. Red squares (■) show where the crew dropped Global Positioning System sondes to measure winds; blue circles (●) show firings of Airborne Expendable Bathythermographs (AXBTs), which measure ocean temperature.

NOAA UNIVERSITY OF WISCONSIN–MADISON SPACE SCIENCE AND ENGINEERING CENTER (*photograph*); BRYAN CHRISTIE (*graphic composition*)

TECHNICIAN James Barr loads AXBTs into firing tubes. Explosives will shoot the probes clear of the plane during the flight.

Gulfstream IV jet has charted atmospheric conditions at various altitudes in the region. Our flight is to be the crux of the assessment: four straight passes through the eye of the tempest.

Marks has weathered dozens of routine flights through hurricanes, and he likes to quip that the most dangerous part of a sortie is the drive to the airport. But he also knows that the pilots face real challenges, especially near the deep banks of cumulonimbus clouds that mark the eye wall. Winds there change speed and direction unpredictably, and intense tornadolike vortices can appear with no warning. Ten years ago Marks was flying in our sister plane, *Kermit,* through Hurricane Hugo as the storm escalated to a Category 5. An engine failed while the plane was at low altitude inside the eye, and a vortex almost threw the plane into the sea. “I am lucky to be alive after that,” Marks recounts.

This morning the crew displayed an easy bravado during the preflight briefing. Some experienced members sport badges on their blue flight suits celebrating the number of eye penetrations they have survived. But as we move up Florida’s eastern coast, the flight engineer seems to enjoy reminding me that hurricanes can change their character within a few hours. Our flight could last nine or more. It seems important to count the number of people on board: 19, including six scientists as well as observers, instrument technicians and the flight crew.

The frailty of the complex equipment we are carrying is suddenly underscored when technician James Barr announces that the Doppler radar in the plane’s tail is not producing intelligible data. This device, along with a second radar in the belly of the fuselage, can reveal wind speeds wherever rain is falling. Marks says we definitely want this information. The flight director approves a hold, and we fly in a circle while Barr and lead electronics technician Terry Lynch attempt a repair. They yank out equipment racks and swap a transmitter.

Ten minutes pass, but something is

RAIN CLOUDS pile up near Dennis’s eye wall. The passage into the eye is the riskiest part of a hurricane flight, because winds can change strength and direction unpredictably. Within the eye, however, all is calm.

HEAVILY INSTRUMENTED *Miss Piggy* is fueled and loaded on the tarmac at MacDill Air Force Base. Researchers prefer turboprop planes because they gain lift more reliably than jets do in a downdraft. The oval structure under the belly houses one of several radars. Transfers emblazoned on the craft (*above*) record hurricanes that the plane has weathered, from Anita in 1977 to Mitch in 1998.

not right. Lynch is muttering under his breath and looking worried. After a few more anxious minutes, he declares victory. Everyone gets back to work.

At our starting point for the mission proper, off the coast a few kilometers north of the Florida-Georgia border, electrical engineer Richard McNamara takes the metallized plastic wrapping off a Global Positioning System (GPS) dropwindsonde. This device, which will be dropped into the storm, unfurls a parachute when it is in free fall and radios back its position to the plane. McNamara programs it by plugging it into his instrument rack for a few seconds, detaches it and places it in a transparent launch tube set in the floor. The flight director gives the "3, 2, 1," and then McNamara presses a trigger. The cabin air pressure blows the meter-long cylinder out of the fuselage with a loud whistling sound, and McNamara confirms the time.

Within seconds his workstation has acquired a signal: the sonde's parachute has deployed. He tracks the probe's location as Dennis whips it away from the plane, betraying the direction and the strength of the winds during its descent to the ocean. He will repeat this routine numerous times during the mission, gradually building a three-dimensional picture of the storm.

We are now heading east at 4,300 meters. The cheery banter of the early part of the flight has dwindled, and I feel a mounting excitement. As the coast recedes behind us and dark gray

LEAD SCIENTIST Frank D. Marks (*foreground*) confers with navigator Dave Rathbun early in the mission. Marks is one of a cadre of scientists who believe that most forecasters have neglected the role of the oceans in hurricanes.

clouds loom ahead, the crew tap away at keyboards controlling a suite of instruments that will make Dennis the most minutely analyzed storm ever.

At 3:15 P.M. our imperturbable pilot, Ron Phillipsborn, comes on the intercom to warn of "weather" ahead. Dense rain now streams over the windows, and the blue sky we set off in is nowhere to be seen: only whiteness all about. People have been walking in the plane since we reached our cruising altitude, but now everyone heads to their seats to strap in.

The ride remains fairly smooth, however, and soon foot traffic in the aisle resumes. The spiral form winding on the radar screens is familiar from the Weather Channel, but it is far more compelling at this moment. Operators compile the maps every 30 minutes and send them by a slow satellite link to the National Hurricane Center at Florida International University in Miami. Researcher Christopher W. Landsea, furiously editing data at one of the consoles, estimates Dennis's eye to be 80 kilometers in diameter, which is larger than that of most hurricanes. The storm is moving slowly northward, brushing the coast. Its waves are now pounding jetties as its winds tear the shingles off roofs.

When we reach the point where we have to fire a probe called an Airborne Expendable Bathythermograph, or AXBT, McNamara flips a switch on his console. An explosive charge shoots the first of the AXBTs, which are preloaded in the plane's belly, out into the storm now engulfing us. AXBTs do nothing as they fall, but when they splash into the ocean they send a thermometer on a wire down to 300 meters and radio the temperature readings along the way.

We approach the eye wall at about 500 kph, shooting out more GPS sondes and AXBTs as we go. Through occasional gaps in the dense clouds I can see the roiling ocean surface, flecked generously with patches of white.

These regions of bubbles, caused when the wind blows the tops off waves, look insubstantial in comparison to the cubic kilometers of air and water heaving all around us. But scientists suspect that they are crucial in determining how a hurricane will change, because they efficiently transfer energy between sea and air. One of the instruments we are carrying, a radiometer, can measure that foaminess by detecting microwave energy reflecting off the sea surface at six different frequencies. It can in principle, anyway. In practice, software glitches have so far hung up the device on all of its previous flights. Marks is hoping that NOAA scientist Peter Black, who is grounded in Florida with a cold, succeeded in his latest attempt to debug the code.

The fuselage shudders and heaves again, and my coffee makes a bid to escape from its plastic cup. Phillipsborn orders us back to our seats once more, but the floor and the seatbacks are now moving targets. We endure a couple of stomach-churning lurches. I start to wonder exactly how much the wings could flap like that before breaking off. McNamara, sitting across the aisle from me, is unfazed, repeatedly firing off GPS sondes alternated with an occasional AXBT. He seems too busy for any idle speculation.

I realize that the nausea-inducing plunges have stopped: we have pierced Dennis's eye. Overhead is the blue sky we left behind. Wind speed outside is about three knots, hardly enough to lift a flag. We hunt for the point where wind speed and pressure are lowest, to get a fix on the center. Not many kilometers distant, huge stacks of rain clouds are visible, strewn in a vast arc. We plunge into the eastern eye wall, dropping more sondes as we do so into the colossal heat engine turning around our plane.

Hours pass as we trace a compass rose centered on the eye. My tension has prevented hunger, but in the late afternoon I cautiously maneuver toward the galley for a sandwich, where I find a crew member calmly reading a newspaper.

The unpredictable drops become familiar but worsen on a slow upwind leg. The repaired Doppler radar is working imperfectly: its output will be less complete than Marks had wanted. Landsea announces that the instrument shows surface winds have reached about 160 kph. Dennis is indeed getting stronger. Yet as it intensifies, it stirs up cooler water from the depths. I learn later that Dennis cooled the water off the Georgia and South Carolina coasts by three degrees Celsius and roughly doubled the depth of the mixed water layer beneath its core. That effect in turn cooled Hurricane Floyd's fury when it passed the same way days later.

We are transmitting readings from the radiometer to the National Hurricane Center. But Marks is still uneasy about the device. Partway through the flight, he is surprised when the plane's radio operator patches through a phone call from Black. It must be urgent, because the radio interferes with the radars, so Marks figures he will be hearing about some new radiometer problem. In fact, Black exclaims that the instrument, which can reveal surface winds in detail, is working perfectly. Marks is sufficiently relieved to announce the good news over the intercom. The mood on the plane brightens noticeably.

The flight wears on. We make a long

GLOBAL POSITIONING SYSTEM SONDE is readied for launch by electrical engineer Richard McNamara. Cabin air pressure blows the devices out of a floor-mounted tube. Once clear of the plane, the sondes deploy a parachute and transmit data about where winds take them during their several-minute fall to the ocean.

traverse over D'Asaro's floats, dropping AXBTs and GPS sondes as the whiteness outside fades into the black of night. On the fourth pass through the eye we again hunt for the center to see how far it has moved: center fixes are crucial for helping forecasters judge where a storm is headed. Dennis's western side is over the Gulf Stream and presumably picking up energy there, but the eye remains farther out in the Atlantic. Marks fears a landfall in North Carolina the following day.

On the way home we make a point of firing off some AXBTs and GPS sondes as close to ground-based measurement stations and buoys as we can, so that the scientists can make cross-checks of the instruments' performance. By the time we touch down at MacDill, it is 10:24 P.M. Marks seems more pleased with the day's work than exhausted by the nearly nine-hour journey.

The next day we rise to learn that Dennis has veered slightly eastward, moving parallel to the Gulf Stream. The churning that cooled the sea surface, along with Dennis's failure to pass right over the Gulf Stream, means that it will not turn into the nightmare storm it might have. Yet it has yielded a treasure trove of information.

The radiometer data are the main prize. But the happy conjunction of *Miss Piggy*'s flight and D'Asaro's floats have made it a scientific field day in other respects, too. We had launched 30 GPS sondes, several of them right into Dennis's eye wall. We had also fired off 15 operative AXBTs; three of these splashed on the east-west line south of the eye where D'Asaro's floats were at work. The Doppler radar data are adequate for most purposes. In addition, Ed Walsh of the National Aeronautics and Space Administration successfully used a scanning radar altimeter during the flight to bring in a good haul of measurements on the direction and height of Dennis's waves. They are highly asymmetric and resemble a pattern Walsh saw earlier in Hurricane Bonnie.

All this information will be grist for hurricane modelers' data mills for years to come. No single storm will answer all the questions about hurricane evolution. But Marks and his crew of technicians and investigators have shown that they can deploy a comprehensive array of high-tech instruments in a dangerous cyclone and emerge with valuable results. As long as they and other riders on the storm are willing to continue risking life and limb for science, the mystery of what makes a hurricane intensify seems likely to diminish—and with it, the opportunities for some future tempest to turn without warning into a killer. SA

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Along the coast of Brazil, 8 percent of a once flourishing forest is left to house a diverse family of bromeliads. A group of biologists scale cliffs and trees to collect these rare beauties

by Gustavo Martinelli
Photographs by Ricardo Azoury

The coast of Brazil was once thick rain forest, a tangle of vegetation that covered 1.4 million square kilometers and rivaled the Amazon in its biodiversity. Only slivers and fragments of this Mata Atlantica, or Atlantic Forest, are left today. A mere 8 percent of the original forest has survived the machetes of sugarcane and coffee growers and the axes of loggers, and it remains scattered along the heavily populated eastern seaboard, some of it protected in reserves, some on private land, some in unlikely stands in and around major cities. These tiny bits of Mata Atlantica make up the most endangered ecosystem in Brazil and are the last refuge for many members of an unusual family of plants, the Bromeliaceae.

Bromeliads—the best known of which are probably the pineapple and Spanish moss—are often beautifully colored flowering plants that are stunning in their diversity. Of the 3,146 species and subspecies in 56 genera, more than half are epiphytes: that is, their roots can attach to tree trunks, rocks or other substrates, and they gather moisture from the air or dew rather than from the ground. Some of these epiphytes hold water in the rosette formed by their leaves and can sustain entire microenvironments. For example, one enormous species that lives in a mountainous, grassy part of the southeastern Mata Atlantica, *Alcantarea imperialis,* can hold 30 liters of water. Researchers have discovered more than 900 organisms—most of them insects, but also frogs, crabs, worms and microorganisms—living in these leafy cisterns. The small creatures and their watery domain, in turn, provide sustenance for other animals, including many birds and some primates, such as the endangered golden lion tamarin.

In certain cases, bromeliads and their inhabitants seem to have co-evolved. One frog, *Hyla venulosa,* hibernates through the dry season of northern Brazil inside *Billbergia zebrina*. By backing into the cavity of the bromeliad and turning its flat broad head at a right angle to its

Text continued on page 91

BROMELIAD from São Paulo State in the south of Brazil, *Nidularium innocentii,* is, like many members of this family, an epiphyte: it can grow on the trunks of trees or on rocks, among other places. Its roots do not need to be in soil but can absorb moisture from the air.

The Bromeliads OF THE ATLANTIC FOREST


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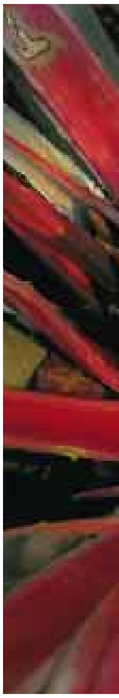

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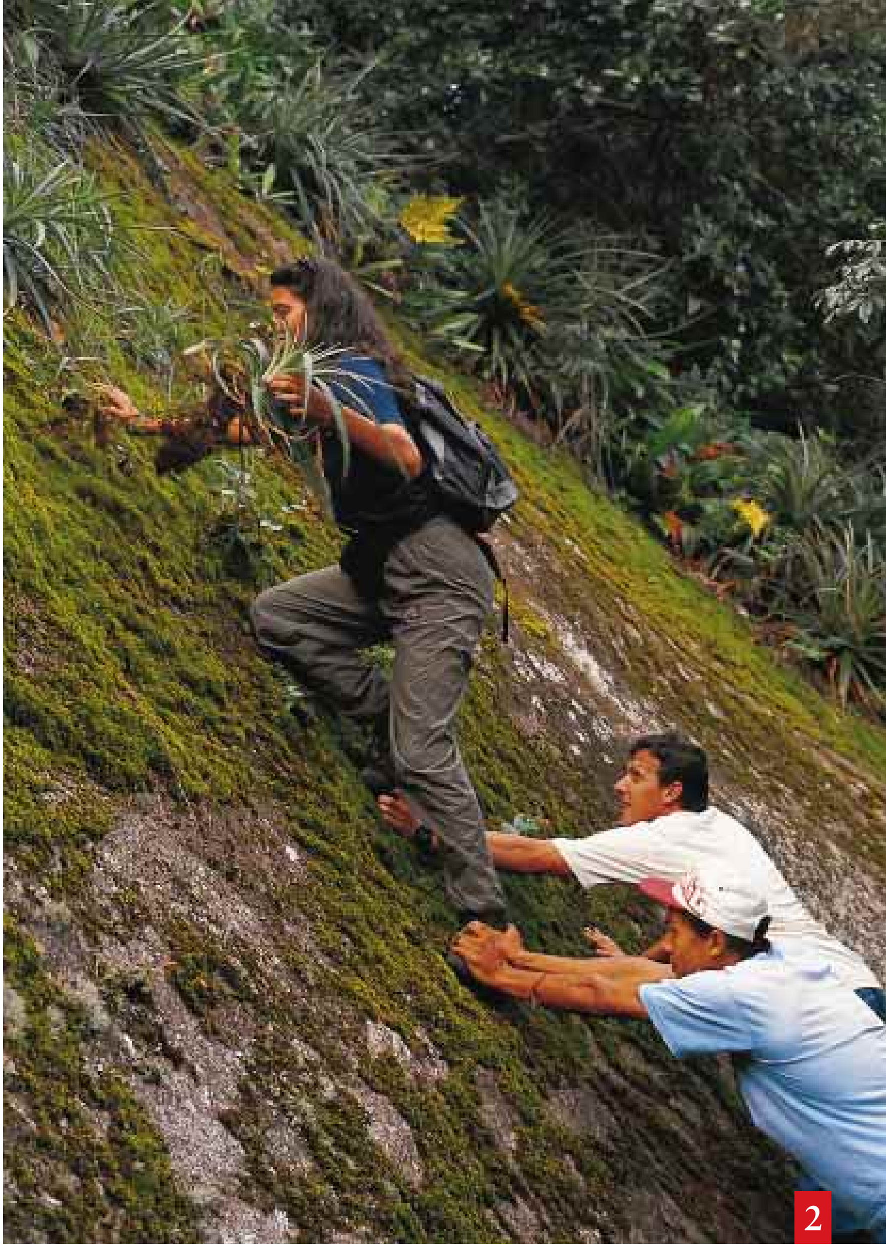

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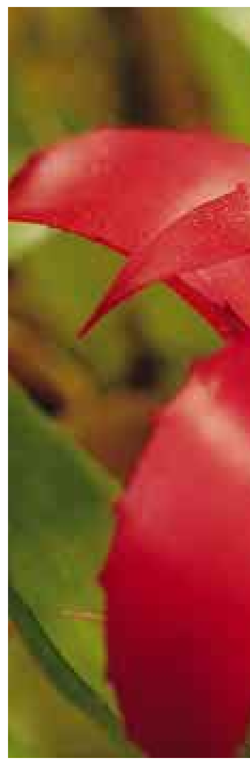
FRAGMENTS of the Brazilian Atlantic Forest are often found around densely populated areas on the coast. This *Alcantarea glaziouana* (*1*), for instance, was discovered above the city of Niteroi, which is just east of Rio de Janeiro. Retrieving the specimens is not always so easy, however. Often biologists have to climb high trees or scale steep inclines, as Thelma Barbará did when she tried to collect *Dyckia encholirioides* (*2*). But sometimes the brilliant hues of a bromeliad in bloom help the researchers locate them: *Neoregelia carolinae* (*3*), *Aechmea nudicaulis* (*4*), *A. ornata* (*5*), *Bromelia plumieri* (*6*) and *Canistrum aurantiacum* (*7*).

7

MANY BROMELIADS, such as *Neoregelia marmorata* (*1*), create small watering holes that support diverse species, some of which have evolved in conjunction with the bromeliads themselves. Investigators have discovered about 900 organisms living in the cisterns of this family of plants—including insects such as this poisonous spider, which depends on *Hohenbergia sp.* (*3*) for shelter. Hummingbirds are among the main pollinators of bromeliads; this one is visiting *Vriesea neoglutinosa* (*5*) in search of food. The other bromeliads shown here are *Bromelia antiacantha* (*2*), *V. rodigasiana* (*4*) and *Nidularium sp.* (*6*).



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Continued from page 86

body, the frog effectively seals the water inside—thereby ensuring itself and the bromeliad a source of hydration. This frog and others in its genus may have played an important selective role in the evolution of the narrow tubular tank of certain *Billbergia* species.

Almost all bromeliads, epiphytes and soil dwellers alike, grow in the New World. They are found between the northern limit of Virginia in the U.S. and Patagonia in southern Argentina and between eastern Brazil and Juan Fernández Islands, about 300 miles off the coast of Chile. Only one species is found elsewhere: for some unknown reason, *Pitcairnia feliciana* occurs in Guinea in West Africa.

The bromeliads of the Mata Atlantica have not been well characterized—many disappeared without a trace centuries ago—and yet they are considered very important because of the high level of endemism in these areas: in some places, more than 53 percent of the trees, 37 percent of the nontree species and 74 percent of the bromeliads occur only in these fragments of forest. Indeed, some scientists argue that the term "Mata Atlantica" is a bit of a misnomer because it conveys the impression that this is uniform forest, when it actually includes seasonal forest, gallery forest and rain forest. In any case, because bromeliads are important to many other species, they offer a window onto these threatened ecosystems.

To record and study the bromeliads of the Mata Atlantica, my colleagues and I set out two years ago to visit as many remnants of original coastal forest as we could. Over a period of 14 months, we made seven expeditions and traveled some 82,400 kilometers. Of the 1,056 species and subspecies we located in our forays, 66 percent are endemic to the Mata Atlantica; eight genera exist nowhere else. We discovered several species that live only on the peak of a single mountain; we found many others that thrive solely within an area of 20 hectares; and we were lucky enough to witness the three-meter-tall flower of a plant that blooms once in 40 years. Although we are still in the process of describing our inventory and will not know for some time exactly what we have found, we estimate that about 119 of the species we collected are endangered, 188 are vulnerable and 58 are near extinction.

This new collection will help us conserve these bromeliads—and just in time. Conservationists estimate that pressure for development along the coast will soon cost Brazil another 70,000 kilometers or so of Mata Atlantica and that only 2 to 3 percent of the original forest will survive in a few protected areas. Accordingly, we have put the 1,842 specimens we gathered in two specially built greenhouses in the Rio de Janeiro Botanical Garden Research Institute. By maintaining the germplasm, we hope to be able to reintroduce certain species if necessary.

At the same time, we hope to discover more


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GIANT BROMELIAD, *Alcantarae imperialis* (*1*), takes 40 years to reach maturity and then produces flowers that stand three meters high. After flowering, the plant dies, without leaving any offshoots. The team was lucky enough to find this plant in bloom in the state of Minas Gerais. Most other bromeliads bloom every year or every several years, producing seeds or offshoots. Most other bromeliads are also more modest in size than *A. imperialis,* including *Vriesea incurvata* (*2*), *Quesnelia edmundoi* (*3*) and *Q. lateralis* (*5*). The process of identifying the bromeliads the author and his team collected is time-consuming, and they tried to get a head start on the road; this specimen turned out to be *Aechmea castelnavii* (*4*).

3

5

about the basic biology of this diverse family of plants. Although bromeliads are used extensively by horticulturists as ornamental plants—because of their beautiful rosettes and flowers, which bloom purple, white, red, blue, yellow, orange and even brown—surprisingly little is understood about their reproductive strategies. We know that hummingbirds and bats appear to be the major pollinators of bromeliads in the Mata Atlantica, but only in the past several years have my colleagues and I determined that most of them are capable of self-pollination as well. If we are to save bromeliads—and the many species that depend on them—in the face of ongoing and severe habitat loss, we will need to know much more about how to get them to reproduce successfully. SA

The Author and the Photographer

GUSTAVO MARTINELLI and RICARDO AZOURY have collaborated on the bromeliad project since 1997, traveling to as many fragments of the Mata Atlantica as possible to collect and photograph this unusual family of plants. Martinelli (*above*) has worked as a botanist at the Rio de Janeiro Botanic Garden Research Institute since 1972. He received his doctorate in ecology at the University of St. Andrews in Scotland and returned to his native Brazil to study the Atlantic Forest. Azoury, a photographer with Saba Press, specializes in environmental topics. He has worked extensively in the Amazon rain forest and travels widely for his stories: from South Africa to photograph sharks to the Hudson River to photograph Atlantic sturgeon.

Azoury and Martinelli thank the Coca-Cola Company in Brazil and the National Council of Scientific and Technological Development for providing funding for the project.

Further Information

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by Shawn Carlson

An Automated Precision Magnetometer

In January of last year I described a delightful device for detecting microfluctuations in the earth's magnetic field. The instrument was a sensitive torsion balance consisting of two small rare-earth magnets affixed to a taut nylon fiber with a tiny mirror attached to the fiber to reflect a laser beam onto a distant wall. When the instrument was properly nulled with additional magnets to cancel the earth's average magnetic field, an infinitesimal change in the earth's field rotated the rare-earth magnets and deflected the laser beam.

Originally developed by Roger Baker of Austin, Tex., this homemade magnetometer created quite a stir in the amateur community. But the device required constant visual monitoring to collect data, so it wasn't really suitable for serious science. Baker, however, suggested how someone could convert his unit into a research-grade instrument. This month I'm delighted to report that Joseph A. Diverdi, a chemist in Fort Collins, Colo., has met that challenge brilliantly.

Following Baker's suggestions, Diverdi placed the magnetometer at the center of a pair of Helmholtz coils, a special electromagnet that produces an extremely uniform magnetic field. Diverdi also designed a detector that could sense tiny displacements in the laser beam's position, and he developed a feedback circuit that runs just enough current in the coil to create a countermagnetic field that precisely cancels any external shift. The current necessary to keep the beam fixed thus tracks the changing field, and a personal computer can record these measurements directly through an analog-to-digital converter.

You'll find a complete description of the Baker-Diverdi magnetometer on Diverdi's Web site (www.xtrsystems.com/magnetometer/). I've reserved this column to give an overview of the device and to offer some fine-point kibitzing.

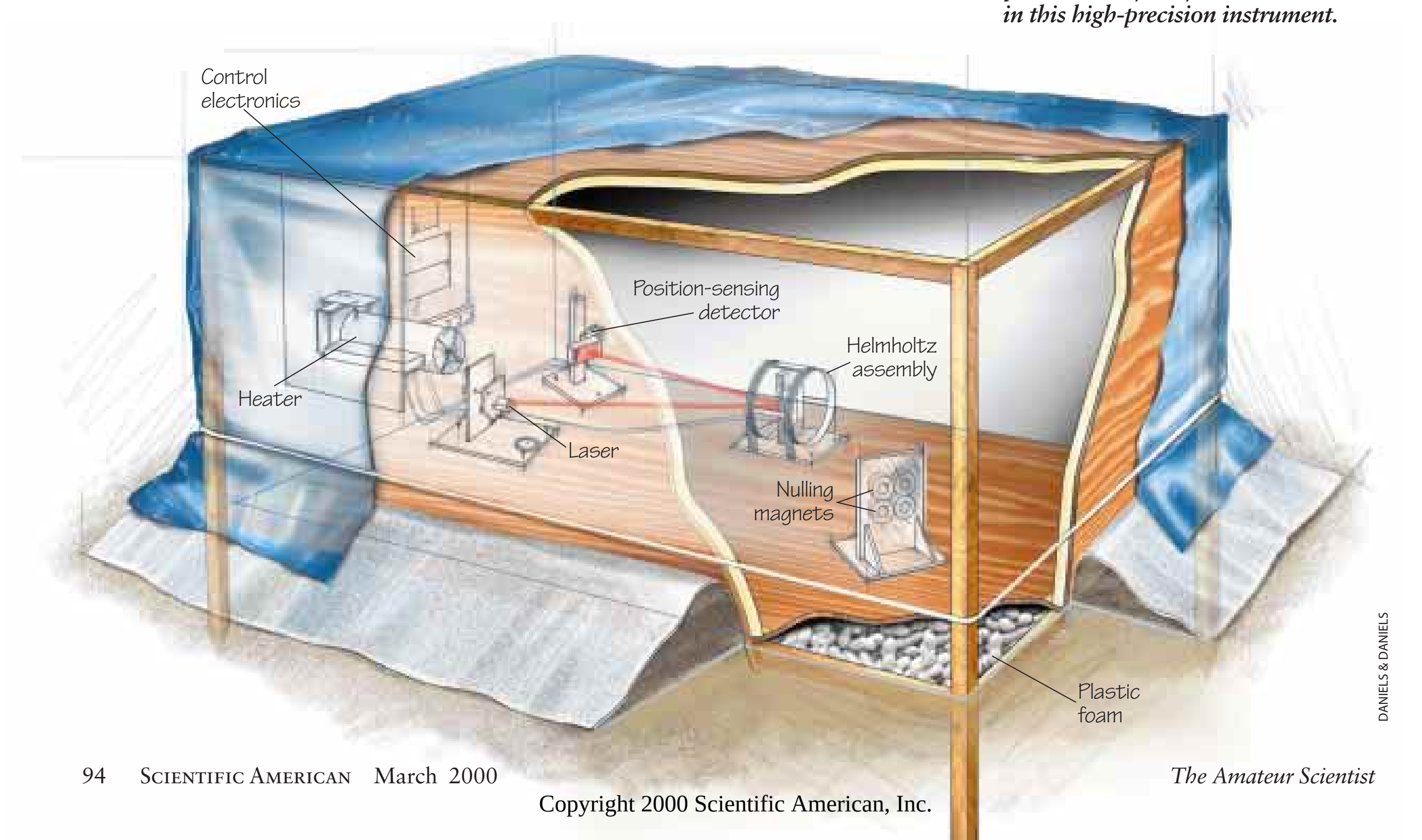
For the Helmholtz coils, Diverdi started with two identical stiff cardboard rings about 6.5 centimeters (2.6 inches) in diameter, but you can use larger rings cut from a cylindrical oatmeal container. Mount the rings on a wooden base parallel to each other at a separation equal to their diameter [*see illustration on opposite page*].

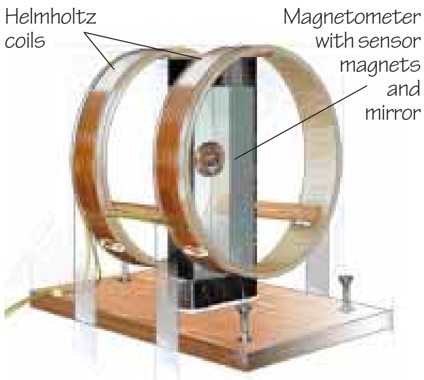
Next, purchase a spool of 30-gauge enamel-coated magnetic wire from an electronics supply store and neatly wrap each ring with 40 turns of the wire. Use one continuous length for both coils so that the same current passes through them and wrap them both in the same direction, either clockwise or counterclockwise. Secure the wire loops with a liberal dose of hot glue.

Diverdi soldered two lead wires to the coils and insulated the joints with shrink-wrap tubing. He hot-glued the tubing to the base of the assembly, leaving some slack so that the wires wouldn't break while the coils were being handled. Because the magnetic field is most uniform at the center of the Helmholtz assembly, be certain to position the rare-earth magnets of the magnetometer there.

To detect minute changes in the laser beam's position, Diverdi has devised a

EARTH'S MAGNETIC FIELD *can be monitored by tracking tiny displacements of a reflected laser beam in this high-precision instrument.*





HELMHOLTZ ASSEMBLY *consists of two electromagnetic coils that maintain a uniform magnetic field around the magnetometer. The magnetometer's mirror reflects the laser beam.*

clever solution. He shines the beam on a small slide of frosted glass with two cadmium sulfide photoelectric cells (Radio Shack part no. 276-1657) positioned a few centimeters behind. The glass spreads the beam, which illuminates the photocells. If the beam is centered directly between the cells, equal amounts of light will shine on each of them. If, however, the beam is displaced even slightly, the output of the photocells will change measurably.

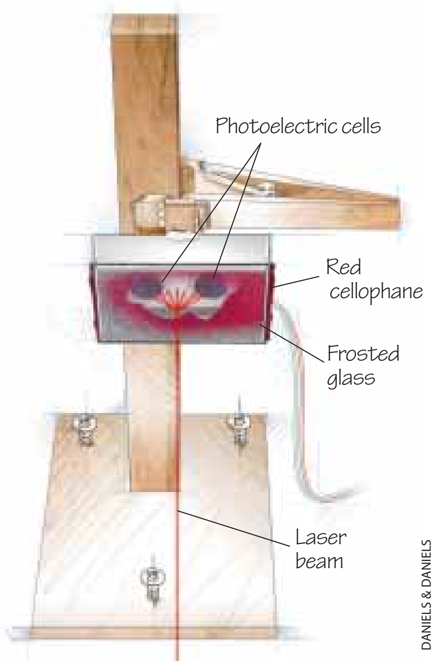
By covering the glass with a filter made from several layers of red cellophane, Diverdi makes the apparatus less sensitive to any stray light that could corrupt the measurements. The cellophane allows the red laser light through while blocking most other wavelengths.

Diverdi mounted the laser, Helmholtz assembly (including the magnetometer), nulling magnets and position-sensing detector on a sturdy wooden base. To isolate this equipment from household magnetic influences, he built a separate wooden enclosure to situate the instrument outdoors. He first constructed a frame slightly larger than the wooden base and about 0.6 meter high, and he nailed plywood sheets around the four sides. Diverdi also fashioned a removable plywood lid. He insulated the walls and lid with four-centimeter-thick sheets of construction insulation and attached sharpened wooden stakes at each corner of the walls to anchor the enclosure in soil. Last, he weatherproofed all exterior surfaces with a clear acrylic sealant.

You should also seal all joints with expanding foam insulation from a spray can, such as Touch 'n Foam. Furthermore, to prevent ambient light from disturbing the photoelectric cells, make the enclosure as impervious to light as possible and paint its interior a flat black.

Most delicate instruments are sensitive to temperature changes and so must be kept in controlled environments. Because it is easier to heat a volume than to chill it, scientists usually maintain a constant temperature by installing a heater to keep an enclosure warmer than its surroundings. Diverdi crafted a nifty homemade heater by using Nichrome wire and a computer fan, but a handheld hair dryer would probably work just as well.

Diverdi also built his own thermostat circuit. I would do the same if only a few batteries were needed to power the heater (see the January column for such a circuit). But when wall current is required, as with a hair dryer, I prefer to buy my thermostats ready-made. Omega Engineering (www.omega.com) in Stamford, Conn., sells several high-precision temperature controllers, some with digital displays and programmable set points, for less than $200. I recommend the CN8591-T1 model ($165) in conjunction with a J-type thermocouple. Mount the controller and thermocouple sensor inside the wooden enclosure away from the heater's hot-air stream. Your instrument will consume less power if you periodically adjust the set point throughout the year to keep the interior about eight degrees Celsius (14 degrees Fahrenheit) warmer than the maximum expected temperature during any given season.



POSITION-SENSING DETECTOR *uses two photoelectric cells to detect small movements of the reflected laser beam.*

Diverdi partially buried his magnetometer by excavating a small plot (about six centimeters deep) well away from his house. He covered the depression with an oversize vinyl sheet and pounded the stakes of the wooden enclosure into place through slits he cut in the plastic. He then created a three-point leveling surface by driving three additional stakes into the ground at the points of an equilateral triangle inscribed within the enclosure's interior. Next, he insulated the floor space with plastic foam shipping "peanuts" and rested the wooden base, containing the laser, Helmholtz assembly, nulling magnets and position-sensing detector, on the stakes. Because the base will be stable but not watertight, you must choose a site that will have adequate drainage. Diverdi also secured a waterproof plastic cover over the entire wooden box for additional protection from the elements.

If you want to monitor the instrument's internal temperature with your home computer, you can piggyback the thermocouple signal from the controller's input. First, though, you must buffer each lead with a field-effect transistor (FET) operational amplifier such as the LF411CN, which has a low bias current. You can purchase this part online for about $1 from Pioneer-Standard Electronics (www.pios.com) in Cleveland.

But thermocouples are plagued with vexing subtleties, so the novice should use an analog-to-digital converter that comes with built-in hardware to interpret the thermocouple signals. National Instruments (www.ni.com) in Austin and Vernier Software (www.vernier.com) in Portland, Ore., sell such systems.

Using his device, Diverdi has obtained some impressive results. If his example inspires you to follow suit, please share your experiences through the Society for Amateur Scientists's Web page. SA

For further information, check the Society for Amateur Scientists's Web site at earth.thesphere.com/sas/WebX.cgi. You may write to the society at 4735 Clairemont Square PMB 179, San Diego, CA 92117, or call 619-239-8807.

MATHEMATICAL RECREATIONS

by Ian Stewart

A Strategy for Subsets

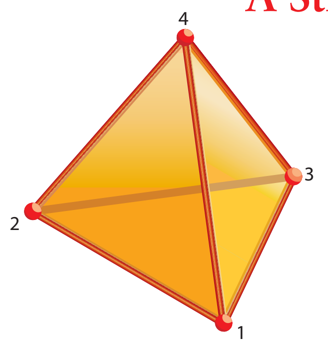
The tradition of explaining mathematics through games and puzzles goes back to the ancient Babylonians, who scrawled arithmetic brainteasers on their clay tablets. In recent years, however, rapid advances in mathematics have given rise to a host of entirely new games. David Gale of the University of California at Berkeley has invented one such diversion, which is described in the book *Games of No Chance,* edited by R. J. Nowakowski (Cambridge University Press, 1996). The game combines ideas from both set theory and topology. Recreational mathematicians will find it especially intriguing because no one has yet determined a winning strategy.

First, a brief refresher on set theory. Sets are collections of objects of some specified kind, and the objects in a set are called its members. If a set has a finite number of members, then we can list them inside brackets. For example, {2,3,5,7} is the set of all prime numbers less than 10. A set X is a subset of set Y if every member of X is a member of Y: the set {3,5,7} of all odd prime numbers less than 10 is a subset of {2,3,5,7}. Every set is considered to be a subset of itself; a subset of X is said to be "proper" if it is different from X. Sets can have only one member: {2}, for instance, is the set of all even prime numbers. A set can also have no members, in which case it is said to be empty.

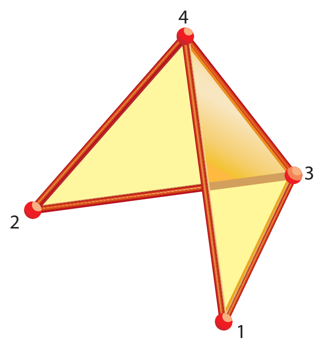
Gale's game is called Subset Takeaway. It starts with a finite set S, which we will take to be the set {1,2, … , *n*} of whole numbers ranging from 1 to *n*. Each player in his or her turn chooses a proper, nonempty subset of S, subject to one restriction: no subset chosen earlier (by either player) can be a subset of the new subset. The first player unable to name such a subset loses. One practical way to play the game is to draw up a set of columns on a sheet of paper, headed by the numbers 1, … , *n*, and mark a line of crosses in the columns that correspond to the selected subset. A new, legal move cannot include all the crosses from some previous move.

Following tradition, let the players be Alice and Bob, with Alice moving first. When *n* = 1, there are no legal moves. When *n* = 2, we have S = {1,2}. The only opening moves available to Alice are {1} and {2}, and whichever she chooses, Bob can choose the other. Then Alice cannot make a legal move, so Bob wins.

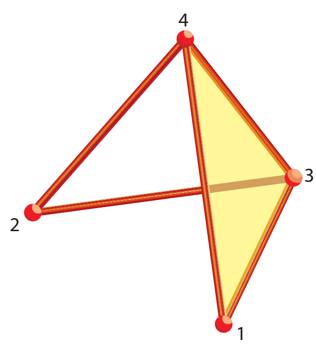
The game becomes more interesting when *n* = 3 and S = {1,2,3}. Suppose Alice chooses a subset with two members, say {1,2}. Then Bob can choose the complementary subset—everything not chosen by Alice—which is {3}. Now Alice can't choose anything that contains 3, so she has to select a subset of {1,2}, and from that point on the game is exactly the same as if the starting set had been {1,2}. So Bob wins again. The same goes if Alice opens with any other two-member subset. Alice, however, has another possible kind of opening: a one-member subset, say {3}. But if Bob chooses the complementary subset {1,2}, the game must again continue as if the starting set had been {1,2}, and Bob still wins. Because Alice's opening must be either a one-member or a two-member subset, Bob has a winning strategy: al-



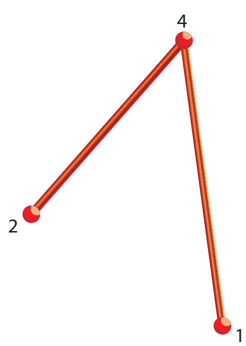
a STARTING POSITION



b ALICE CHOOSES {1,2}



c BOB CHOOSES {2,3,4}



d ALICE CHOOSES {3}

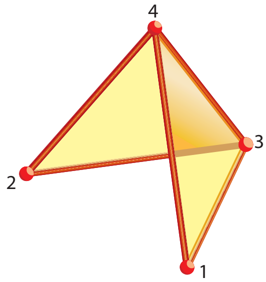
e BOB CHOOSES {4}

f ALICE CHOOSES {2}

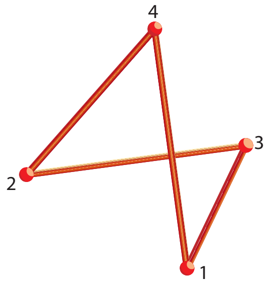
g BOB CHOOSES {1} AND WINS!

BRYAN CHRISTIE

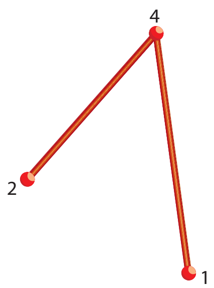
GAME OF SUBSET TAKEAWAY *can be represented topologically. The starting position is a tetrahedron* (a). *The two players, Alice and Bob, alternately choose subsets, and pieces of the tetrahedron are removed until nothing is left* (b *through* g).



a ALICE CHOOSES {1,2}



b BOB CHOOSES {3,4}



c ALICE CHOOSES {3}

BRYAN CHRISTIE

***COMPLEMENTARY STRATEGY** fails in this version of Subset Takeaway because Bob cannot choose the complementary subset of Alice's second move* (c).

ways play the complement of Alice's move. Before reading on, you may wish to consider whether the same strategy gives Bob a win when n is larger than 3.

Now we move on to topology, which is sometimes described as rubber-sheet geometry. To create a geometric representation of Subset Takeaway, we use one of the basic techniques in topology, which is to triangulate a shape—that is, split it up into triangles that join edge to edge. Strictly speaking, this description applies only to surfaces, but the same approach works for higher-dimensional shapes if we replace triangles with generalized objects called simplexes. For instance, a three-dimensional simplex, or 3-simplex, is a tetrahedron, with vertices labeled 1, 2, 3, 4 [*see illustration on page 96*]. It has four faces, six edges and four vertices. The faces are triangles (called 2-simplexes in this terminology), the edges are line segments (1-simplexes), and the vertices are points (0-simplexes). Moreover, these bits of the 3-simplex correspond exactly to subsets of {1,2,3,4}. The tetrahedron itself corresponds to the whole set {1,2,3,4}. The faces correspond to the three-member subsets {1,2,3}, {1,2,4}, {1,3,4} and {2,3,4}. The edges correspond to the two-member subsets {1,2}, {1,3}, {1,4}, {2,3}, {2,4} and {3,4}. And the vertices correspond to the one-member subsets {1}, {2}, {3} and {4}.

In fact, any $(n - 1)$-simplex can be identified with the set $\{1,2, \ldots, n\}$, and its various lower-dimensional parts can be identified with proper subsets. Subset Takeaway can now be reformulated as Simplex Erasure. Players start with a given simplex. A move consists of choosing a proper subsimplex of any dimension and erasing its interior as well as the interiors of all the higher-dimensional subsimplexes that contain it. But the move does *not* erase the boundary of the chosen subsimplex—for example, the three edges of a triangular face, or the two end points of an edge.

We can use this representation to analyze Simplex Erasure for a 3-simplex, which corresponds to Subset Takeaway for $n = 4$. The starting position is a complete 3-simplex—that is, a tetrahedron. The illustration on page 96 shows a series of legal moves. A systematic consideration of all such sequences shows that Bob can always win the $n = 4$ game. The same goes for $n = 5$ and $n = 6$. Gale has conjectured that whatever the value of n, Bob has a winning strategy. To the best of my knowledge, this has not yet been proved or disproved.

So what is Bob's winning strategy for $n = 4, 5, 6$ and higher? Should he always choose the complement of Alice's move—the strategy that worked for $n = 3$? When $n = 4$, Alice may start with a vertex, an edge or a triangular face. If she chooses a vertex and Bob selects the complement, the game reduces to the $n = 3$ case, and Bob wins. If she chooses a triangular face and Bob chooses the complementary vertex, the game again reduces to the simpler version. But what if Alice chooses an edge—say, the edge that corresponds to {1,2}—and Bob chooses the complementary edge, which would be {3,4}?

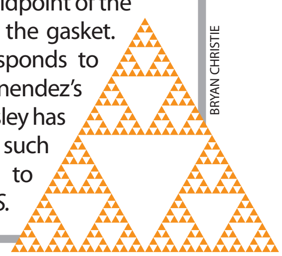
The illustration at the upper left shows what happens next. If Alice chooses {3}, Bob cannot choose the complementary subset {1,2,4}, because it is not a legal move (in simplex terms, that triangular face has already been erased). So the "complementary" strategy fails. Some mathematicians have conjectured that for all n, Bob's correct response to any opening move by Alice is to choose the complementary subset for his first move. Thereafter, however, he may be forced to deviate from choosing the complement of Alice's move, as we've just seen.

And what about poor Alice? Is it true that Bob can always defeat her in all versions of Subset Takeaway? Computer searches may well prove or disprove this conjecture for $n = 7$, 8 or other small values. For a larger n, the proof will require a new approach. Any interesting suggestions from readers will be reported in the Feedback section. SA

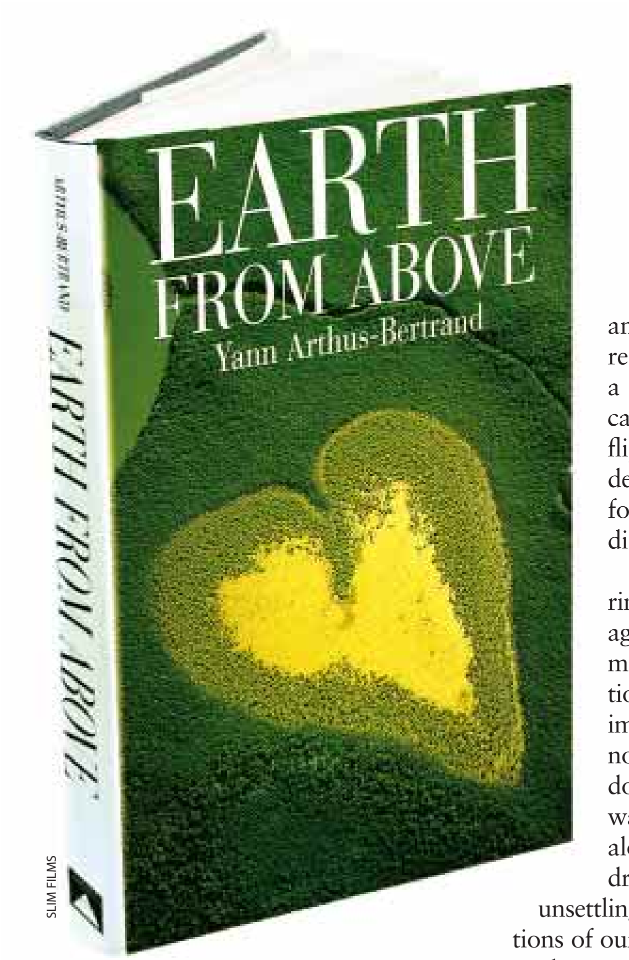
FEEDBACK

Ron Menendez of Chatham, N.J., has noted yet another interesting property of the Sierpinski gasket (*below*), which I discussed in "Sierpinski's Ubiquitous Gasket" [August 1999]. Take an equilateral triangle with vertices A, B and C and pick any point X in the triangle's plane. Choose one vertex at random—for example, roll a die and let 1 or 2 correspond to A, 3 or 4 to B, and 5 or 6 to C. Find the midpoint of the line joining X to the chosen vertex: this is the new position of X. Now repeat the procedure, always choosing a random vertex and moving X to the midpoint between its previous position and that vertex. Aside from a few initial points where the random walk is "settling down," the resulting cloud of points is a Sierpinski gasket!

This surprising outcome is explained by mathematician Michael Barnsley's theory of self-similar fractals. The Sierpinski gasket has three corners, which can also be labeled A, B and C. It is made from three smaller copies of itself, each with sides half as long as the gasket's side. If you draw a line between any point in the gasket and A, B or C, the midpoint of the line will also lie in the gasket. This feature corresponds to the rules for Menendez's random walk. Barnsley has proved that any such walk "converges" to the gasket. —*I.S.*



BRYAN CHRISTIE



SLIM FILMS

A WHIRLYBIRD'S-EYE VIEW OF THE WORLD

Review by Douglas C. Daly

Earth from Above
by YANN ARTHUS-BERTRAND
Harry N. Abrams, Inc., New York, 1999 ($65)

To many people over the past five years, preparing for the millennium meant surveying restaurants, hotels, parties, then trying to get a reservation and (more challenging) maybe a baby-sitter. To Yann Arthus-Bertrand it meant surveying the entire world and trying to get a sense of it. During the five years, he overflew and photographed 75 countries, shooting out the open door of a helicopter. The result is *Earth from Above* (*Terre Vue du Ciel* in the original French edition), at 424 pages and 11 by 15 inches almost more of a coffee table than a coffee-table book. It is weighty with thoughts and concerns about the millennium, with insightful observations about far-flung places and above all with 170 large color photographs, many of them stunning.

The book is divided into 11 sections, each anchored by a thematic essay. In each essay two foldouts contain thumbnail-size reproductions of the preceding and following images, so the reader can locate the image on a map and read the detailed captions without having to flip back and forth to an index. This is a clever way to inform about an image without distracting from it.

The most consistently recurring topic in the essays and images is our troubled and in many ways dysfunctional relationship with nature. Several images are of natural disasters, not just aftermaths of tornadoes and floods but also those waiting to happen. The view along a stretch of the San Andreas Fault is chilling. Most unsettling are the disastrous conditions of our own making. The text tells us that 19 countries suffer from serious drought and that between 1.6 billion and 1.8 billion people do not have access to potable water. A photograph shows us the perfect, white, prostrate "silhouette" of a tree that has been felled and burned to ash in northern Ivory Coast.

The distinction between natural spectacles and man-made landscapes is a relatively recent one that arose with the burgeoning scale of our manipulation of the environment. In one of the best essays, French geographer and archaeologist Pierre Gentelle writes, "We take comfort in nature, forgetting that at one time we feared it." Humans were cowed by nature in earlier times, but now it is almost an object of pity. The urbanized majority doesn't really want to live in nature or by any means to be affected by it; we simply want it to be there for aesthetics, or for visits. Gentelle takes the view that nature roped off in reserves is no longer authentic or untamed but rather more of a stage set.

The natural spectacles that Arthus-Bertrand sought and selected take implicit exception to Gentelle's rule. There is nothing either comforting or false about the nature presented in the images of the toothy karst formations of the Tsingy of Bemaraha in Madagascar or the gannet colony on Iceland's Eldney Island (*below*). Aesthetic, yes, but inseparable from awesome, and our capacity still to be awestruck by nature is essential to our survival, because it prevents us from arrogance, from the obliviousness to the environment that leads us toward oblivion. Some of the most exquisite shots are of inaccessible,

FROM EARTH FROM ABOVE

Worker resting on bales of cotton, Ivory Coast

Gannet colony, Iceland

Carpets, Marrakech

Boats caught in water hyacinths, the Nile, Egypt

inhospitable World Heritage sites; we may never get to see most of them, but we need to know they exist.

Many of the best images are actually of man-made patterns, be they fields of bright carpets in Marrakech (*above*) or swirling agricultural fields in the interfluve between the Uruguay and Paraná rivers in Argentina. Although our touch turns everything to sand or ash in so many places, some of the photographs evince how approaches to agriculture can cleave to topography and to the demands of extreme conditions.

The photographs are wonderful. The spacious format of course enhances their impact. Arthus-Bertrand clearly loves the long shadows of late afternoon (as in the caravan of dromedaries below); in some images large blocks of shadow accentuate what is lit, the way well-placed pauses brighten music. He uses the beauty of the images to great effect with disturbing subjects, because it fascinates and makes them even more terrible. An immense plague of locusts makes a Seurat painting of the landscape below it. What first strikes the eye as huge splashes of color turns out in one case to be destitute people picking through a garbage dump in Mexico City, in another the teetering poverty of a hillside *favela* above Rio de Janeiro. Pleasingly abstract patterns prove to be the aimless crush of burned-out tanks in Iraq after Desert Storm or the awful symmetry of a B-52 parking lot.

Words and Images

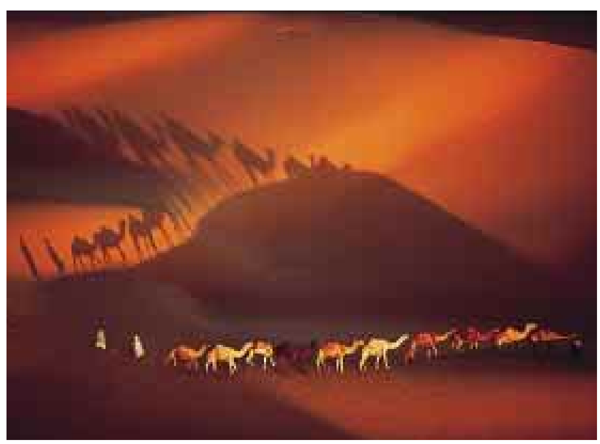
Marrying the visual and the textual in a book like this is very difficult, and in most cases the two parts seem less integrated than tacked together. Few photographers attempt the text, and only a very few (such as Loren McIntyre) can do justice to their own images. To be fair, on the scale of the millennium, who on earth would be equal to the task?

The essays, written by editors of the annual *L'état du monde,* are data-intensive and relentlessly macro as they tackle such topics as the origins of culture, the evolution of cities, population growth, climate change and sustainable development. They are well written and thought-provoking, and the translations are virtually seamless, but juxtaposed with the intimacy, poetry and passion of the images they can seem bland and detached, victims of millennial ennui.

Moreover, they are pretty dismal, the hope expressed sounding hollow among all the discouraging trends they describe. An example is the evolution (or devolution) of cities, where the cited trends of overexpansion, contamination, the growth of edge cities and literal decentralization point nowhere but downhill, despite the author's optimism about a new dynamic. Some of the recommendations are too sweeping to have any impact: take action, eliminate inequalities, do more research and so on.

The book is reinforced by the photo captions, apparently the work of the photographer and his field team. They are substantial, and many are small gems that convey both detail and larger lessons. Most are well researched, although in the caption accompanying the image of logs being floated down the Amazon, I would dispute the assertion that Brazil's principal economic asset is timber. This implies a mercifully

Grand Prismatic Spring, Yellowstone National Park



Dromedary caravan, Mauritania

unrealistic efficiency in deforesting the nation, and at present Brazil's status as the world's seventh largest economy owes very little to timber.

Finding much fault with the photographs is neither necessary nor possible. A bit of repetition reflects Arthus-Bertrand's fascination with agricultural landscapes. Some of the more familiar subjects (Nazca, Inishmore, Stonehenge) are less than captivating. In a few, people on the ground squint up at the helicopter and break the spell that lets us believe we are not intruding.

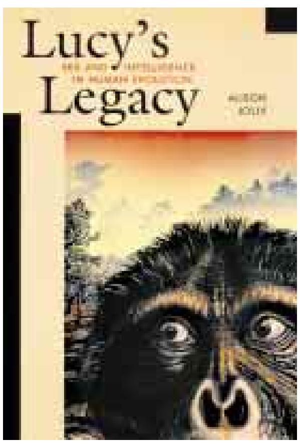
In most instances, however, the "whirlybird's-eye view" taken by Arthus-Bertrand is effective. It is high enough to see patterns but not so high as to render the subjects completely abstract. The book satisfies a need at this moment to step away from—and above—our circumstances to understand them better. From this perspective, we are presented with a spectrum of environments, lives, harmonies and dissonances, a tableau that is exquisite, ghastly, and sometimes both. The last photograph is a dusty blur of children near Korhogo, Ivory Coast, mobbing the helicopter and mugging for the camera. At the end, it is strange to be on solid ground—we have been taken on quite a journey.

DOUGLAS C. DALY is curator of Amazonian botany at the New York Botanical Garden in Bronx, N.Y.

THE EDITORS RECOMMEND

Lucy's Legacy: Sex and Intelligence in Human Evolution. Alison Jolly. Harvard University Press, Cambridge, Mass., 1999 ($29.95).

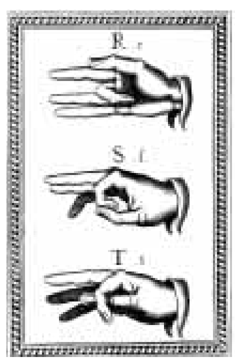
Lucy's legacy is us. Lucy (who may have been male) is the small Australopithecine hominid whose nearly complete skeleton—dating back 3.2 million years—was found in Ethiopia. It was an important transition in the evolution toward modern humans when Lucy and her kin began walking on two legs and strode off into the African savanna. Jolly, a primatologist who is a visiting lecturer in the department of ecology and evolutionary biology at Princeton University, traces four major evolutionary transitions in this compelling book and says we are in the early stages of a fifth. Her theme is that cooperation figured prominently in all of them. "Chemicals bonded in the prebiotic soup and elaborated as bacteria, then bacteria joined in the cellular community of one, then cells cloned multicellular bodies. Social groups of such bodies coalesced among insects and vertebrates. One social species communicates through speech, writing, and now electronic impulses. This is leading us to a fifth level of cooperation: specieswide, planetwide."



The range of things Jolly knows is stunning, and the connections she finds among those things are often startling. She flavors her gripping tale with lines from poems. Occasionally she throws in a joke, as in noting that the sea squirt, having accomplished its hardwired mission of attaching to a rock, then "eats its brain (like an associate professor getting tenure)." She is hopeful that the fifth transition will turn out well. "There is no need to dwell on what happens if globalization goes wrong. Global misery, the elite in their bastions, anarchic parts of the world written off as no-go zones, poor regions enslaved, environmentally devastated regions hungry and thirsty—all this is happening now.... The story less often told is our first steps toward global housekeeping: conscious responsibility for the health of our planet."

I See a Voice: Deafness, Language and the Senses—A Philosophical History. Jonathan Rée. Metropolitan Books, Henry Holt and Company, New York, 1999 ($27.50).

Rée, who teaches philosophy at Middlesex University in England, presents a book that is both philosophy and science. In the two mainly philosophical parts, he considers how people have viewed the five human senses over the centuries. In the mainly scientific part, he focuses on one of the senses, hearing, and its close connection with speech, by way of examining the experience of people who lack the sense—who are deaf. "Ever since the sixteenth century," he notes, "they have been attended by troops of priests, doctors, teachers and philanthropists dedicated to releasing them from their silent world (or perhaps expelling them from it against their will), by devising ways of making them understand language, despite their inability to hear it." Rée bolsters his history of those efforts with a number of unusual pictures, among them a French "voice machine" of 1908 that synthesized vowel sounds by pumping air past rotating perforated disks and then through rubber replicas of human mouths.



FROM *I SEE A VOICE*

The Eternal Trail: A Tracker Looks at Evolution. Martin Lockley. Perseus Books, Reading, Mass., 1999 ($26).

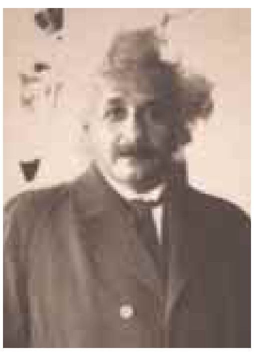
Lockley's eternal trail includes the visible tracks of animals through time. They help mightily to trace the steps in the evolution of life on Earth, and that is Lockley's central story. But he has a vision of the trail as part of a grander scheme, "the evolution of the universe." And so he follows the trail through three distinct phases: "the physiosphere—the world of rocks and atmospheres; the biosphere—the integrated web of plant and animal life; and finally, the 'noosphere'—the name given to the phenomenon of superorganic mind by such luminaries as the great paleontologist-philosopher-priest Pierre Teilhard de Chardin ... and the biologist-philosopher Julian Huxley." Lockley is professor of geology and paleontology at the University of Colorado at Denver. His account of tracks and what they tell about evolution is informative and well illustrated. Opinions may vary about his view of the eternal trail's relation to the evolution of the cosmos, but it makes for stimulating reading.

Just Six Numbers: The Deep Forces That Shape the Universe. Martin Rees. Basic Books, New York, 2000 ($21).

Rees, Astronomer Royal of Great Britain, advances the arresting proposition that the six numbers of his title play "a crucial and distinctive role in our universe, and together they determine how the universe evolves and what its internal potentialities are." Indeed, the numbers constitute a recipe for a universe, and "the outcome is sensitive to their values: if any one of them were to be 'untuned,' there would be no stars and no life." His cast of numbers is: N, measures the strength of the electrical forces that hold atoms together; E, defines how firmly atomic nuclei bind together and how all the atoms on Earth were made; Ω, measures the amount of material in the universe; Λ, represents "an unsuspected new force—a cosmic 'antigravity,'" that controls the expansion of our universe; Q, represents the ratio of two fundamental energies; D, states the number of spatial dimensions in our world. Rees, smoothly traversing a scale of size from the cosmos to the atom, ponders a profound question about the fine-tuning of the six numbers as they affect our universe. "Is this tuning just a brute fact, a coincidence? Or is it the providence of a benign Creator? I take the view that it is neither. An infinity of other universes may well exist where the numbers are different. Most would be stillborn or sterile. We could only have emerged ... in a universe with the 'right' combination."

The Truth about Cinderella: A Darwinian View of Parental Love. Martin Daly and Margo Wilson.
Divided Labours: An Evolutionary View of Women at Work. Kingsley Browne.
Shaping Life: Genes, Embryos and Evolution. John Maynard Smith.
Neanderthals, Bandits and Farmers: How Agriculture Really Began. Colin Tudge. All from Yale University Press, New Haven, Conn., 1999 ($9.95 each).

These little books, about 5 by 7, none longer than 70 pages, begin a series entitled Darwinism Today. Their aim is to make cutting-edge ideas in evolutionary theory available to a general readership. They succeed at that, probably at the risk of raising hackles among people who disagree with some of the theses.


FROM EINSTEIN'S GERMAN WORLD

Daly and Wilson, professors of psychology at McMaster University in Ontario, assert that Cinderella's abuse by a cruel stepmother typifies the situation in many households with stepchildren. "Because parental love carries with it an onerous commitment," Daly and Wilson say, "it would be strange if merely pairing up with someone who already had a dependent child were sufficient to fully engage the evolved psychology of parental feeling."

Browne, professor of law at Wayne State University, writes that "the biological and psychological literatures are bulging with data revealing robust differences between the sexes." He argues that those differences may account for such things as the gender gap in pay and the glass ceiling in promotion. And, he says, the differences suggest that "our patriarchal social structure—to the extent we have one—may be more an effect of sex differences than their cause."

Maynard Smith, emeritus professor of biology at the University of Sussex in England, describes "a revolution" during the past decade "in our understanding of development, the process whereby an egg turns into an adult organism." The progress in this field "is being made by applying the ideas and techniques of genetics to the processes of development."

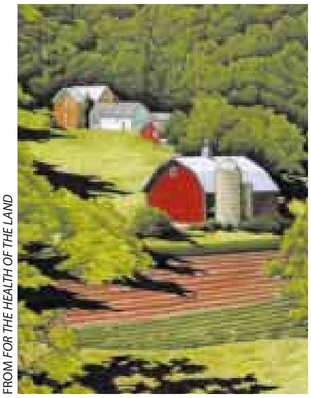
Tudge, a research fellow at the Center for Philosophy at the London School of Economics, puts the advent of agriculture at a much earlier time than the usual estimate of about 10,000 years ago. He argues that "from at least 40,000 years ago ... people were managing their environment to such an extent that they can properly be called 'proto-farmers.'" In the light of this idea, he says, "much that is otherwise mysterious falls easily into place."

Einstein's German World. Fritz Stern. Princeton University Press, Princeton, N.J., 1999 ($24.95).

"It could have been Germany's Century," Raymond Aron said to the author in 1979 as they walked in West Berlin past "bombed-out squares and half-decrepit mansions of a once proud capital." But it was not, partly because the authoritarian regimes of Kaiser Wilhelm II and then Hitler put the country's science in turmoil by presenting scientists with the hard choice of loyalty or resistance. Their plight is Stern's subject in the first half of this book. He examines the attitudes of such luminaries of German science as Paul Ehrlich, Max Planck, Fritz Haber and Albert Einstein as the regimes drove the nation into two losing wars. Stern, a historian, is university professor emeritus at Columbia University. He sees Germany's course through that era as "stoppable self-destruction." Nobel physicist Max von Laue, "who had not made any compromises with the [Hitler] regime," reflected years later on the predicament that he and his colleagues had faced. We "knew that injustice prevailed, *but we did not want to see it*."

For the Health of the Land. Aldo Leopold. Edited by J. Baird Callicott and Eric T. Freyfogle. Island Press, Washington, D.C., 1999 ($22.95).

Leopold (1886–1948) was an ecologist before ecology gained much recognition. As professor of game management (now called wildlife ecology) at the University of Wisconsin, he produced many essays on the management of land—particularly farmland—in such a way as to achieve a "harmony between men and land." The 53 essays that the editors present in this book amount to a manual on conservation. They also trace the development of modern ideas on ecology. "Doesn't conservation," Leopold wrote, "imply a certain interspersion of land-uses, a certain pepper-and-salt pattern in the warp and woof of the land-use fabric? If so, can government alone do the weaving? I think not. It is the individual farmer who must weave the greater part of the rug on which America stands."


FROM FOR THE HEALTH OF THE LAND

Exquisite drawings by Abigail Rorer of the wild plants and animals that were Leopold's chief concern add savor to the book.

The Code Book: The Evolution of Secrecy from Mary, Queen of Scots, to Quantum Cryptography. Simon Singh. Doubleday, New York, 1999 ($24.95).

The ancient battle between people who want to preserve secrets and people who want to discover them proceeds as a form of evolution. Codemakers devise a better means of encryption; codebreakers solve it, forcing the encoders to find another improvement. Singh, trained in physics but now an author of works on science, spins an absorbing tale of codemaking and codebreaking over the centuries. Does the simple monoalphabetic substitution cipher, which replaces each letter of a message with a letter from a cipher alphabet, no longer suffice? Replace it with a code using two or more cipher alphabets. When that no longer outwits the cryptanalysts, encode with a Vigenère square, in which a plaintext alphabet is followed by 26 cipher alphabets. And so on through one-time pad ciphers, cryptographic machines and public-key cryptography.

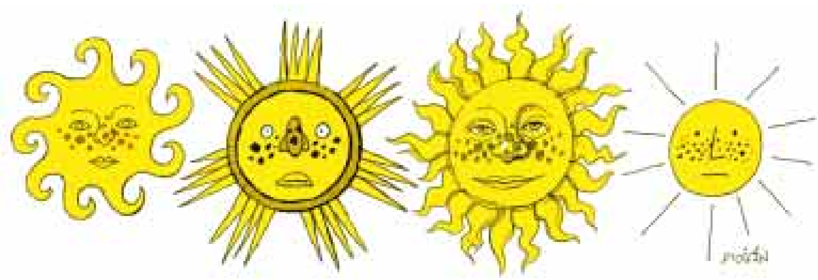
Singh explains them all deftly. Looking to the future, he sees "one idea in particular that might enable cryptanalysts to break all today's ciphers." It is the quantum computer. If it can be built, "it would be able to perform calculations with such enormous speed that it would make a modern supercomputer look like a broken abacus." Or perhaps the cryptographers will triumph with quantum cryptography. "If quantum cryptography systems can be engineered to operate over long distances, the evolution of ciphers will stop. The quest for privacy will have come to an end." SA

WONDERS

by Philip and Phylis Morrison

Sun-Stains

From a cloudless blue sky the resplendent solar disk dazzles the eye. But during the tempered glow of crimson sunsets or through a veil of thin cloud, the eye can sometimes spy areas of darkness. In 1607 Johannes Kepler himself, brilliant theorist and no mean observer, glimpsed a "little daub" on a projected image of the sun. Two years later he published a tentative explanation, positing the "Extraordinary Phenomenon, or Mercury in the Sun," an infrequent transit of Mercury silhouetted against the glaring disk. He could not be quite sure, for his planetary tables were still not reliable enough to predict a transit, and he was in fact wrong.



DUSAN PETRICIC

There is a second distinct kind of sun-stain, no shadow but a true blemish, physically rooted in the sun itself. Each one is a kind of long-lived cyclone called a sunspot, a feature of the changeable magnetic weather in the hot solar atmosphere. The year 2000 marks a newsworthy maximum in the 11-year cycle of sunspots as they appear, grow, often merging, then finally die away.

In 1613 Galileo used his telescope to map and vividly describe spots he observed, although the Chinese had first noted them 1,000 years or more earlier. Both Kepler and Galileo wrote of two kinds of dark sun-stain: the neat circular planet dot that moved off in a few hours, and the large, complex sunspot areas that may endure to return after the four weeks of a solar rotation. The annals of Charlemagne, emperor of the West, as reported by Galileo from his history of the Franks, record that eight centuries earlier in France many people had noticed a dark mark on the sun lasting eight days. The emperor assembled his savants, who agreed that the spot must have been Mercury. Galileo is stern; the shame of those old astronomers who did not know that no transit of Mercury could last even eight hours! (One may suspect that they had simply kept the puzzle's secret to themselves, for a predictable dot already gone is less disturbing than spots of unknown nature.)

By 1629 Kepler's best tables allowed him to predict transits. Attention, astronomers! Two transits for 1631: Mercury in November, Venus weeks later. Mercury's dot (too small to fit Kepler's 1607 daub) was seen by telescope in Paris just before it left the disk about five hours early. "The cunning god … I found him out," wrote the cunning astronomer Pierre Gassendi to a colleague. The latest transit of Mercury came in the afternoon of November 15, 1999, watched as a pleasure by an astronomer friend of ours in Denver, right on time by present tables. The 18th century tried hard to use precise timing of Venus transits from different places for scaling the solar system, but the method has long since been supplanted. Mercury transits a dozen or so times each century, next in 2003. Venus trespasses rarely, a century or so passing between successive closely spaced pairs of crossings. The last Venus transit was in 1882; the next will be in 2004.

Transits arise from fortunate remote alignments, but sunspots are physical events, associated with a variety of solar eruptions. Great plasma clouds fly out past our planet and disturb our magnetic weather. At the last spot maximum in 1989, electrical power failed for six hours over most of Quebec as the consequence of strong ground currents. Many Earth satellites risk electronics damage from similar effects in orbit. This year the northern lights are likely to appear once or twice even way down south in Dixie. Spots2K may be more evident than Year2K! Try not to miss the bright colorful auroras, the dark sunspots themselves (safely watched by projection onto paper) or the surprising behavior of short-wave radio.

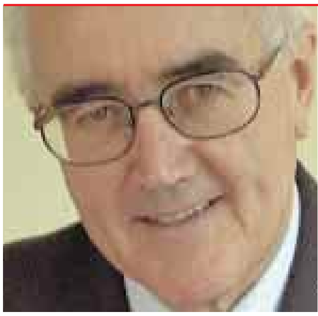
More than two dozen faint planets around distant sunlike stars have been found, without a glimpse of even one of them. Such finds use slow to-and-fro movements that any close-in big planet enforces on its massive star by their reciprocal gravitational pull. One unseen planet appeared to promise a fair chance of a transit visible here every few days. In so remote a transit no planet dot is to be seen, for distance has shrunk the whole disk of the star to a bright point of light. The transit came on time in mid-November; the star's light dimmed by almost 2 percent when the big planet crossed in front of its star 150 light-years out there. The telltale dimming in starlight (and a repeat on time at the next orbit) wonderfully confirmed the indirect measurements. Certainly a mere dimming is no substitute for detailed images. It now looks as though transits can identify planets as small as Earth, whose meager pulls on their own suns are undetectable.

To catch the rapid dimming requires looking at the right time from the right direction at an unexamined star. How could we hope to win a lottery like that? There is one way: buy plenty of tickets! Translated: your instruments need to stare for years at many, many stars of the sun's kind just as they stand in the sky. Measure brightness star by star, each time ready to catch the rare diagnostic dimming of the light by only one part in 10,000 or 12,000. Miss the few hours of transit, and you have wasted time on that star. Many stars will vary in myriad other ways, but seek one pattern, a sudden minor dimming that lasts for hours and then strictly repeats at much longer intervals. No other star variation is like that. (Don't fail to check out the prediction of the third transit for a star; once it tells you three times, it's true.) Repeat, repeat, repeat, measuring brightness for some years.

Check out the prediction of the third transit for a star; once it tells you three times, it's true.

By then you can expect to have located up to a few hundred Earth-class planets orbiting their suns among some 150,000 random stars, plus shelves full of other star variations. What is proposed is a space probe, its overall weight under a ton, bearing a telescope one meter in aperture and a few meters long, that looks into a deep pool of stars as the craft orbits the sun, a little outside Earth's own path. The focal plane is filled by 21 of the latest CCD photodetector arrays, in all some 90 million pixels; the probe is precisely guided to hold each star image on its own small patch of pixels. The design is well advanced. If all lab tests go well, launch into solar orbit a few years from now. Kepler—the proposed probe is named after the first predictor of transits—is the work of a team led by William Borucki and David Koch at the NASA Ames Research Center.

Seining a whole sea of stars for the telltale transit dimming pattern looks like the easiest scheme so far for finding Earth-like planets (unless we hear first from remote astronomers in residence). SA



DAVE PAGE

CONNECTIONS

by James Burke

Wuff, Wuff

DUSAN PETRICIC

Today the publisher of my next book asked me about prepublication copies, and I was on the verge of making a long list when I was humbled to recall that Charles Darwin sent out only three. One of them went to his biologist pal (and jellyfish maven) Thomas Huxley, who liked it so much he went on to become known as "Darwin's bulldog" when he successfully defended Darwin's theory in a great public debate. Another copy of *Origin* went to Charles Lyell, who had provided Darwin with much of the geologic proof that the earth was old enough to support a process as slow as evolution.

Lyell had a painterly godbrother (Lyell's dad, also Charles, was the guy's godfather), Dante Gabriel Rossetti, who in 1848 organized a group of artistic smoothies with tendencies toward hypochondria and "naughty" art. They went for all things medieval, calling themselves the Pre-Raphaelite Brotherhood, and produced Victorian versions of Disney versions of the 13th century. Fine, if you like the pallid. Poor old Rossetti's wife, never too robust, took a terminal laudanum overdose in 1862. Ten years later Rossetti tried the same trick. Fortunately for him, Dr. John Marshall was at hand.

The amount of ether required to relax muscles was just short of that which induced fatal paralysis.

Marshall was a Brotherhood groupie and gave lectures to wanna-be artists about human anatomy. He was also the acknowledged expert on varicose veins and the system of circular wards (about which perhaps some reader will enlighten me). Marshall was chummy with a real medical big cheese, Robert Liston, fastest scalpel in London. Who risked all in 1846 with the first non-American use of ether (nitrous oxide) to anesthetize a patient for a leg amputation. Problem being that the amount of ether required to relax muscles was just short of that which induced fatal paralysis. Liston's operation followed one conducted two months earlier at Massachusetts General in Boston, where W.T.G. Morton administered the new anesthetic for the first time during removal of a neck tumor.

As an undergraduate at Harvard, Morton had studied chemistry under Charles T. Jackson, a colorful character (he finally went nuts) who accused Morton of having stolen the surgical anesthesia idea from him and began years of (unsuccessful) litigation. Jackson also claimed to have invented guncotton before Christian Schönbein (see an earlier column). He also took to task Samuel Morse, to whom he claimed to have divulged the secret of the telegraph when he and Morse were returning from Europe to the U.S. on the same ship in 1832 (see an even earlier column). At this time Morse was still hoping to make his name as a painter by getting the commission to paint the remaining murals in the Rotunda on Capitol Hill. Fortunately for the future of telecommunications, he didn't.

The four already completed Rotunda murals had been done by John Trumbull, a second-rate artist with only one working eye (so the close-up work in his small-scale, first-stage outlines was much better than what finally went on the walls). This dauber had started life as the aide-de-camp to George Washington during the War of Independence (so guess why he got the Rotunda work). At one point Trumbull spent 10 years in London seeing to the implementation of the Jay Treaty, signed to avert another war between Britain and the U.S. and dubbed a sellout back in the States.

Whether it was or not, the whole affair ruined the presidential prospects of one of the American treaty negotiators, Trumbull's boss in London, John Jay. Who was on his *second* peace treaty with the Brits. The first having been 12 years before, in a follow-up to the aforesaid American war, on which occasion Jay had played second banana to Ben Franklin, who was on his *third* schmooze with the Brits (on the first two occasions representing various American colonies and on this third, the newly U.S. of A.).

It will come as no surprise that early in his diplomatic career, anytime Franklin met somebody pro-American, he'd recruit them to the cause. In one case, an out-of-work, two-ex-wives English pamphleteer, who was easily persuaded that since everything for him was going west he might as well go West. Once in Philadelphia, Tom Paine made his name with a piece read to the troops at Valley Forge by Washington himself ("These are the times that try men's souls," etc.). Once more back in England, a rush of blood to the head over French Revolutionary stirrings triggered Paine's magnum opus, *The Rights of Man*. This book went over like a lead balloon with the Brits, who banned it and indicted him for treason. At which point he escaped to France, there to foment further unrest over all forms of monarchical injustice. In 1802 Paine returned to the U.S. for the final time (to find he'd been forgotten) and then, in 1809, died.

No rest for the wicked, some might

have said. A decade after his interment, Paine's bones were dug up for return transatlantic shipment (and lost after they got as far as Liverpool) by an admirer: another pro-American, social-reforming thorn in the side of the British establishment, William Cobbett, of whom I have spoken before. This time I just want to mention that apart from his immensely readable diary of a journey among the disfranchised, poverty-stricken and oppressed members of Britain's lower agricultural orders (*Rural Rides*), Cobbett also did a puff piece on (the admirable character of) Richard Brinsley Sheridan, dramatist and from 1776 manager of the Drury Lane Theater in London. Where in 1777 he staged the first performance of his highly successful play *The School for Scandal*. Sheridan was also a politician who took Parliamentary debate so seriously (on occasion he would speak for four hours) that when his theater burned down he wouldn't leave the House of Commons to deal with it.

One of his colleagues in the Palace of Westminster (and fellow gambler at the London clubs) was one of those guys who was almost too good to be true. An idol with no clay feet: William Wilberforce, the universally admired, kindly, widely read philanthropist who shepherded antislavery legislation through Parliament single-handedly. It's almost a relief to discover that his most famous son (who became Bishop of Oxford, no less) rejoiced in the nickname of "Soapy Sam." This, thanks to criticism of his saponaceous speaking style and the ability to look both ways at once rather than take a position on almost anything. Bishop Wilberforce went down in history principally for two things: his success with the reform of the Church of England and his failure (in spite of having taken a first-class honors degree in math at the same university) to win a very public Oxford science debate in 1860.

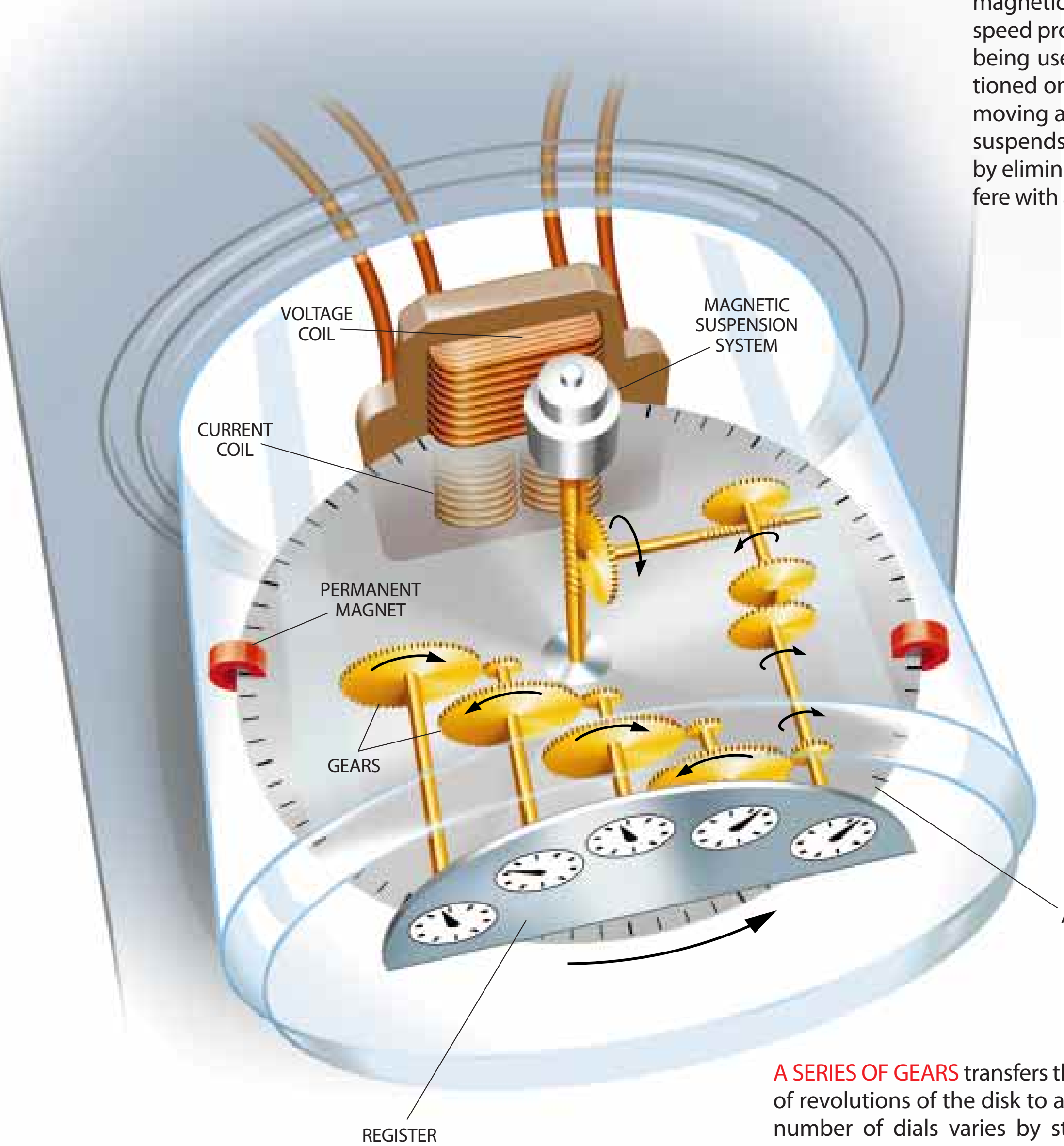
His victorious opponent in argument was Darwin's bulldog. Huxley clinched matters with the famous words: "If … the question is put to me, would I rather have a miserable ape for a grandfather or a man highly endowed by nature and possessed of great means of influence, and yet who employs these faculties and that influence for the mere purpose of introducing ridicule into a grave scientific discussion—I unhesitatingly affirm my preference for the ape." SA

WORKING KNOWLEDGE

ELECTRICITY METERS

by Les Rosenau
Product Planning Engineer, GE Industrial Systems

The glass-enclosed meter that hangs on a wall of your home, in your basement or outside on a nearby pole, works by recording the energy flow into your residence from the power company. It measures both the current—that is, the flow of electrons, which is expressed in amperes—and the voltage, or pressure, that pushes electricity through the wire. To determine the wattage used, the meter automatically multiplies amperes by volts.



THE METER is essentially a small motor run by the magnetic forces created as electricity flows through coils. The incoming wires are connected to a voltage coil; current then flows through the meter's current coil to the household wiring. When current passes through these two coils, the induced magnetic field turns an aluminum disk at a speed proportional to the number of watts being used. Permanent magnets are positioned on either side of the disk to keep it moving accurately; another magnetic field suspends the disk and its shaft in air, thereby eliminating any friction that could interfere with a correct reading.

EACH REVOLUTION of the disk typically measures 7.2 watt-hours. (For comparison, a 100-watt bulb uses 100 watt-hours of electricity every hour.) The more power the household uses, the faster the disk turns. Because utilities measure electricity consumption in large units—that is, in kilowatt-hours—every 138.88 revolutions of the disk indicates 1 kilowatt-hour (1,000 watt-hours) of electricity consumption. Accordingly, every 1,000 spins of the disk indicates 7.2 kilowatt-hours of use.

A SERIES OF GEARS transfers the information about the number of revolutions of the disk to a series of dials on a register—the number of dials varies by style of meter. The meter reader records the kilowatt-hour dial position and determines this month's energy consumption by subtracting the previous reading. New technology—which is already in place in some regions—will ultimately allow most meters to communicate kilowatt-hour readings to a central location using radio waves, telephone lines or even the actual power line itself.

GEORGE RETSECK