HANDS-FREE COMPUTING • MARTIAN FOSSILS UPDATE • OIL SPILL AFTERMATH

SCIENTIFIC AMERICAN

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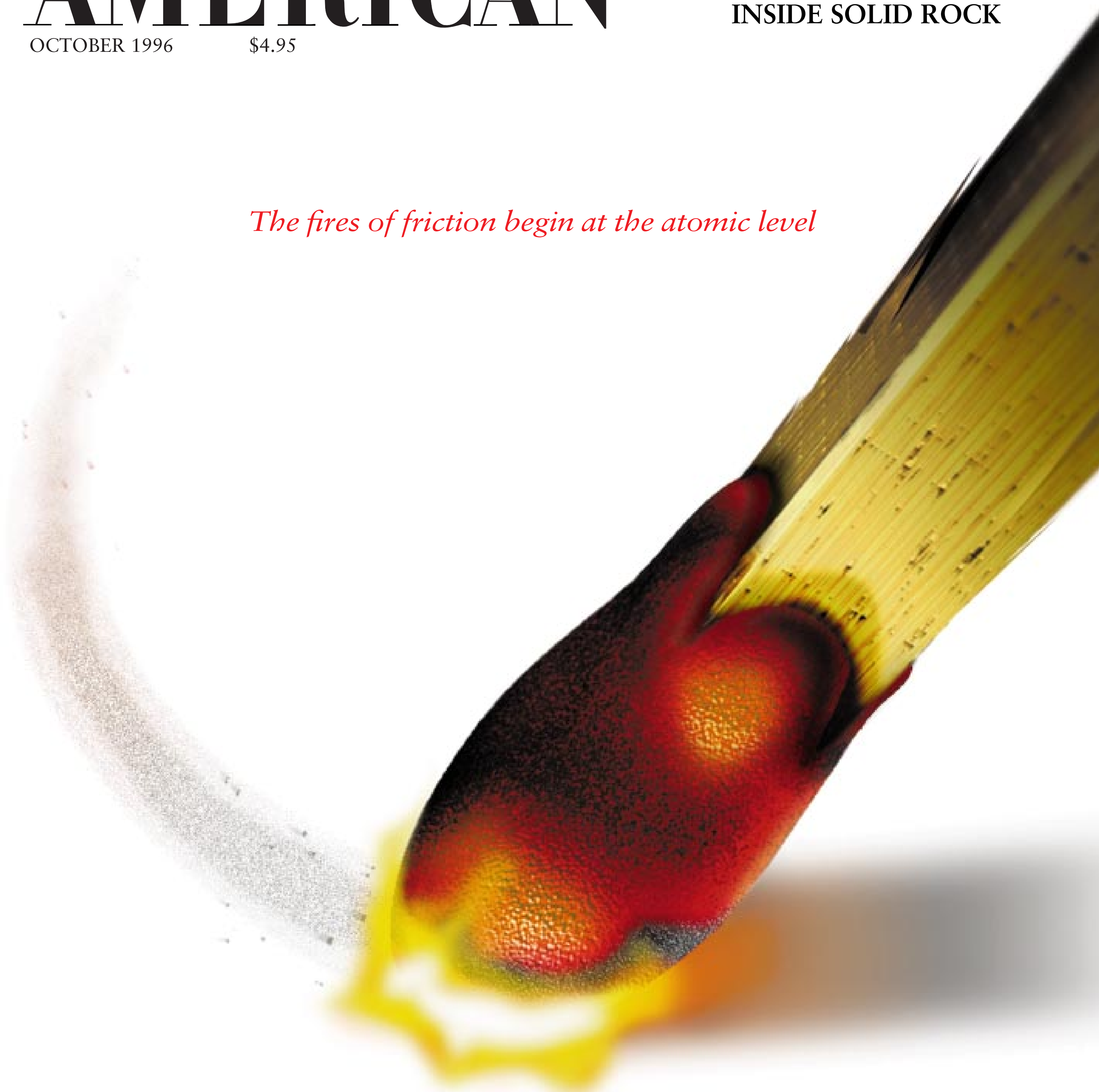
HELL'S CELLS:

MILES UNDERGROUND, DESPITE SCORCHING HEAT, LIFE THRIVES INSIDE SOLID ROCK

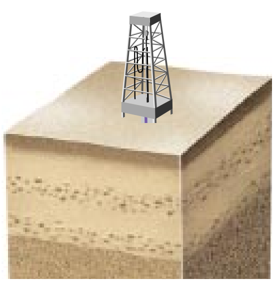
The fires of friction begin at the atomic level



SCIENTIFIC AMERICAN

October 1996 Volume 275 Number 4

NEWS AND ANALYSIS



REVIEWS AND COMMENTARIES

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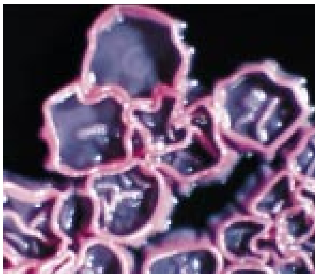
About the Cover
Striking a match, skating on ice and sanding wood depend on friction, one of the oldest forces exploited by technology. Yet many principles behind friction have been obscure. Image by Slim Films.

FROM THE EDITORS

Microbes from Mars? Maybe

The news has just broken about the tentative but tantalizing evidence for life on Mars as I write this, and the scientific community is therefore still ping-ponging between giddiness and wary skepticism. NASA's announcements of its discoveries are intriguing, exciting, but ambiguous. The Martian meteorite recovered from the ice fields of Antarctica does not contain anything so clear-cut as a piece of H. G. Wells's tripod death machines, or a six-legged monster out of Edgar Rice Burroughs, or a crystalline artwork from Ray Bradbury's *The Martian Chronicles.* Just polycyclic aromatic hydrocarbons and submicron-size rods that might be the fossilized remains of alien bacteria. For a thorough evaluation of the findings, see "In Focus" on page 20.



LIFE UNDER THE EARTH raises hopes for Martian cells.

Even if something did inhabit Mars billions of years ago, there is no reason to think it must still be around. The *Viking* landers of the 1970s did not find convincing evidence in their biological surveys. But those tests literally just scraped the surface of Mars. Enthusiasts have wondered whether we might find more if we burrowed deeper into the Martian soil and crust—and recent work on Earth adds reasons to think so.

James K. Fredrickson and Tullis C. Onstott explain why in their article, beginning on page 68. Drilling experiments have confirmed what had long been a matter of speculation, that microorganisms survive at considerable depths inside Earth's crust, sometimes living inside solid formations of granite. Like the communities of organisms that live around hydrothermal vents on the ocean floor, these subterranean microbes have substituted volcanic fires for solar ones as an energy source. Some cells are still tied to the surface world by a dependence on nutrients filtering through the strata above, but others can obtain essential elements directly from the surrounding rock. As the authors note, organisms on Mars might have acquired the same or similar tricks to live comfortably underground, even as that world's atmosphere and water all but disappeared.

Next month *Scientific American* will publish a further article, one that explores where and how water once flowed on Mars, information that might signpost the most promising places to dig for living or fossil organisms. If more work confirms that Mars did or does harbor life, researchers will have to look more closely, too, at whether other bodies in our solar system might be havens for it. Some moons around the outer planets are superficially forbidding, but they are aboil with interesting chemistry—who knows whether their interiors might offer sanctuary to life-forms coming in out of the cold? Maybe our solar system will turn out to be crowded with citizens.

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

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LETTERS TO THE EDITORS

SPACE STATION UNDER SCRUTINY

In the article on the International Space Station ["Science in the Sky," June], Tim Beardsley and the editors at *Scientific American* would have done well to resist the temptation to play the "my research is more important (read: worthy of funding) than yours" game. Congressional science funding is not a zero-sum game in which killing one program results in a windfall for another. Our fortunes rise and fall together.

JAMES F. BUCHLI
Boeing Defense & Space Group
Houston, Tex.
Buchli is a former shuttle astronaut.

The current cyberspace generation is attuned to more abstract forms of exploration than following the doings of a few humans on the space station. Hyperlinks to Martian landscapes or images of extrasolar planets generated by sensors on telescopes, probes or rovers seem a lot more compelling than experiments detailing long-term human performance in space. I suspect citizens of the next century will vote with their browsers to fund the unmanned designs Daniel S. Goldin has commissioned.

TOMAS VALIS
Toronto, Ontario

I read with concern Beardsley's article because it presented a one-sided perspective of the economics of space station science and technology. For example, his comments on the Space Vacuum Epitaxy Center imply a futility in our efforts to utilize the space station that is simply unfounded. Beardsley writes that "no facility for orbital molecular-beam epitaxy could operate within 50 miles of the space station," yet we have successfully operated the Wake Shield Facility for molecular-beam epitaxy as close as 15 miles from the space shuttle.

He also indicates incorrectly that we have "not persuaded any business to fund epitaxy research in space" and that the Centers for the Commercial Development of Space (CCDS) "are being bankrolled by NASA." Epitaxy research at the Space Vacuum Epitaxy Research Center has received funds from industry of more than $2.3 million over the past seven years. And in the 1994 fiscal year, other funding going to the CCDS totaled more than $48 million, compared with the $18.6 million allocated by NASA—a far cry from "bankrolling."

ALEX IGNATIEV
Director, Space Vacuum Epitaxy Center
University of Houston

Beardsley replies:

The assessment that no manufacturing facility for molecular-beam epitaxy could operate within 50 miles of the space station was offered to me by a technical staff member of the Space Vacuum Epitaxy Center. The staff member explained that experiments 15 miles from the shuttle have failed to produce epitaxial material suitable for manufacturing and that semiconductor companies have so far declined to initiate substantial space epitaxy development efforts. This source also stated that industry has restricted itself mainly to contributions of materials and staff time.

Regarding the subsidy that NASA provides to the CCDS, a National Research Council report recently described the arrangement as "fundamentally flawed" and recommended auctioning commercial facilities on the space station to the highest bidder. The subsidy from NASA—and government funds for science projects in general—are valid topics for public debate and should not be left unexamined for fear that all research grants might evaporate under scrutiny.

OLYMPIC GOLD

Just one look at the fancy bicycle featured on the cover of your June issue and pictured in Jay T. Kearney's article, "Training the Olympic Athlete," indicates just how unsuccessful regulation to encourage pure athletic performance over technological (and financial) prowess has been. International cycling rules specify that "bicycles shall be of the type that is or could be purchased by anyone practicing cycling as a sport." But this "anyone" should be prepared to spend at least $20,000 if he or she wants a Superbike II.

BORIS STAROSTA
Charlottesville, Va.

DAMAGE ASSESSMENT

"Confronting the Nuclear Legacy: Ten Years of the Chornobyl Era," by Yuri M. Shcherbak [April], prompted considerable mail from readers questioning the author's assessment of the number of casualties caused by the Chornobyl nuclear power plant explosion. The commentary that follows is adapted from an article that first appeared in Swiat Nauki, *the Polish edition of* Scientific American.

Ambassador Shcherbak's article is one of many recent publications presenting the Chornobyl catastrophe in black colors. The paper has clear antitechnology motivations, describing the Chornobyl accident as an example of an "ever growing threat of technology run amok." I do not wish to correct all the errors and distortions in Shcherbak's paper, but I will rather present the number of injuries and deaths as a result of the accident as estimated by the international community of radiation protection experts. I will base my comments on reports of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR)—the most distinguished international scientific body on the matters of ionizing radiation—as well as a recent report from the Organization for Economic Cooperation and Development and the proceedings of Chornobyl symposiums held recently.

An assessment of the impact on human health caused by the meltdown at Chornobyl should be limited to the effects of ionizing radiation and heat, as well as mechanical injuries, excluding losses caused by psychological factors such as hysteria. (Symptoms of psychosomatic origin resulted from the stress of the evacuation of hundreds of thousands of people, leading to disruption of community, family networks and traditional ways of life.) During the first few hours of the catastrophe, 237 people—employees of the nuclear power station and rescue workers—were irradiated with doses of radiation ranging from 2,000 to 16,000 millisieverts. For comparison, the global average of natural lifetime radiation exposure is 168 millisieverts, although in some countries the average dose is much higher. For example, in some districts of Norway, the lifetime dose is 1,500 millisieverts, in India, 2,000 millisieverts and in Iran, 3,000 millisieverts. The 237 people at Chornobyl were hospitalized with suspected acute radiation sickness (ARS). Doctors confirmed this diagnosis in 134 cases.

During the first three months after the accident, 28 patients died of ARS. Another two died from mechanical or thermal injuries, and one person died from coronary thrombosis. Over the past 10 years, out of the original 134 people diagnosed with ARS, 14 died, but probably because of other causes. And among the general public, three children died of thyroid cancer related to exposure to radioactive iodine released during the accident. Thus, the total number of people who died from radiation or injuries stemming from the heat or the explosion stands at 48.

GROCHOWIAK/KEPLICZ *Sygma*

Between 1986 and 1989 the 270,000 residents of the contaminated areas near Chornobyl received radiation dosages ranging from five to about 250 millisieverts, with the average dose falling at approximately 40 millisieverts. Among the 135,000 people evacuated in the first few weeks after the event, the average exposure was 15 millisieverts. The 800,000 "liquidators" (who buried the most dangerous wastes and constructed the building now surrounding the reactor) received on average 170 millisieverts in 1986 and 15 millisieverts in 1989. A small number of these people received more than the emergency dose limit, which was set at 250 millisieverts.

How dangerous were these levels? Among residents of Hiroshima and Nagasaki, malignant tumors were not observed in people who received radiation doses to the whole body of less than 200 millisieverts. Furthermore, mortality from leukemia in these cities was lower among people who were exposed to fewer than 100 millisieverts than in nonexposed people. Thus, many experts did not expect an increase in cancer rates after Chornobyl, and subsequent studies carried out by teams in Ukraine, Belarus and Russia confirmed this prediction. In regions contaminated with Chornobyl debris, the rising cancer rate is identical to the increase observed in other regions of Ukraine and can be explained by the growing elderly population.

Irradiation of thyroid glands in children is a different story. Because high doses of radioactive iodine can become concentrated in the small mass of the gland, researchers expected a significant increase in the rate of thyroid cancer six to eight years after the catastrophe; instead the increase showed up after only four years. But whether the increase was the result exclusively of radiation from Chornobyl or of other agents as well is still a matter of discussion. In any event, until the end of 1995, a total of 682 children with thyroid cancer had been identified in Ukraine, Belarus and Russia. As previously noted, three of these patients died.

Economic losses in Belarus alone are expected to reach $55 billion in 1995, soaring to $190 billion by 2010. Most of these expenses—$86 billion—will be spent on pensions, rents and other compensations for millions of people who will receive doses of radiation lower than the natural levels present in many regions of the world. In terms of economic devastation, the accident at Chornobyl qualifies as an enormous industrial catastrophe. But in terms of human fatalities, it cannot be regarded as a major one. After 10 years, fatalities total 48, a number that pales in comparison to fatalities from other industrial accidents—the 6,954 who died in the 10 years after the chemical accident in Bhopal, India, to name just one example.

ZBIGNIEW JAWOROWSKI
Central Laboratory
for Radiological Protection
Warsaw, Poland

Shcherbak replies:

In my numerous meetings with people who, like Jaworowski, call themselves the "international community of radiation protection experts," I could not but be surprised by their open cynicism. From the very beginning, they denied any tragic consequences of the catastrophe and hid information about radiation levels in certain areas. These people did not want to notice the growth in children's thyroid cancer and, following the mendacious Communist regime propaganda, proclaimed those who physically and mentally suffered from the disaster as experiencing hysteria.

Dozens of highly qualified experts from the former U.S.S.R.—medical doctors, radiobiologists, geneticists, nuclear physicists and others—have convincingly shown that the disaster at Chornobyl had an unprecedented and ominous character. I never belonged to the "catastrophists" who thought that Chornobyl would cause millions of deaths. As any unbiased reader could see, I was very cautious with figures in my article, avoiding ungrounded conclusions and using only verified data. But at the same time, I consider it absolutely immoral to ignore the medical importance of this event.

Finally, I have a proposal for Jaworowski: if he believes the Chornobyl catastrophe "cannot be regarded as a major one," I could ask Ukrainian officials to find a nice-looking home within the area contaminated by strontium, cesium and plutonium where he could settle down with his family. There he could demonstrate that one need not describe the Chornobyl disaster in black colors but in rosy ones.

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

ERRATUM

Because of a printing error, the first full sentence on page 31 of the August issue ["Cyber View," by John Browning] is incomplete. It should read: "And at the office, new network-supplied computing services might be made to provide bursts of specialized processing power—for example, the number crunching that is needed to run a simulation."

50, 100 AND 150 YEARS AGO

SCIENTIFIC AMERICAN

OCTOBER 1946

Fuel costs are such a relatively small figure in the overall expense of generating electricity that atomic power plants would reduce residential electric bills only slightly, according to a recent Westinghouse estimate. The investment required for central generating stations and distribution stations, and equipment maintenance, far outweighs the fuel bill."

"Some unusual set-ups are being used to give an accelerated but accurate measure of the way materials perform as parts of an entire unit. A refrigerator door, for example, may have a fine appearance and work well for a few times, but this is no assurance that it will function satisfactorily over a period of years. Therefore, in place of waiting for a housewife to open and close the refrigerator door to death, a machine was made which performs that operation continually—verging on the slamming side for good measure—24 hours a day to failure. An equivalent door life of 15 years is compressed to about 12 days by the robot door-slammer."

" 'Teacher, I can't see the board' used to be a familiar cry at the Bowditch School in Salem, Massachusetts, before the establishment of Room 4 as an experiment in schoolroom lighting. Keys to better seeing include triangular fluorescent luminaires that produce an asymmetric light distribution, with the greatest illumination facing the blackboard, and when louvers on windows can not adequately control sky glare, the fluorescent lamps are switched on or off by a 'monitor' pupil according to the indications of a simplified light meter fastened to his desk."

OCTOBER 1896

Cycling, which was yesterday the fad of the few, is today the pastime of the many. Unfortunately, this progress has been attended with numberless casualties. One temptation to many cyclists is to see how speedily they can sacrifice their lives on hilly ground. The moment the brow of a hill is reached the reckless cyclist seems impelled to take his feet from the pedals and to allow the machine to descend with all the rapidity which gravity gives it. A good brake affixed to the back wheel would considerably reduce the number of accidents from this cause; but, unfortunately, there is an idea that a brake adds an inconvenient weight to the machine."

"Leydenia gemmipara Schaudinn is the name given to a parasitic amoeboid rhizopod which Berlin professors have recently found in the fluid taken from patients suffering from cancer of the stomach, and which they think may possibly be the cause of the disease."

"A new variety of window glass invented by Richard Szigmondy, of Vienna, has the peculiar virtue of non-conductivity for heat rays. A pane of this glass a quarter inch thick absorbs 87 to 100 per cent of the heat striking it, in contrast to plate glass, which absorbs only about 5 per cent. If Szigmondy's glass is opaque to heat rays, it will keep a house cool in summer, but tend to make it warmer in winter."

OCTOBER 1846

Animal magnetism, with all its boasted advantages in rendering people insensible to pain, appears likely to be superseded by a discovery of Dr. William T. G. Morton, of Boston. It is no other than a gas or vapor, by the inhaling of a small quantity of which, the patient becomes immediately unconscious, and insensible to pain, thus giving an opportunity for the most difficult and otherwise painful surgical operations, without inconvenience." [*See illustration on page 124.*]

"Jean-Baptiste Fourier, a French philosopher, established that there are three states in which material bodies exist and proved that when a solid body or a liquid (such as molten iron) becomes incandescent, the light which it emits is polarized; and that the light of incandescent gases, such as flame, is unpolarized. Now M. François Arago has, with most beautiful sagacity, established that the light from the sun is not polarized; the conclusion is inevitable, that the surface of the sun is covered by an atmosphere of flame." [*Editors' note: Plasma, the fourth state of matter, was not recognized until 1952. The surface of the sun does give off unpolarized light but is actually composed of plasma.*]

"Our engraving represents a recent invention, the Fire Shield, having for its object the protection of firemen from the excessive heat of the flames, while engaged in their gallant calling. The head is more sensitive to heat than any other part of the body, often compelling firemen to stand aloof, when, could their faces have protection, the flames might be approached much nearer; resulting, perhaps, in the rescue of valuable property. For this purpose a stiff leather mask has been constructed, with pieces of clear mica for eye-glasses and a small tube near the mouth for inhalation."

The Fire Shield

NEWS AND ANALYSIS

IN FOCUS

BUGS IN THE DATA?

The controversy over Martian life is just beginning

COURTESY NATIONAL AERONAUTICS AND SPACE ADMINISTRATION/JET PROPULSION LABORATORY

***MARTIAN SURFACE** showed no signs of life when tested by the* Viking *lander—but conditions may have been much more favorable billions of years ago.*

"New hint of life in space is found: Meteorites Yield Fossilized, One-Cell Organisms Unlike Any Known on the Earth," shouted a headline in the *New York Times*. "Something Out There," *Newsweek* chimed in. Respected scientists told crowds of reporters that their work, published in a prestigious journal, revealed complex hydrocarbons and what looked like fossilized bacteria buried deep within a meteorite. This, they claimed, was "the first physical evidence for the existence of forms of life beyond our planet."

That was 1961, and the meteorite in question was not the one from Mars that has made recent headlines but another that had fallen a century earlier in Orgueil, France. Under closer scrutiny, the astonishing evidence was eventually thrown out of the court of scientific opinion. The organic chemicals and "fossils" turned out to be ragweed pollen and furnace ash.

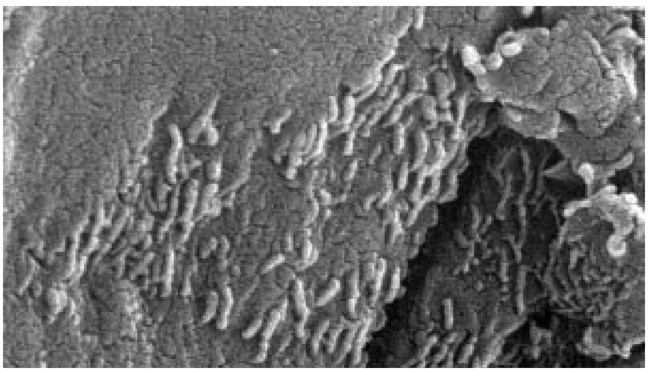
So it is with understandable skepticism that scientists are greeting the bold assertions, made by David S. McKay of the National Aeronautics and Space Administration Johnson Space Center and eight colleagues, that the peculiar features they found in meteorite ALH84001 are best explained by the existence of primitive life on early Mars. Despite public enthusiasm about the conclusions, published in *Science,* many leading researchers who study meteorites and ancient life have weighed the evidence and found it unconvincing. "There are nonbiological interpretations of McKay's data that are much more likely," concludes Derek Sears, editor of the journal *Meteoritics and Planetary Science*.

On August 7 the nightly news recounted ALH84001's impressive résumé: born 4.5 billion years ago in Mars's depths; splashed by a huge impact into interplanetary space to drift for 16 million years; captured in Earth's gravity and dragged into Antarctic snow; buried in ice for 10 to 20 millenia until 1984, when meteorite hunters picked it up and made it famous. That much nearly everyone agrees on; the controversy centers on the rock's less glamorous inside story.

McKay and his collaborators build the case for life on four lines of evidence. The first are blobs, no bigger than periods, that dot the walls of the cracks and crevices perforating the meteorite's shiny crust. These multilayered formations, called carbonate rosettes, tend to have cores rich in manganese, surrounded by a layer of iron carbonate and then by an iron sulfide rind. Bacteria in ponds can produce similar rosettes as they metabolize minerals. But "that is a perfectly reasonable sequence to find in a changing chemical environment as well," counters Kenneth H. Nealson, a biologist at the University of Wisconsin.

The second line of evidence centers on the discovery of organic compounds called polycyclic aromatic hydrocarbons, or PAHs, in and around the carbonate. Richard N. Zare, a Stanford University chemist and co-author of the *Science* paper, reports that the rock contains an unusual mixture of certain lightweight PAHs. "In conjunction with all the other data, it seems most likely to me that they all came from the breakdown products of something that was once alive," he says.

Critics suggest other possible explanations, however. "Hydrothermal synthesis could take inorganic carbon and water and make aromatic organics; you would get the same ones they report," points out Bernd Simoneit, a chemist at Oregon State University. "And look at the Murchison meteorite, thought to come from the asteroid belt," adds Everett Shock of Washington University. "Hundreds of organic compounds have been identified in it, including amino acids and compounds closer to the things organisms actually use. It has carbonate minerals in it, too—and real solid evidence of water—yet there isn't anybody saying that there is life in the asteroid belt."



NASA

MARTIAN ANIMAL, VEGETABLE OR MINERAL?

Training high-power electron microscopes on ALH84001, McKay's group found its third and most cogent bit of evidence: tiny, teardrop-shaped crystals of magnetite and iron sulfide are embedded in places where the carbonate is dissolved, presumably by some sort of acid. The authors note that certain bacteria manufacture broadly similar magnetite and iron sulfide crystals. Joseph Kirschvink, a biomineralogist at the California Institute of Technology, agrees that the mineral formations are intriguing. "If it is not biology, I am at a loss to explain what the hell is going on," he says. "I don't know of anything else that can make crystals like that." Shock remains unconvinced. "There are other ways to get those shapes. And in any case," he continues, "shape is one of the worst things you can use in geology to define things."

The final thread of evidence has drawn the sharpest attacks. Examining bits of ALH84001 under an electron microscope, McKay's team found elongated and egg-shaped structures within the carbonate; the researchers interpreted these as fossilized nanoorganisms. Many scientists are unconvinced that such organisms ever existed on Earth, let alone elsewhere. There is also a real danger of an observer effect at work.

"The problem," says NASA exobiologist Jack Farmer, "is that at that scale of just tens of nanometers, minerals can grow into shapes that are virtually impossible to distinguish from nanofossils." But Everett K. Gibson, Jr., another of McKay's co-authors, responds that "we eliminated that possibility for most of our examples by noting the lack of crystal growth faces" and other mineralogical features.

Some critics also find the small size of the "fossils" hard to square with the other evidence. "These structures contain one one-thousandth the volume of the smallest terrestrial bacteria," points out Carl R. Woese of the University of Illinois, who studies the chemistry of ancient life. "They really press the lower limit," he says, of how tiny a living unit can be. Moreover, the putative Martian bacteria are hardly larger than the mineral crystals they are supposed to have produced.

If not life, then what can account for this odd collection of features? One possibility is a hydrothermal process. "Imagine hot fluids flowing through the crust," suggests John F. Kerridge of the University of California at San Diego. "The crystallization of magnetite, iron sulfides and carbonate with a change in the chemistry over time is perfectly reasonable. If anywhere in the subsurface of Mars there are PAHs, then they would be carried by this fluid and deposited where the fluids crystallize. I think the nanostructures are most likely an unusual surface texture resulting from the way in which the carbonate crystallized."

Then there is the specter of contamination. Jeffrey Bada of the Scripps Institution of Oceanography in La Jolla, Calif., notes that PAHs have been found in glacial ice, albeit at very low concentrations; when he analyzed a different Martian meteorite, he found that terrestrial amino acids had worked their way into the rock. McKay and his colleagues tried to avoid being fooled by contaminants by running the same tests on several Antarctic meteorites. They showed, among other things, that nothing was living inside ALH84001 at the time it was analyzed, that most (but not all) of the carbonates harbored isotopes associated with Mars and that PAHs were more concentrated inside the rock than on its surface. "These arguments are flaky and simplistic," Sears rebuts. "Weathering is a sloppy process. Things leach in, then leach out; they do not do the obvious."

The search for better answers is already under way. Researchers in many disciplines are scrambling to obtain pieces of ALH84001 and the 11 other meteorites identified as Martian. Zare says he wants to search for amino acids and to compare the carbon 13 in the PAHs with that of Mars—work that some feel he should have done before going public with his results. McKay has talked about obtaining electron micrographs of thin sections of the nanofossils, but such efforts will push the limits of present technology.

If the results hold up, some suspect it may be just the tip of the iceberg. "My impression is that bacterial life exists on planets around one in 10 stars, maybe more," speculates Stanley Miller of U.C.S.D. "I would view life on Mars not as a surprise but as a new frontier." —*W. Wayt Gibbs and Corey S. Powell*

ENVIRONMENTAL POLICY

FISH FIGHT

A struggle over resources in Indian waters comes to a boil

On August 7, Thomas Kocherry of the National Fishworkers' Forum (NFF) in India began an indefinite hunger strike; three days later fisherfolk around the nation followed with a blockade of harbors. The protesters were demanding the revocation of licenses granted to foreign vessels for fishing within the Indian maritime zone. The enormous capacity of these ships, they claimed, threatened the livelihood of more than eight million traditional fishermen.

This skirmish is only the latest in a decades-long war between the government and the fishermen of India. In 1970 the Ministry of Food Processing Industries subsidized the purchase of 180 high-tech trawlers to exploit waters deeper than 50 meters. These vessels dragged weighted, fine-mesh nets across the seafloor in search of shrimp, collecting entire ecosystems. The ravaged seabed lost its ability to nurture fish, and at least 350,000 tons of nontarget species, or "trash fish," were tossed out annually. By 1990 the shrimp grounds were overfished and most of the trawlers idle. Although the richer inshore waters were reserved for small boats, Harekrishna K. Debnath of the NFF asserts that the trawlers routinely encroached within 50 meters. The traditional sector saw its catch drop precipitously.

In 1991, when a wind of liberalization blew across India, the ministry invited the owners of foreign fleets to team up with Indian partners in joint ventures. Noting that the total catch in

FIELD NOTES

Building a Better T-Bone

I step out of my rental vehicle and get a lungful of the end product of bovine digestion. There are flies buzzing around and cattle as far as the eye can see, which is very, very far on the flat Texas Panhandle. I'm about 20 kilometers southwest of Amarillo, in the Randall County Feedyard, surrounded by about 60,000 cattle. There are Black Anguses, Brahmins, Limousines, Herefords, Charolais, Simmentals, Holsteins and countless intermixtures. Pretty soon, they'll all be steaks. But besides meat, the carcasses of these animals will yield a wealth of data perhaps only a cattle breeder could love.

GLENN ZORPETTE

Such information is the stock-in-trade of Theodore H. (Ted) Montgomery, who directs the Beef Carcass Research Center at nearby West Texas A&M University, as well as the associated Cattlemen's Carcass Data Service, a unit of the National Cattlemen's Beef Association. Montgomery is an ample, affable, plainspoken man, notwithstanding his Ph.D. and other credentials. (His first words to me are "You look like a Yankee from New York City.")

Montgomery notes that rigorous data collection already enables those who raise chickens and pigs to exert considerable control over the efficiency and consistency of meat production by tinkering with breeding, feeding and veterinary treatments. Beef cattle, however, lead a less sheltered and controlled existence, with several different owners over their (typically) 14- to 24-month lifetime. Such factors work against consistency—making one sirloin tender and another tough, even in the same supermarket on the same day.

Data collection can begin with the birth of a calf, when cowhands give the animal an ear tag and note the animal's sex, parentage, birthweight and any difficulties with the birth. Later, they record the weaning weight—how big the calf is when it stops nursing—which is a good indicator of how efficiently the animal converts food to edible tissue. Information is also collected on inoculations and illnesses. (The cattle industry being somewhat behind the technological vanguard, the information may be scribbled on a piece of feed sack before making its way to the computer.) The data could be useful in tracing any major maladies—such as the "mad cow" disease that has affected British cattle recently.

The "bottom-line" data, as Montgomery calls them, are recorded after the animal is slaughtered. They are used to compute the yield grade and the quality grade; the former comes from measurements of the carcass weight, the rib-eye area and the fat inside the body cavity. Those figures are fed into an equation that estimates the percentage of boneless primals—round, loin, rib and chuck—which tells the breeder which animals produced the highest percentage by weight of lean meat. A grade of one means that at least 52.3 percent of the animal's carcass weight became trimmed steaks and roasts; five means that less than 45.4 percent did. The quality grade is a more subjective measure of the meat's color, texture, intramuscular fat ("marbling") and the age of the animal's skeleton.

So far Montgomery's group collects such statistics on only one tenth of 1 percent of the 25 million or so "fed cattle" in the U.S. His long-term goal is to provide data to enough cattle breeders, feeders and others to make more of the steaks purchased in supermarkets and restaurants consistent, especially in tenderness and marbling. In the meantime, as a reality check, he fondly harbors a secret plan: to consume and compare 10 steaks (not all on the same day, of course) from each of several restaurants. One presumes that martinis might be necessary to make the experiments as realistic as possible. What some people won't do in the name of science. —*Glenn Zorpette*

IN BRIEF

Hormonal Relief from Alzheimer's
Evidence from animal research and from studies on postmenopausal women suggests that estrogen replacement might help fight Alzheimer's disease. The finding has prompted federal funding of clinical trials in 38 medical centers around the U.S. Researchers, led by Sally Schumacher of the Bowman Gray School of Medicine in North Carolina, will investigate the effectiveness of estrogen supplements in preventing the debilitating disease in women. (Preliminary evidence also suggests that supplements of testosterone, which is converted to estrogen in the brain, might delay or prevent the disease in elderly men.)

Garden of Earthly Stench
Anticipating a whiff of the notoriously malodorous *Amorphophallus titanum* plant, hundreds of people crowded the Princess of Wales Conservatory at Kew Gardens in London on July 31, only to have botanist Peter Boyce tell them they had missed the "treat." The meter-high Sumatran titan arum, which last flowered 33 years ago, reportedly emits an odor likened to a mixture of "rotting fish and burnt sugar with an overtone of urine"—but only when ready to be pollinated. Boyce claims the entire greenhouse reeked the night before, but the following day the crowd couldn't smell a thing.

AP/WIDE WORLD PHOTOS

Remarkable Sight
True or false: (a) Falling anvils are harmless. (b) Spinach makes you superhumanly strong. (c) Some animals can pop their eyes out of their head at will. If you answered false to (c), zoologists at the University of Michigan and Northern Arizona University have news for you. They recently photographed *Scolecomorphus kirkii* sticking its eyes out of its head. This limbless amphibian from East Africa performs the trick using protrusible tentacles on either side of its snout.

Continued on page 28

1989 was 2.2 million tons, whereas the projected yield was 3.9 million tons, the officials argued there was room for new fishing technology. A 1992 report by the Food and Agriculture Organization (FAO) stated, however, that most of the unharvested fish were noncommercial species, so that only 164,000 additional tons could be profitably caught. According to the NFF, 194 joint-venture licenses have been granted, many of them to trawlers. (The ministry did not respond to *Scientific American*'s requests for information.) The vessels are exempt from customs, sales and excise taxes, are allowed up to 95 percent foreign equity, and export 80 percent of their catch.

As before, the foreign vessels are instructed to stay in deep waters, but Debnath alleges that they do not. "The government says it is transfer of technology. But it is a transfer of crisis from their place to ours," he attests, referring to the overfishing of northern waters. In 1995 the government convened an expert committee to study the situation. By February the committee had handed down its recommendation—cancellation of all joint-venture licenses.

The actual damage done by the foreign ships is debatable. Sebastian Mathew of the International Collective in Support of Fishworkers points out that no more than 34 vessels have been sighted in Indian waters. Snelling R. Brainard of Consolidated Seafood Corporation in Boston, which holds licenses for 75 long-liners, explains that his fleet targets big-eye tuna in international waters off the southern coast. One major concern of the NFF is that the licensing of some foreign vessels makes it harder for the Indian coast guard to identify unlicensed ones. Purwito Martosubroto of the FAO concurs that the weakness of fishery surveillance systems in South Asia leaves room for poaching.

But also in dispute are the economics of the joint ventures. Each license costs a maximum of $700, amounting to no more than $136,000 in revenues from licensing fees. In contrast, the Seychelles islands earned $6.7 million in licensing fees in 1989, from 55 foreign vessels fishing in its waters. Because the foreign vessels can transfer their catch in mid-sea, there are no independent estimates of its value. The government claims, however, earnings of $11 million in annual royalties; in addition, unspecified amounts are remitted to the Indian partners. These partners, Debnath argues, help explain the policy: they reportedly include some very well-connected individuals. Intriguingly, the Indian partners for 125 out of 159 joint-venture vessels registered in 1994 were located in New Delhi—a landlocked city that is the seat of political patronage in the nation.

The class wars are exacerbated by one other aspect of industrial fishing. The by-catch from the foreign trawlers and liners is nowadays ground up to feed farmed shrimp, poultry or pigs—for consumption in the developed world.

ROBB KENDRICK *Aurora*

FISHERMEN IN INDIA complain of overfishing by high-tech vessels.

These trash fish used to be a primary source of protein for poor Indians. But because fishermen bring home less of the no-name fish, prices have increased fivefold in the past decade, putting this essential food out of reach of the poor.

At the root of all this trouble is the lack of a coherent policy for managing the fisheries. Although the Ministry of Food Processing Industries has issued the licenses, the Commerce Ministry is responsible for promoting marine products—and fisheries as a whole are run by the Agriculture Ministry. The government's figures are not credible to fishermen: Mathew contends that in 1990, after the protests first gathered strength, the Central Marine Fisheries Research Institute changed sampling techniques to come up with an unprecedentedly high catch in the state of Kerala. "One of the greatest contributions of the movement," he states, "is that it exposes the mess." *—Madhusree Mukerjee, with additional reporting by Sanjay Kumar in New Delhi*

In Brief, *continued from page 26*

Ultraviolet Radiation on the Rise

Since 1972 the amount of damaging ultraviolet rays reaching the earth's surface has risen dramatically, atmospheric scientists from NASA report. Data from the Total Ozone Mapping Spectrometer mounted on board the *Nimbus 7* satellite reveal that ultraviolet radiation has risen an average of 6.8 percent a decade in the Northern Hemisphere and 9.9 percent a decade in the South. Dwindling protection from the diminishing ozone layer is most likely to blame.

Choosing Abortion

About half of all U.S. women will opt to abort an unwanted pregnancy at some point in their life, a survey from the Alan Guttmacher Institute finds. These women, two thirds of whom intend to have children in the future, come from every age group, race, social class and creed—including those thought to oppose abortion. Catholic women, for example, had an abortion rate that was 29 percent higher than that of Protestant women. Six out of 10 women having abortions used protection.

A Fish Smarter Than a Man

The human brain uses 20 percent of the oxygen that the body does—way above the 2 to 8 percent common in other vertebrates. Now the diminutive African elephant-nose fish has nudged humans aside: its brain needs fully 60 percent of the oxygen that its body consumes. According to the *Journal of Experimental Biology,* the large ratio comes from the creature's being cold-blooded, as well as its enormous brain. Of the fish's body mass, 3.1 percent is brain—compared with 2.3 percent for a human.

JANE BURTON *Bruce Coleman Inc.*

Spinal Repairs

Researchers at the Karolinska Institute in Stockholm have devised a technique to repair severed spinal cords in rats. After cutting the spinal columns of two rats, they implanted tiny nerves in the gap and applied acidic fibroblast growth factor. Within six months new axons had bridged the spinal divide. Yet neither rat recovered coordinated locomotion, leaving open the question of how much the technique would help quadriplegic humans.

Continued on page 32

GEOPHYSICS

A SPINNING CRYSTAL BALL

Seismologists discover that the inner core rotates

Researchers are now probing what may turn out to be the most curious small body the solar system has yet presented for scrutiny: a globe the size of the moon that appears to be a well-ordered crystalline entity. This body is poised little more than 5,000 kilometers away, yet it is completely invisible. Located at the center of the earth, it is known simply as the inner core. Two seismologists have just shown that this strange crystal sphere is turning slowly within the rocky and liquid metal enclosure that keeps it all but hidden from scientific investigation.

Geophysicists realized decades ago that a solid inner core exists, but they knew precious little else about it. They believed the inner core and the liquid shell surrounding it were made largely of iron, yet other features of the heart of the planet remained enigmatic.

But during the 1980s, seismologists examining earthquake waves that pierce the inner core made a startling find. Rather than being "isotropic" (the same in all directions) in its physical properties, the inner core proved to be somewhat like a piece of wood, with a definite grain running through it. Waves traveling along the planet's north-south axis go 3 to 4 percent faster through the inner core than those that follow paths close to the equatorial plane.

Geophysicists have struggled to explain why this grain (or "seismic anisotropy") should exist. The leading theory is that at the immense pressures of the inner core, iron takes on a hexagonal crystal form that has inherently directional physical properties. Some force apparently keeps the hexagonal iron crystals all in close alignment.

Lars Stixrude of the Georgia Institute of Technology and Ronald E. Cohen of the Carnegie Institution of Washington note that whatever texturing mechanism operates to form the anisotropic grain of the inner core, it must be almost 100 percent efficient. Otherwise the seismic anisotropy would not be as large as measured. "The very strong texturing indicated by our results suggests the possibility that the inner core is a very large single crystal," they boldly stated in a article published last year in *Science.*

The seemingly absurd notion—that a body the size of the moon could be just one big crystal—is less ridiculous than it sounds. The central core may have grown gradually to its present size as liquid iron at the bottom of the outer core solidified and attached itself to the inner core. That process would occur exceedingly slowly, with few outside disturbances—just like the conditions that favor the growth of large crystals in a lab. Slow solidification of iron might

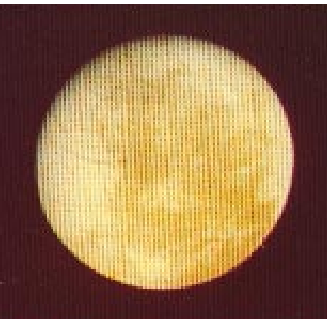
WORLDSAT INTERNATIONAL/J. KNIGHTON & BUCKMINSTER FULLER INSTITUTE/SCIENCE SOURCE

***SEISMIC RAYS** traveling from Novaya Zemlya* (a) *to Antarctica* (b) *pass through the earth's center—as this 20-sided globe shows when assembled.*

In Brief, *continued from page 28*

JET PROPULSION LABORATORY

An Ocean on Jupiter's Europa?
Scientists have long wondered whether Europa, a moon of Jupiter, harbors a liquid ocean beneath its icy crust. Fuzzy pictures from the *Voyager* spacecraft revealed surprisingly few craters; perhaps upwelling water filled them in.



If so, conditions might have been compatible at some point with the existence of life. Such speculation got a boost in August when images retrieved from *Galileo* showed a surface riddled with filled cracks similar to those seen in Earth's polar ice floes. Closer flybys in December and February will gather more detailed evidence. For more images, see http://www.jpl.nasa.gov/releases/europh20.html

FOLLOW-UP

Software Gone Awry
Investigators appointed by the European Space Agency reported in July that a software bug brought down the new $8-billion *Ariane 5* rocket, which exploded in June and was supposed to have a major role as a platform for space exploration. The team found that an unused, unnecessary routine in the software controlling the rocket's engines was ultimately responsible for the crash. Apparently, further testing of this guidance software might have caught the glitch. (See September 1994, page 86.)

Halt, Aquatic Interloper
Ships currently change their ballast water at sea to prevent species—such as the zebra mussel—from upsetting marine ecosystems that they are not native to. But a recent National Research Council (NRC) report found that the technique is dangerous because it can destabilize ships. Further, the practice is not completely effective, as some organisms remain glued to the bottom of the tanks. The NRC recommends instead that ships filter their ballast water before it is taken in or else treat it with heat or biocides to kill organisms before it is discharged. (See October 1992, page 22.)

—Kristin Leutwyler and Gunjan Sinha

SA

have allowed the inner core to grow quietly for billions of years, becoming in the end a gargantuan single crystal, more than 2,400 kilometers across.

But slow crystal growth does not explain the alignment of the inner core's axis of anisotropy with the earth's rotation axis. The process also fails to account for the seismological evidence that the anisotropic grain is not uniform. Xiaodong Song, a seismologist at Columbia University's Lamont-Doherty Earth Observatory, says that the anisotropy at the top of the inner core "is likely to be very weak—less than 1 percent." So it would seem that some other physical mechanism must keep the deeper hexagonal iron crystals in line.

Although several explanations have been proposed, the most reasonable theory calls on internal stress (generated by the earth's rotation), which is strongest along the north-south axis. Thus, the hexagonal iron that constitutes the inner core could crystallize (or recrystallize) in parallel with the spin axis—as do the mica flakes that form in rocks squeezed by tectonic forces. Internal stress could thus keep the inner core's grain well aligned with the spin axis—perhaps too well aligned. It turns out that the grain of the inner core is not exactly parallel to the earth's rotation axis: in 1994 Wei-jia Su and Adam M. Dziewonski of Harvard University reported that the axis of anisotropy is in fact tilted by about 10 degrees.

At about the same time, Gary A. Glatzmaier of Los Alamos National Laboratory and Paul H. Roberts of the University of California at Los Angeles were working on a computer simulation of how the earth's magnetic field operates. Although the tumultuous churning of the outer core's liquid iron creates this magnetic field, Glatzmaier and Roberts found that the influence of the solid inner core was needed for proper stability. Their modeling also indicated that the inner core may be shifting slowly eastward with respect to the earth's surface, impelled by persistent fluid motions at the base of the outer core.

Reading that result and realizing that the seismic grain of the inner core was not wholly aligned with the spin axis,

ANIMAL BIOLOGY

ON THE TAIL OF THE TIGER

Is a Tasmanian legend still wandering the bush?

Sixty years ago this September, Benjamin—renowned for being the last Tasmanian tiger—died at the zoo in Hobart, Australia. Legends about the creature have not died, however, and debate about *Thylacinus cynocephalus* (in Latin, "pouched dog with a wolf's head") is quite alive. It seems that Tasmania has its own version of the Loch Ness monster.

Several months ago Charlie Beasley of the Tasmanian National Parks and Wildlife Service reported seeing a creature "the size of a full-grown dog. The tail was heavy and somewhat like that of a kangaroo." A decade earlier respected wildlife researcher Hans Naarding said he saw a tiger 30 feet from his vehicle. "It was an adult male in excellent condition with 12 black stripes on a sandy coat," he wrote in his report.

No irrefutable photographs, fur or plaster casts of tracks have provided confirmation, but such tantalizing sightings have helped make the tiger, also called the thylacine, into a Tasmanian obsession. Images of the two-foot-high, shy, nocturnal predator can be found on city seals, traffic signs, T-shirts and beer bottles. The parks service receives notice of dozens of sightings every year; a ranger systematically tallies and evaluates all of them.

Part of the animal's mystique is the nature of its demise. The world's largest marsupial carnivore disappeared recently enough that hunters remember killing it for the $2 bounty. The thylacine was not protected until two months before Benjamin died. "There's almost a guilty conscience about its disappearance," says Mark Holdsworth of the parks service. His colleague Steve Robertson agrees: "It's the idea of redemption. We killed it off, but now it's back."

Sheep raisers who settled on the island of Tasmania in the early 1800s considered the thylacine a threat to livestock. Van Diemen's Land Company first offered bounties on tiger scalps, and the royally chartered company's records show thousands of thylacines killed. The tiger population, low to begin with, was further diminished by an epidemic of a distemperlike disease in the early 20th century, says Robert H. Green, a tiger buff and former curator of the

Song and his colleague Paul G. Richards decided to look for seismic evidence that the canted grain of the inner core was indeed swiveling around relative to the rest of the earth. Their idea was to examine seismic recordings of waves that traveled through the inner core decades ago and to compare them with more recent signals. If the core rotates, the time it takes these waves to traverse the inner core should change systematically. The challenge was to find recordings of seismic waves that passed close to the north-south axis and to devise a way to compare them precisely enough to detect the slight differences that result from less than 30 years of change (the span of seismic records). But they solved both problems and found evidence of rotation quite quickly. "Everything happened in three weeks," Richards notes.

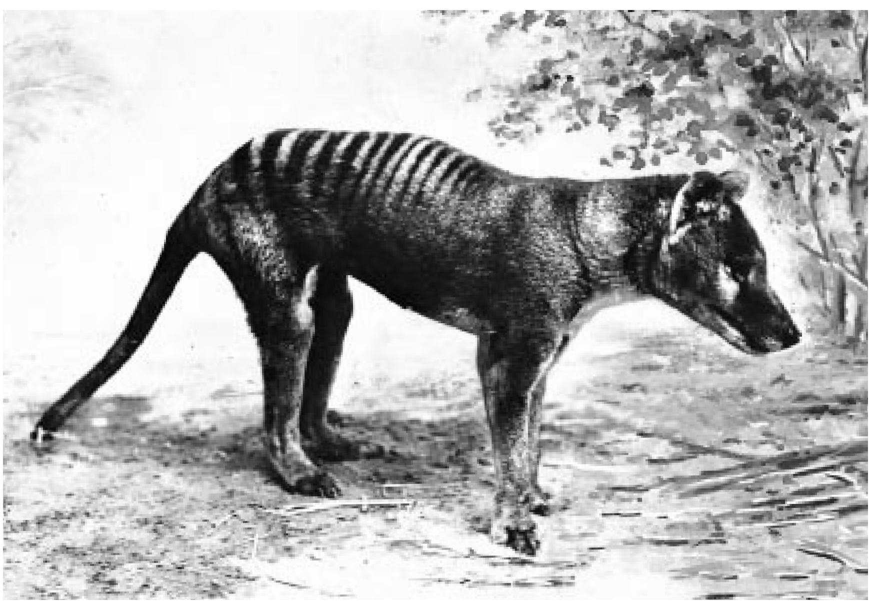
The team started by looking at seismic traces recorded in Antarctica caused by nuclear tests made at Novaya Zemlya in the Soviet Arctic. Traveling from one pole to another, these seismic waves penetrated the core. Examining data that had been collected over the course of a decade, Song and Richards observed what appeared to be a change of two tenths of a second in the travel time of the waves that passed through the inner core as compared with those that just skirted it. They then scrutinized a set of seismic recordings made in Alaska of earthquakes that occurred between the tip of South America and Antarctica and found similar results to confirm that the inner core was in fact moving. They presented their discovery in the July 18 issue of *Nature*.

Although the detection of inner core movement was itself a remarkable experimental achievement, the correspondence in direction and speed of this motion (eastward at a degree or two a year) with the predictions of Glatzmaier and Roberts was more remarkable still. But geophysicists are far from having figured out the workings of the inner core. No one yet understands for sure what causes its anisotropic grain. Nor can scientists explain why the anisotropy should be tilted. According to Glatzmaier, "It's anybody's guess at this point." *—David Schneider*

Queen Victoria Museum in Launceston.

Green is convinced that some tigers remain and claims their population is actually increasing. He says the animals are not seen, because they "live in the bush, where they can get all the tucker [food] they want." Green adds that the island's large size and impenetrable terrain provide plenty of room to hide. And he blames the lack of concrete evidence on the Tasmanian devil—a marsupial version of a jackal. Devils devour all the flesh, hair and bone they come across while scavenging.

Playing devil's advocate is Eric R. Guiler, retired dean of science at the University of Tasmania and author of several books on the region's wildlife, including



AMERICAN MUSEUM OF NATURAL HISTORY

TASMANIAN TIGER,
the world's largest marsupial carnivore, may not be extinct, say some observers.

one coming out soon on the thylacine. He holds that the tiger's historic habitat was destroyed by humans and discounts most urban and suburban sightings; the observers, Guiler says, "are quite mad, you know." He also argues that if thylacines existed, there would be some hard evidence, such as road kills.

Nevertheless, Guiler admits to the possibility of the thylacine's survival. In the early 1960s he himself found what looked like tiger tracks at the Woolnorth sheep station on the northwest peninsula. (If the thylacine does survive there, it is having the last laugh: Woolnorth is the only sheep station still owned by Van Diemen's Land Company.)

For his part, Holdsworth of the parks service finds large-scale searches for the tiger frustrating. He thinks the focus should instead be on protecting existing endangered species. There is only one benefit of the misplaced public interest in the Tasmanian tiger, Holdsworth maintains: "The thylacine is a good reminder of extinction and endangerment. We're still making the same mistakes."

—Daniel Drollette in Tasmania

METEOROLOGY

HURRICANE HULLABALOO?

Atlantic cyclones prove to be in decline

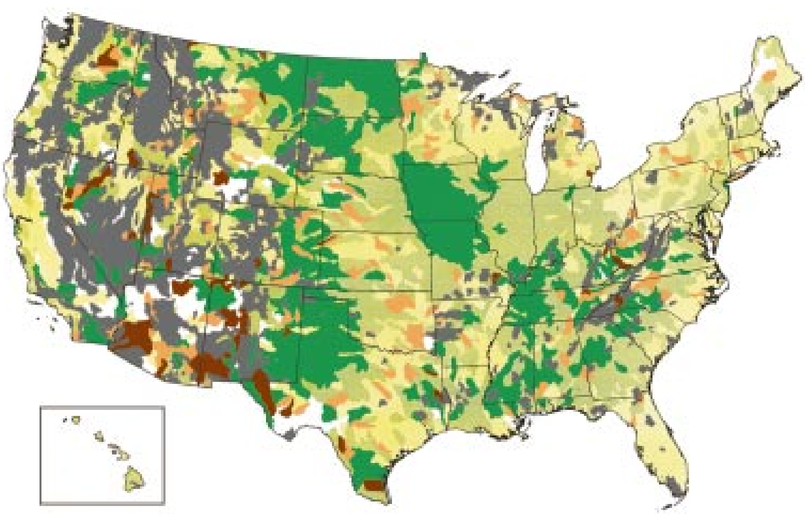
In a 1990 publication entitled *Windstorm,* Munich Re, one of the world's largest reinsurance companies (firms that provide coverage to other insurers), stated that tropical cyclones

BY THE NUMBERS

Soil Erosion of Cropland in the U.S., 1982 to 1992

America's position as the world's leading exporter of grains depends largely on a layer of topsoil typically less than a foot thick. This layer usually erodes but can be replenished through the accumulation of organic matter, the process of weathering, the activity of earthworms and microorganisms, and other means. As a rule of thumb, it takes 30 years to form an inch of topsoil—and much longer in areas of little rainfall. An inch of topsoil, however, can be lost in less than a decade of such improvident farming practices as excessive grazing, monocropping and destruction of ground cover. Heavy and frequent rain can wash away topsoil, particularly where vegetation is sparse and where the ground slopes. Wind erosion is especially destructive during prolonged droughts, such as that of the 1930s, which produced the infamous dust bowl in parts of the Great Plains.

The devastation of the dust bowl led to the creation of the Soil Conservation Service, recently renamed the Natural Resources Conservation Service. Since 1982 the NRCS has systematically measured erosion and other soil characteristics for the entire country in its National Resources Inventory. The map, created from this database, shows that in most areas with extensive cropland, there has been an improvement or at least no increase in average erosion rates. In 1992 wind and water caused tolerable levels of erosion on 68 percent of cropland, an improvement of 21 percent over 1982. Some of the improvement was the result of crop rotation and better tilling methods but more important have been the efforts of the Conservation Reserve Program, in which the government pays farmers to remove environmentally sensitive cropland from use.



SOURCE: National Resources Inventory, Natural Resources Conservation Service, U.S. Department of Agriculture

CHANGE IN TOPSOIL (TONS PER ACRE PER YEAR)

- INCREASE OF MORE THAN 3
- INCREASE OF 0.5 TO 3
- LITTLE CHANGE (–0.5 TO 0.5)
- DECREASE OF 0.5 TO 3
- DECREASE OF MORE THAN 3
- NO CROPLAND OR RESERVE LAND IN 1982 AND 1992
- 95 PERCENT OR MORE FEDERAL LAND

RODGER DOYLE

Nevertheless, some cropland in the eastern three fifths of the country was eroding excessively in 1992—most notably in southern Iowa, northern Missouri, parts of western and southern Texas, and much of eastern Tennessee and the Piedmont region. (Still, all these areas were averaging less erosion in 1992 than they were in 1982.)

The Great Plains, a region of mixed crop- and rangeland, remains one of the most environmentally unstable areas in the U.S. A recent report by Daniel Muhs of the U.S. Geological Survey suggests that large areas of sparsely vegetated land in this region—stretching from the Nebraska Sand Hills to the Monahans dune area in northeastern Texas—could expand and coalesce into a vast Sahara-like desert if conditions became sufficiently arid. Something like this apparently happened during the severe drought of the 1860s. The area recovered only to be threatened again, most recently in the 1930s. Mercifully, the rains came, and the threat receded. *—Rodger Doyle* "will increase not only in frequency and intensity but also in duration and size of areas at risk." That notion echoes throughout much media commentary on the effects of global warming, and just last year the U.S. Senate's task force on funding disaster relief reported that such hurricanes "have become increasingly frequent and severe over the last four decades as climatic conditions have changed in the tropics." But this worrisome conclusion has recently been challenged by four scientists. They looked carefully at the long-term trend in the occurrence of Atlantic hurricanes and found that these storms have become less threatening over the past half century.

GREG LOVETT *Palm Beach Post/Sygma*

STORM DAMAGE (like that caused by Hurricane Hugo) is not a good measure of meteorological trends.

Christopher W. Landsea, a meteorologist with the National Oceanic and Atmospheric Administration Hurricane Research Division, and three colleagues analyzed the history of hurricanes in the North Atlantic Ocean, the Gulf of Mexico and the Caribbean Sea. They focused on these regions because their weather patterns have been subject to aerial reconnaissance since World War II, whereas reliable records for other tropical seas extend back only to the late 1960s. Their results appeared in the June 15 issue of *Geophysical Research Letters.*

What these meteorologists found was a definite decline in the frequency of intense Atlantic hurricanes. They also observed a modest slackening in the highest winds sustained by each year's most intense hurricane, although that slight decrease may not represent a statistically significant trend.

With this evolution toward more benign conditions, why do so many in the eastern U.S. perceive the situation as worsening with time? According to Landsea and his colleagues, the reason is straightforward: the amount of damage from hurricanes inevitably grows even if the storms are slowly moderating simply because population and property development are on the rise along many stretches of the Atlantic coast. As Landsea, himself a new resident of Florida, aptly notes, "Miami is a great example of that." —*David Schneider*

PHYSICS

UNICORN HUNTS?

Searching for monopoles, free quarks and antimatter

Bigfoot and other legendary creatures remain popular in part because they could exist—their presence does not necessarily violate any natural law, and their discovery would cause a sensation. The same can be said for long-sought, primordial beasts of physics. They need not exist, and there are reasons to suspect they don't. But despite the unlikelihood, some researchers find them too irresistible to pass up.

The search for particles called magnetic monopoles is one example. Rather than having north and south poles, magnetic monopoles would have only one pole and could weigh as much as a few micrograms; they could have emerged during the big bang from early defects in space. But hundreds of searches in this century have come up empty. The most recent disappointment came last year. Hunmoo Jeon and Michael J. Longo of the University of Michigan sifted through 112 kilograms of meteorite, hoping to locate some of the primordial stuff trapped within. "It's getting harder and harder to believe we're going to find them," Longo admits. The best bet may be underground neutrino detectors, which can also record any monopoles zipping through. But if they don't appear, there is no cause for any theoretical anxiety. Modifications to the big bang theory (most prominently, inflation) obviate the need for monopoles.

The same can be said for free quarks. Quarks are the fundamental building blocks of matter, combining into pairs or triplets to form protons, neutrons and other subatomic particles. They also remain forever trapped within the particles they create. But some physicists speculate that despite the strong arguments for quark bondage, free quarks might have formed during the big bang (a few moments after monopoles) and managed to remain unfettered. But three decades of searching have proved fruitless. The late William Fairbank of Stanford University reported positive results in the 1980s, but his work could not be reproduced. The lack of success and, subsequently, funding has forced physicists galore to drop out of the chase.

Only Martin L. Perl of Stanford remains. Relying on a variation of the famous Millikan oil-drop experiment, Perl sends micron-size droplets between two charged plates; the plates deflect the droplets depending on their charge. Quarks carry a 1/3 or 2/3 charge, so a free quark might give a droplet an additional fractional charge. Searches begin next year using ground-up meteorites.

Perl knows finding free quarks is a long shot. "It's the kind of thing a ten-

ANTI GRAVITY

Just Say NO

Nitric oxide, former molecule of the year as pronounced by the journal *Science,* has not just been resting on its laurels. For one thing, it's been spewing out of car exhausts, inadvertently messing up at least one laboratory's research and raising the intriguing possibility that NO is better for you than Nancy Reagan could ever have dreamed.

Pharmacologists at the Free University of Berlin kept getting strange results in their experiments with the enzyme guanylyl cyclase, which is important in the biochemistry of lung tissue. Knowing that guanylyl cyclase is a receptor for NO, the researchers, led by Doris Koesling, began to wonder if their samples were being exposed to some NO wafting in from outside. So Koesling took the lab on the road and measured guanylyl cyclase activity at a site 30 feet from one of the city's main highways. The enzyme's activity shot up as much as six times when measurements showed an atmospheric NO concentration of 550 parts per billion, according to Koesling's recent report in *Nature.*

In the lung, NO stimulates guanylyl cyclase, which causes a chain of biochemical events that ultimately relaxes smooth muscle, making it easier for blood to flow. Koesling says the enzyme's response to atmospheric NO furthers the case for using this compound as a treatment for lung disorders. In 1993 a *New England Journal of Medicine* paper showed that inhaling NO helped people with pulmonary hypertension and acute respiratory failure.

MICHAEL CRAWFORD

Guanylyl cyclase's sensitivity to NO—no matter its origin—raises provocative questions for those persnickety breathers who prefer smooth, rather than chunky, air. Could people who seek out the pure air of the southwestern desert save plane fare and content themselves with two weeks at the airport taxi stand? Might New Yorkers congregate outside the gaping maw of the Lincoln Tunnel during the evening crush to suck in life-giving exhaust fumes? Are some urban dwellers with lung conditions already benefiting unwittingly from polluted air?

"It cannot be ruled out," Koesling says. (Stop here when you read this on the air, Mr. Limbaugh.) But don't take NO for an answer just yet. "On the other hand," she continues, "these effects are going to be counteracted by the other toxic constituents of air pollution." At last report, carbon monoxide, sulfur dioxide, ozone and nitrogen dioxide, other major pollutants in the air, were still no NO's. —*Steve Mirsky* ured professor can do. A young person wouldn't get money from funding agencies," he notes. "It would wreck their careers." Winner of the 1995 Nobel Prize for Physics, Perl does not have that worry, although he plans to abandon the pursuit if nothing turns up in the next four years.

Leveraging his own prize, Samuel Ting of the Massachusetts Institute of Technology has initiated an unlikely hunt, too—for primordial antimatter. Created during the big bang (shortly after free quarks), it might exist in distant pockets of the cosmos, producing an oppositely charged, complementary universe. But no one has ever seen anything resembling celestial antiobjects. (Antiparticles exist in cosmic rays, but they emerge as by-products of collisions of particles in space.) Theorists postulate that a slight asymmetry in the laws of physics early in the big bang favored the production of matter over antimatter. That asymmetry, observed in experiments in particle accelerators, has convinced many that bulk antimatter is not around.

Such thinking amounts to little more than theoretical prejudice, claims Ting, who has organized an international effort to loft an antimatter detector into orbit. The instrument consists of a giant permanent magnet that would deflect charged particles to detectors. The device, called the alpha magnetic spectrometer, or AMS, will be 100,000 times more sensitive to antimatter than current technologies are. Tests begin on the space shuttle in May 1998; full-time operations are scheduled to start on the International Space Station in 2001. "For the first time, we'll have a particle detector big enough and up long enough to cleanly distinguish particle from antiparticle," says AMS project member Steven P. Ahlen of Boston University.

Not that it matters, says Gregory Tarlé of the University of Michigan and a critic of AMS. If primordial antimatter existed within the device's detection range of about one billion light-years, then certain clues would be evident, most notably in the number of photons. The universe would literally be a brighter place. Besides, if any antimatter exists, the magnetic field between galaxies will keep antiparticles from reaching the detector, Tarlé concludes. "Primordial antimatter is not going to be seen," he predicts. "It's like looking for monkeys on the moon." A somewhat pricey trip to the zoo as well: $20 million, not including labor and launch costs.

In Tarlé's opinion, politics, not science, spawned AMS. The Department of Energy, the project's sponsor, wanted to keep Ting busy after Congress killed the Superconducting Super Collider, Tarlé says. The National Aeronautics and Space Administration, too, stood to benefit: Ting's project would be used to fend off criticism that the space station has little scientific merit.

"If all AMS was going to look for was antimatter, then maybe it's not worth doing," Ahlen concedes. The project is worthwhile, he argues, because AMS has secondary tasks: it will investigate the origin of cosmic rays and the dark matter thought to permeate the universe.

The quest for exotica stems partly from the state of particle physics. "We're in a quiet, stagnant period," Perl comments, likening the time to optics in the 1930s. Only after masers and lasers appeared in the 1950s did the field boom. "I believe there will be breakthroughs," he adds. "When, I don't know." So don't hold your breath. *—Philip Yam*

Television by Any Other Name

European governments are discovering the Internet, and they aren't too sure they like it. The Net is a hotbed of free speech, from the brilliant to the vile. But even at the best of times, European commitment to free speech has never been absolute. There is no First Amendment on this continent. Many countries have passed laws against racist and other "hate speech"; many also have privacy laws that restrict what can be reported about public figures. So when confronted with millions of people from around the world speaking whatever happens to be on their minds, the first instinct of many European public servants is to try to get a grip.

For most Europeans, this is akin to a stranglehold. It seems to mean slotting the Net into the regulatory regimes established to control television and radio broadcasts. Because spectrum has traditionally been limited, governments have assumed a duty to determine content in a way that will provide the greatest good for the greatest number. For governments worried about neo-Nazis, pornographers, prostitutes, bomb makers and other downright revolting free speakers now popping up on the Net, extending such regulations seems a very tempting option. These governments are gradually laying a patchwork of contradictory—and sometimes senseless—rules.

Since last spring, the European Commission has classified the World Wide Web as a broadcast medium for the purposes of the ironically named "Television without Frontiers" directive. These regulations require European broadcasters to show a minimum percentage of European-made television shows, films and the like. So far the commission has kept the directive sufficiently laced with loopholes that it has had little real impact. But should anyone try to enforce it, the commission would have to determine the Web equivalent of hours of broadcast television as well as how to ensure minimum levels of European content. Not an easy task. Even the most chauvinistic European might object to this browser error message: "Not available: American content quota exceeded."

France, meanwhile, will soon have to wrestle with such questions in earnest. In June telecommunications minister François Fillon set up a new regulatory body, the Conseil Supérieur de la Télématique (CST), to lay down rules for both Minitel and the Internet. So long as Internet service providers follow the recommendations of the CST about what should and should not be available, they are absolved from any potential liability for the material carried on their sites. The first challenge for the CST, though, is to come up with a workable definition of what banning a site or a newsgroup might mean.

The Internet allows national borders to be leapt with the click of a mouse, yet the CST's powers are limited to France. The CST could certainly stop anybody from storing a Web site on a disk drive located in France. But that wouldn't keep the user from accessing the same material from a computer outside the country. The CST could, in turn, demand that Internet service providers block direct communications with foreign computers known to carry offensive material. But that wouldn't stop communications routed via a third computer. Strong encryption is illegal in France. Yet even without strong encryption it is not feasible for the CST to review for banned content all the packets coming into or out of the country. So what constitutes "off the air"?


DAVID SUTER

In Germany the government is taking a more direct approach—or would be if the federal government there did not disagree with the various state governments, provoking a minor constitutional crisis. The federal authority admits that it can do little by itself and has proposed international regulation, perhaps by UNESCO or some other United Nations organization. The state governments want to have a go at it anyway.

These provincial bodies already license broadcasters and have proposed a law that would require operators of Web sites to register with them as well. An early draft of the law requires suppliers of "media services" in which texts are diffused on a periodic basis to give the authorities the name of a responsible German resident who would be, among other things, "subject to unlimited criminal liability." That provision would certainly provide someone to blame if the law's ban on hate speech, images of death, exhortations to violence, and material that might expose minors to "moral danger" is breached. Still, it doesn't address the question about what to do with the millions of non-German-resident newsgroup participants and Web site providers who neither know about the legislation nor care.

Britain seems to prefer regulation with a wink and a nod. In early August, Scotland Yard met with the Internet Service Providers Association (ISPA), and told them that it had a list of about 150 newsgroups that contain pornography. It told the providers that they could remove the groups voluntarily or face prosecution. As of mid-August, the ISPA had proposed that it might work with the police to maintain a list of banned newsgroups. If there is to be censorship, objectors argue, then it should be a judge who decides what is pornographic.

Ultimately, it may be the contradictions in Europe's Internet regulations that save the continent from its attempts to muffle the newest, freest medium. Although the European Commission is no friend to the Internet—or to free speech, for that matter—it is certainly the sworn enemy of contradictory regulations that might hinder the free flow of goods and services. The Internet is potentially creator, provider and purveyor of just the kinds of international services it is the commission's duty to encourage. Doing so may yet require the commission to cut the tangles of red tape with which European governments threaten to bind the Net. In the meantime, Europeans have starker choices when looking at the sheer cluelessness of their governments' approach to new media: laugh, cry or fight. —*John Browning in London*

CANCER THERAPY

"X" (RAYS) MARK THE TUMOR

A technology used to develop nuclear weapons may lead to an effective cancer treatment

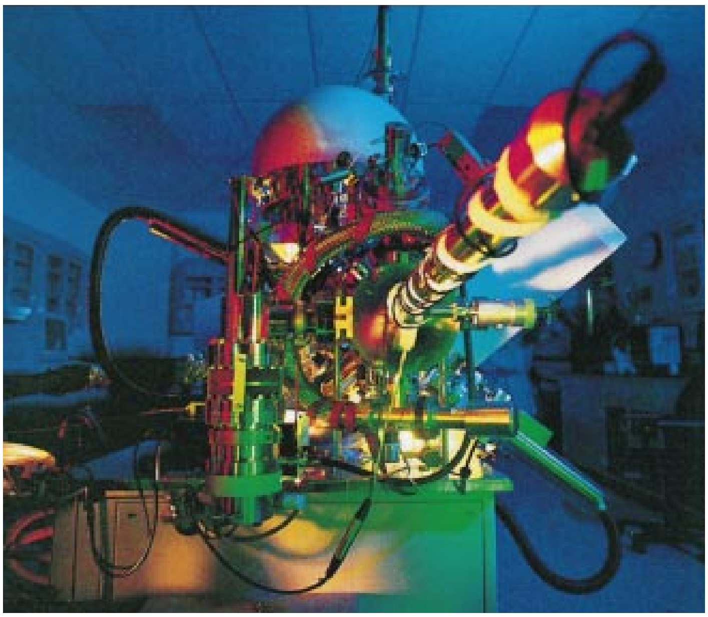
One of the most seductive propositions in cancer therapy research is that the body's immune system may somehow be stimulated or trained to fight more effectively and even to destroy the cancerous tumors that can spread throughout the body. From humble beginnings more than a century ago, work on such treatments, which fall under a broad classification known as immunotherapy, has lately benefited from revolutionary advances in the understanding of the immune system.

Now, in what is surely one of the most unusual twists in immunotherapy, researchers in Amarillo, Tex., have taken an instrument originally used in the development of nuclear weapons and applied it to a key immunotherapeutic challenge: boosting the body's immune response to a tumor. They say the technique could be used against any adenocarcinoma, a category that includes the most deadly cancers, such as those of the breast, prostate, lung, colon, liver and ovary.

At the heart of the experiments is a technique called x-ray photoelectron spectroscopy (XPS). Using this device, researchers bathe a sample substance in x-rays. Atoms in the sample absorb the x-ray photons and then eject electrons. Measurements of the kinetic energy of these photoelectrons indicate which atoms are present at the surface of the molecules in the sample. In other words, XPS allows investigators to characterize the surface of the molecules in a certain substance.

The team unites scientists from the Texas Tech University Health Sciences Center, the Veterans Affairs Medical Center in Amarillo and the Mason & Hanger Corporation. Under contract to the U.S. Department of Energy, Mason & Hanger runs the Pantex plant, a sprawling complex northeast of Amarillo where the U.S. assembled most of its nuclear weapons. Mason & Hanger scientists used their $700,000 x-ray photoelectron spectrometer to improve the way that conventional high explosives were united to substances known as binders, which enabled the explosives to be molded into the necessary shapes.

In the cancer research, on the other hand, the scientists are studying a substance called mucin, a component of mucus (mucin is what makes mucus slippery). Mucin is a widely studied and fairly well understood tumor-specific marker; these markers are proteins that are distinctly altered when they are produced by cancerous cells. When created by a healthy cell, a mucin molecule consists of a protein core surrounded by a carbohydrate (sugar) coating. Ordinarily, the protein makes up 20 percent of the mass of the molecule, and the coating makes up the rest. When manufactured by a cancerous cell, however, the mucin molecule partly or completely lacks its carbohydrate coating; this absence lets the body's immune system recognize the molecule as an antigen and to launch an immune response against it. Unfortunately, the response triggered by an initial exposure is insufficient to eliminate the cancerous cells associated with the aberrant mucin.



ERIC O'CONNELL

PANTEX MACHINE, *x-ray photoelectron spectrometer, is shedding light on cancer.*

By subtly altering such mucin molecules and testing the affinity of isolated (laboratory) antibodies and white blood cells for them, the Amarillo team was able to get an idea of how mucin interacts with the immune system. Specifically, workers used XPS to study the surface of the molecule, which let them begin figuring out the relation between the molecule's coating—or lack thereof—and immune response.

They then used this information to create mutated mucin core proteins, which were exposed to the white blood cells and antibodies. Antigens associated with some of these mutated mucin molecules initiated cellular immune responses more vigorous than those associated with unmutated molecules. In one startling assay, a mutated mucin protein resulted in the production of 30 times more tumor-specific white blood cells than did an ordinary mucin core in the same period. "People have tried to do this in the past, but the resolution hasn't been there," says Kenneth E. Dombrowski, a biochemist at the Veterans Affairs Medical Center and a professor at Texas Tech University. "Now we're seeing things that haven't been seen before."

To add more detail to their picture of mucin and its interactions with white blood cells and antibodies, the Amarillo researchers are collaborating with scientists at Duke University, who are using nuclear magnetic resonance and mass spectroscopy techniques to determine the structure and size of the mucin molecule. A molecule's structure, size and surface features all seem to play a role in the intensity of the immune response triggered by the molecule, Dombrowski notes.

Treatments stemming from these findings could take one of at least two forms.

Mutated mucins could be used outside the body to stimulate the production of tumor-specific white blood cells, so that there are more of them available to destroy the cancerous cells; these white blood cells could then be put back inside the body to reproduce and to battle the tumor. Further in the future, a genetic vaccine might be engineered to enter cells and induce the cells' own protein-making machinery to make the desired mutated mucin, which would stimulate the heightened immune response directly. Because the mutations needed to evoke the immune response are the same regardless of malignancy, the same vaccine would work for essentially any adenocarcinoma.

While cautioning that it may be several years, at least, before trials can be conducted in human patients, researchers are also quick to note the advent of what appears to be a promising union. "The marriage of XPS and protein biochemistry is in its infancy," Dombrowski asserts. —*Glenn Zorpette*

BIOTECHNOLOGY

PICKING ON COTTON

Engineered crops need fewer pesticides but may foster resistance

U.S. cotton growers who had hoped that gene technology would relieve them of the need to spray their crops suffered a disappointment this year. In many southern states, fields of cotton engineered to produce their own supply of a naturally occurring insecticide—*Bacillus thuringiensis* toxin, or *Bt*—have succumbed to an unusually severe attack of the cotton bollworm.

Farmers have had to dust off their chemical sprayers and treat the infestation in the old-fashioned way. The bollworm's stand against the insecticide has renewed concerns that the rapid adoption of *Bt*-producing crops could encourage the evolution of *Bt* resistance among pests. Mindful of that alarming prospect, the Environmental Protection Agency recently restricted sales of a new *Bt*-producing corn to states that do not produce cotton. The combination of *Bt* corn and *Bt* cotton is worrisome because several pests migrate between the two plants, making it all the more plausible that having both crops in proximity might in some circumstances in fact speed the development of resistance.

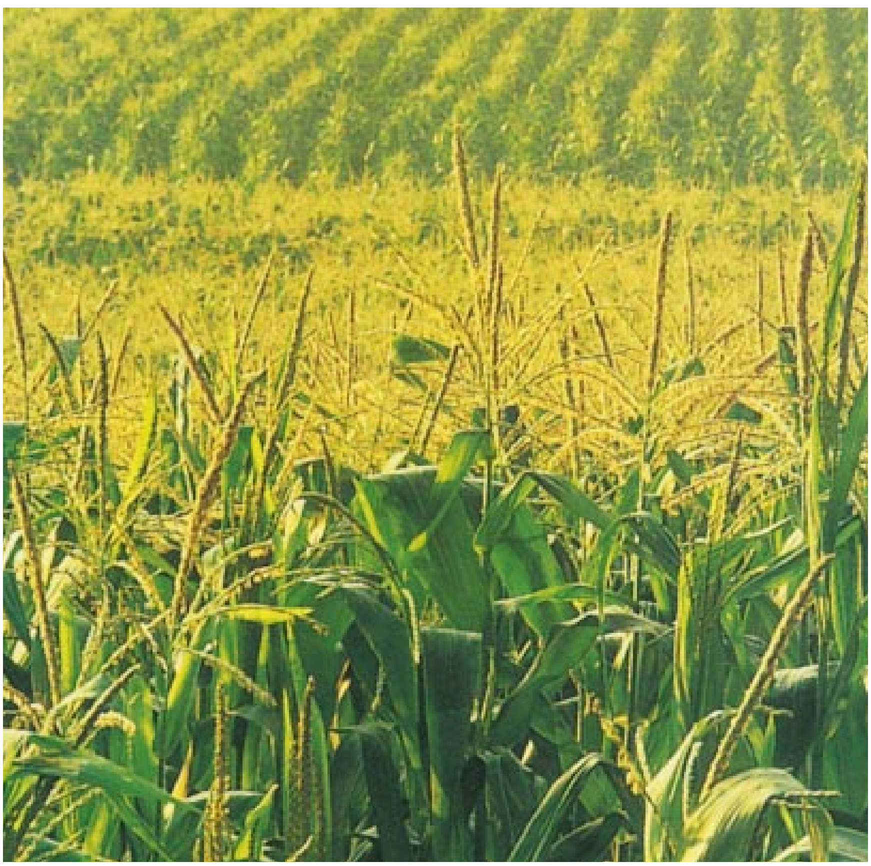
According to Monsanto, the developer of the *Bt* cotton, the majority of the two million acres of the crop planted this year have not required extra spraying. Randy Deaton, Monsanto's scientist in charge of the product, estimates it is probably killing the same proportion of bollworms as it did during testing, but because bollworm numbers are in some areas the highest they have been in 20 years, the insect survivors are more noticeable. Moreover, Deaton points out, *Bt* cotton is still highly effective against another pest, the tobacco budworm, so farmers who planted the high-tech crop are still likely to come out ahead. Deaton maintains there is no evidence that *Bt* cotton, which is sold by Delta and Pine Land Company under license, has failed to produce the expected amounts of the toxin, a situation that might foster resistance.

That assurance does not satisfy Margaret Mellon of the Union of Concerned Scientists (UCS), who argues that the bollworm's incursion into *Bt* cotton fields means the resistance management plan that Monsanto accepted as a condition for approval of its product has failed. The UCS has accordingly asked the EPA to suspend *Bt* cotton sales.

The agency sees no reason so far to justify such a move, and researchers agree resistance is, in any event, unlikely to occur for several years. Yet the severe restrictions that the EPA has placed on sales of a new, high-*Bt*-producing corn plant it approved in August indicate that concerns about resistance may ultimately limit cultivation of *Bt* crops. The *Bt* corn, sold by Northrup King and also based on Monsanto technology, cannot be sold in nine southern states and parts of four others. (The company is currently appealing the restriction.)

Fred L. Gould, an entomologist at North Carolina State University, points out that resistance to conventional pesticides has become "a real headache." In time, he believes, resistance to *Bt* will also emerge, but if properly managed it should be possible to keep under control. "Our concern," he declares, "is that they don't overuse it."

—Tim Beardsley in Washington, D.C.


COMSTOCK

CORNFIELDS
in nine states may not include some transgenic plants because of concerns about resistance among pests.

COMPUTING

PROGRAMMING WITH PRIMORDIAL OOZE

Useful software begins to crawl out of digital gene pools

Computer programmers ascended the economic food chain by inventing clever algorithms to make manufacturing and service laborers redundant. But some programmers may one day find themselves automated out of a job. In university labs, scientists are teaching computers how to write their own programs. Borrowing from the principles of natural selection, the researchers have built artificial ecosystems that, for a few problems at least, can evolve solutions better than any yet devised by humans. Someday such systems may even be able to design new kinds of computers.

The idea of evolving rather than inducing algorithms is not new. John H. Holland of the University of Michigan worked out the method 21 years ago. But Holland's strategy, based on a rigorous analogy to chromosomes, is limited to problems whose solutions can be expressed as mathematical formulas. It works well only if a human programmer figures out how many numbers the computer should plug into the formula.

In 1992 John R. Koza, a computer scientist at Stanford University, extended Holland's method to evolve entire programs of virtually any size and form. A field was born, and this past July several hundred disciples gathered at the first Genetic Programming Conference to show off their latest creations.

Jaime J. Fernandez of Rice University, for example, reported evolving a program to help control a prosthetic hand. The software analyzes the erratic nerve signals picked up by three electrodes taped around a subject's wrist and can tell, with perfect accuracy, which way he moved his thumb. Fernandez's team is now collecting data from amputees missing a hand to see whether the technique can be applied to them.

Brian Howley of Lockheed Martin Missiles and Space guided the evolution of a program that can figure out how to maneuver a spacecraft from one orientation to another within 2 percent of the theoretical minimum time—10 percent faster than a solution hand-crafted by an expert. And researchers at University College in Cork, Ireland, grew a system that can convert regular programs, which execute instructions one at a time, into parallel programs that carry out some instructions simultaneously.

To create their software, Fernandez and Howley did not have to divine insights into neurophysiology or rocket science. The task of the genetic programmer is simpler. First, build an environment that rewards programs that are faster, more accurate or better by some other measure. Second, create a population of seed programs by randomly combining elements from a "gene pool" of appropriate functions and program statements. Then sit back and let evolution take its course. Artificial selection works just like the natural variety: each program is fed data and then run until it halts or produces a result. The worst performers in each generation are deleted, whereas the best reproduce and breed—that is, swap chunks of code with other attractive programs. Occasionally, a random mutation changes a variable here or adds a command there.

The technique can generate solutions even when the programmers know little about the problem. But there is a price: the evolved code can be as messy and inscrutable as a squashed bug. Fernandez's gesture-predicting program consists of a single line so long that it fills an entire page and contains hundreds of nested parenthetical expressions. It reveals nothing about why the thumb moves a certain way—only that it does.

Just as in the real world, evolution is not necessarily the fastest process either. Howley's speedy workstation churned for 83 hours to produce a satellite-control program that beat human ingenuity in eight test cases. And when it was presented with situations it had never encountered, the program failed, a common problem with evolved software. (Of course, the human expert's program failed on the new cases as well.)

To address some of these limitations, computer scientists are extending their technique. Lee Spector of Hampshire College in Amherst, Mass., allows the programs in his ecosystems to share a common memory as they compete to demonstrate their fitness. "This means that a 'good idea' developed by any individual may be preserved for use by all others," Spector says—essentially, it allows the community of programs to evolve a culture. He reports that the innovation reduced the computational effort required to solve a tricky mathematical problem by 39 percent.

"It is possible," Spector says, "to use genetic programming to produce programs that themselves develop in significant, structural ways over the course of their 'life spans' "—a strategy he calls ontogenetic programming. He demonstrated one such system that can predict the next value in a sequence of numbers so complicated that it has stumped regular genetic programming systems.

Ultimately, evolved software may lead to evolved hardware, thanks to the recent invention of circuit boards that can reconstruct their circuit designs under software control. Adrian Thompson of the University of Sussex turned a genetic programming system loose on one such board to see whether it could produce a circuit to decode a binary signal sent over an analog telephone line. Using just 100 switches on the board, the system came up with a near-perfect solution after 3,500 generations. Although the task is simple, "it would be difficult for a designer to solve this problem in such a small area and with no external components," Thompson says.

"Hardware evolution demands a radical rethink of what electronic circuits can be," he argues, because evolution exploits the idiosyncratic behavior that electrical engineers try to avoid. Although genetic programs are largely still fermenting in their primordial ooze, it seems just a matter of time until they crawl out to find their niche.

—W. Wayt Gibbs in San Francisco

COMPUTING

Recently Netted...

Snailmail Fights Back. Starting this winter, the U.S. Postal Service can stamp your e-mail with a time and date, according to Ken Ceglowski of the USPS. Customers will be able to send their e-mail or documents to a USPS server; the machine will electronically postmark the correspondence, digitally sign it and forward it to an e-mail address or World Wide Web site. The process—which will cost about 22 cents for documents 50K in size or less—should take about two minutes, Ceglowski says. Mail dispatched electronically by the USPS will probably travel with legal protection similar to that guarding physical mail: the electronic postmark will be analogous to an envelope's cancellation mark, widely recognized as "proof" that the message existed at a specific moment; the authentication routines will be equivalent to the seal of a paper envelope, guaranteeing that the message has not been altered since it arrived at the mailbox—in this case, the USPS server. This legal protection may prove to be a strong selling point, for garden-variety e-mail carries with it no penalties for tampering.

Cookies Redux. Cookie technology is still with us in Netscape 3.0. A "cookie" is a nugget of information about you that is established by the Web site server when you go visiting—it provides information about what pages you see, for instance, or what language you speak. The cookie is stored on your hard drive; when you revisit a site, it is retrieved by the machine that set it in the first place. This can be very useful if, for example, you want information about, say, your preferred method of payment immediately known when you reach a favorite on-line shopping site.

But if cookies are handy for Web shoppers, site developers, advertisers and trackers, they are irritating and intrusive to many users who do not want to leave behind a digital fingerprint. Cookie filters and browser proxies offer inventive ways to avoid the files. PrivNet's Internet Fast Forward (http:// www.privnet.com) blocks the browser from sending cookies. (The program can also block ads, eliminating not only the banners but the time spent downloading them.) Anonymizer (http://www.anonymizer.com) is similar to a proxy service; it acts as a go-between. Justin A. Boyan, a graduate student at Carnegie Mellon University, wrote the software. "Surfing feels anonymous, like reading a newspaper," he comments, "but it's not." The latest version of Netscape Navigator—as well as other browsers that support it, such as Microsoft Explorer—permits users to reject cookies, but they must do so one by one. "What Netscape needs is a feature saying, 'Look, I never want to see another cookie again,' " Boyan advises.

—Anne Eisenberg (aeisenb@duke.poly.edu)

PROFILE: WAYNE B. JONAS

Probing Medicine's Outer Reaches

The high-speed Polaroid photograph has just emerged from the camera, revealing the places where my fingers have touched the film. Joe Hall, the president of Clarus Systems, a maker of "personal energy" products, notes that the outlines of my fingertips form a series of broken dots and not a continuous ellipsoid, indicating that my body's energy centers, or chakras, are not resonating properly.

Hall thinks I may have been exposed to excessive man-made electromagnetic radiation, which has increased, he informs me, 100-millionfold since 1940. Broadcasts of Lucille Ball and Don Imus no doubt bear the blame. But for $129, Hall is willing to sell me the Q-Link—a microchip equipped with an antenna—that when worn around the neck brings one into "harmonic resonance."

Unfortunately, I have little time for the Q-Link at this alternative-medicine conference in Alexandria, Va. Nor can I submit to the tongue and fingernail analysis by a Dr. Chi or examine the toothbrush he sells with the magnets that supposedly suck plaque off teeth.

The reason for my rush is an appointment at the massive National Institutes of Health complex in Bethesda, across the Beltway. There, in the same complex of buildings that houses the directors of institutes that devote themselves to research pursuits ranging from cancer to mental health is the Office of Alternative Medicine (OAM). The OAM administers a $7.48-million-a-year program to assist the medical establishment and the public in making sense of assorted nostrums, potions and electromagnetic-field generators.

Wayne B. Jonas is the tall, athletic-looking, 41-year-old head of the OAM. His job—and that of about a dozen other NIH employees—came about because of Congress's desire in 1991 to get the world's largest health research institution to stop ignoring the potential benefits of unorthodox remedies such as bee pollen for allergies and antineoplastons (peptides originally derived from urine) for cancer. Jonas took over in July 1995 from Joseph Jacobs, who had resigned nearly a year earlier after complaining about being hounded by congressional staffers pushing pet projects and an OAM advisory council that included many advocates of unproved cancer cures.

By many accounts, Jonas has built the administrative structure needed to run a research program. On paper, he has the ideal background to juggle the competing claims placed on the office by mainstream researchers and the alternative-medicine community. He is a primary-care physician, who, as a lieutenant colonel in the army, had the opportunity to study and then teach research methods at the Walter Reed Army Institute of Research in Washington, D.C.

Alternative-medicine advocates are reassured by the fact that Jones has received training in practices ranging from homeopathy and acupuncture to bioenergetics and spiritual healing. Moreover, he has had no significant prior association with the NIH, the Food and Drug Administration, the American Medical Association or the pharmaceutical industry. (Advocates of alternative medicine sometimes characterize officials at these institutions as "jack-booted thugs.")

LEONARD FREED *Magnum*

Still unclear, however, is whether Jonas can reconcile his commitment to running a serious research program with his personal belief in the merits of alternative medicine. When we first meet, his subdued, no-nonsense manner reminds me more of an army logistics specialist than of a lifelong student of alternative therapies, an impression he makes little attempt to allay. "I came to the office to try to get this area in shape and do good science, and what better way to do it than to apply a little military discipline," remarks the lieutenant colonel, who once headed a clinic on a military base in Germany.

During his first year as head of the OAM, Jonas appears to have met his self-set goal. He expanded the staff and put in place procedures and guidelines for managing a program that had been described by observers as chaotic. His low-key manner belies a forceful personality: after he expresses irritation at some of my questions and comments, the OAM's press officer, Anita Greene, calls *Scientific American* to ask that another writer be assigned to the story.

Like a mantra, Jonas repeats the idea

that rigorous research will separate the good from the bad in an environment that he likens to a "circus." During the interview, his interest in homeopathy seems objective and clinical. He acknowledges that homeopathy—which often involves administering a substance in doses so small that, in theory, not even a single molecule of it remains—may serve only as a placebo. Even if it does, Jonas adds, the mechanism by which it works deserves study.

But Jonas is more of a true believer than he at first lets on. Most practitioners of alternative medicine readily ply journalists with the latest book they've written or promotional literature about their favorite therapy. While I am in his office, Jonas omits to mention that he has just co-authored a book—*Healing with Homeopathy: The Complete Guide*—that was published in August by Warner Books.

"Fringe ideas" might transform science.

Jonas later says he had not wanted to promote his work on "official" time, but this explanation seems somewhat disingenuous. The book's narrator exudes an emotional depth and passion for alternative medicine—feelings never expressed during the interview.

In his writing, Jonas describes the Bowman Gray School of Medicine in North Carolina, where his interest in alternative medicine led him to be repeatedly rebuffed by his professors. After he suggested a homeopathic remedy for a patient with severe antibiotic-resistant pneumonia, his supervisors asked him to repeat his rotation in medicine. "Use of nonconventional treatments, when appropriate, requires an open mind, a skill usually not taught in medical school," Jonas remarks in one chapter.

In another passage, he forwards the notion—echoed by many alternative-medicine practitioners—that his views may one day transform medicine and science. "Just as the discovery of infectious agents revolutionized our ability to care for many diseases at the turn of the century," he states, "the discovery of what happens when a homeopathic preparation is made and how it impacts the body might revolutionize our understanding of chemistry, biology and medicine."

The infrastructure established by the OAM that might allow homeopathy, herbal remedies and Ayurvedic medicine (traditional Hindu healing) to complement modern Western medical practices is built around a nucleus of 10 university-based centers as well as a basic research program at the NIH. The centers will conduct or manage research in areas such as AIDS, cancer, women's health, pain and addiction. The challenge faced by the centers—and by Jonas—is to get epidemiologists, microbiologists and clinical investigators to work alongside alternative practitioners whose view of the natural world does not necessarily fit within the framework of scientific rationalism.

This extrascientific perspective was in evidence at a recent meeting at the NIH of the OAM advisory council—a group of alternative-medicine advocates as well as mainstream researchers. There, council member Beverly Rubik, an expert in bioelectromagnetic fields, asked a researcher who had just reported the results of an acupuncture study whether he had taken into account the variable of "external chi"—in other words, did he evaluate the levels of vital energy circulating in the environment around the subjects of the study? Jonas himself believes that researching alternative methods might require an open-mindedness that some scientists and physicians would characterize as naive, gullible or simply wrongheaded.

In his book, although he acknowledges that homeopathic effects might be placebo-induced, he is also willing to entertain a number of other explanations for why these approaches work: the transfer of a patient's "unhealthy" electric field to the remedy by the coupling of "biophotons" or the ability of thoughts to "nudge potential effects into existence." His acceptance of these claims as worthy of study leaves critics aghast. "What's happening here is that ancient religious practices are being dressed up with New Age technobabble," remarks Robert L. Park, a physicist at the University of Maryland and a frequent critic of the OAM—one whose views probably reflect those of most establishment scientists.

Jonas's openness could undercut the credibility of the OAM's findings. And despite his seeming administrative prowess, Jonas has little experience managing an ambitious research endeavor. He has never directed a large program and, except for literature reviews, has almost no published research of his own. His main research training came during a yearlong stint from 1990 to 1991 at the Walter Reed Army Institute of Research. "One year in a laboratory does not a researcher make," comments Carol A. Nacy, executive vice president for the biotechnology firm EntreMed. Nacy formerly supervised the laboratory at Walter Reed in which Jonas worked.

At Walter Reed, Jonas tried to pursue his interest in alternative medicine. He performed a study that purportedly showed that a homeopathically prepared solution of pathologic bacteria produced immunelike protective effects in mice; three immunology journals rejected the ensuing paper. Nacy and another manager at Walter Reed declined to add their names to Jonas's report. "I couldn't find a rationale for why it worked," Nacy says. "We told him," she adds, "that there are many ways to do science, and the most difficult way is to try to prove the rationality of a discredited scientific endeavor. To do so, you'll always be swimming upstream."

In response, Jonas stands firm in defending his pursuits. The search through what he calls "fringe ideas," he says, is justified because it holds the promise of bringing forth new types of knowledge that might transform science. He adds that no researcher would have the breadth of knowledge to encompass all the areas that fall under the OAM's purview. His job, he emphasizes, is to fulfill the office's mandate of acquiring the outside expertise to build a solid collaboration between the mainstream and the alternative-research communities.

Even those who question Jonas's methods do not doubt the sincerity of his motivation. Skeptical superiors at Walter Reed acknowledged Jonas's desire to provide patients with better care. Nacy remembers that Jonas would often volunteer to minister to the needs of anyone in the laboratory who had taken sick. Some people even took him on as a family physician.

Jonas's attraction to unconventional healing practices stems from nostalgia for a more compassionate interaction between physician and patient, the antithesis of the managed-care ethos. "People get treated today as if they're a disease or an organ," Jonas says of high-technology medicine. But whether Jonas and the OAM will be able to humanize medicine by conducting studies on vanishingly dilute solutions of elemental sulfur, poison ivy and bushmaster snake is far less certain. *—Gary Stix*

Single Mothers and Welfare

For the first time since the Great Depression, large numbers of families are homeless. Recent welfare revisions will put even more women and children on the streets

by Ellen L. Bassuk, Angela Browne and John C. Buckner

In 1992 the Better Homes Fund, a nonprofit organization based in Massachusetts, began a study of 216 women in low-income housing and 220 homeless women, along with 627 of their dependent children. All these women in Worcester, Mass., were raising their families single-handedly, and the majority were receiving cash assistance. Despite this aid, most of the families lived below the federal poverty level ($12,156 for a family of three in 1995). We wanted to understand what had pushed some of these families into homelessness, what their lives were like and what role welfare—in their case, Aid to Families with Dependent Children (AFDC)—played in their survival.

We found that these low-income women often faced insurmountable barriers to becoming self-supporting. Unlike popular stereotypes, most of the women who received welfare were neither teenage mothers nor the daughters of women who had been on welfare; they used welfare episodically, in times of crisis, rather than chronically. Despite limited education and the demands of child care—the average age of their children was five and a half years—approximately 70 percent of them had worked for short periods. Yet the study revealed that even full-time employment at minimum wage is not enough to enable a single mother to climb out of poverty. Many of the housed mothers lived in extremely precarious circumstances, only one crisis away from homelessness.

We also discovered that there was little significant difference in the quality of life of homeless and housed mothers. The housed mothers typically lived in dilapidated apartments, doubling or tripling up with other families to reduce the rent burden. Most of the women in both groups had histories of violent victimization that resulted in emotional and physical problems. Having had to escape repeatedly from abusive situations, many of them were bereft of social supports such as family. Indeed, we found that a major factor protecting these women and their children from becoming homeless was AFDC.

The welfare revisions passed by Congress on August 1, 1996, abolished AFDC as an entitlement, ending six decades of guaranteed federal assistance to poor parents and their children. Cash relief is now tightly tied to work, and strict time limits are set on maintaining support. In addition, the legislation severely restricts eligibility for food stamps, Medicaid and other benefits, cutting $56 billion from antipoverty programs. What remains of welfare will now be directly administered by the states through block grants. This reform, we expect, will put many of the housed families in our study on the streets. Nationwide, 12.8 million people on welfare—of whom eight million are children—are now at risk of homelessness.

Case in Point

Sally, a 26-year-old white woman, was born in New Hampshire. When she was five, Sally's mother left her abusive husband—and also Sally and her two older brothers. The family moved in with Sally's paternal grandmother. Sally's father was an alcoholic, always in and out of jobs—and, because he had wanted a third son and resented Sally, he often become violent with his daughter.

When Sally was 13, her father remarried. Sally's stepmother had four children and was angry when Sally was forced to move in with them. The stepmother confined Sally to her room after school; she also beat Sally with extension cords and wood boards to "discipline" her and once held her underwater, threatening her with drowning. Sally

DONNA BINDER *Impact Visuals*

MOTHER AND CHILD at Forbell Street Shelter in Brooklyn, N.Y., are one of the 88 percent of homeless families in the U.S. headed by women.

fled when she was 16, moving in with some friends in Massachusetts. She began drinking; at the same time, she worked at odd jobs and obtained her high school equivalency degree.

Sally then moved to Texas and found full-time employment. At the age of 21, she became pregnant and decided to stop drinking. After the child was born, Sally found temporary care for her and entered a detoxification program. Once her substance abuse problem was identified, however, she was declared an unfit mother, and her child was taken away.

After completing the program, Sally worked full-time for two years in a manufacturing plant for $4 an hour. At 24 years old she became pregnant again. The father of her second child was abusive during her pregnancy, threatening to kill her and punching her in the head and stomach. Sally went into labor during one of these attacks and delivered three months prematurely. The child survived but had severe developmental delays as well as attention and behavior problems. Sally briefly received AFDC in Texas, but, unable to find affordable child care and thus unable to work, she decided to return to Massachusetts.

She moved into a two-room apartment with two other women and their children but was only able to stay there for a month. There was a six-month delay in receiving benefits in Massachusetts. Having no income, Sally requested emergency shelter—where we met her.

Although Sally was diagnosed with post-traumatic stress disorder (PTSD), we found her to be hard-working and optimistic. While job hunting during her shelter stay, Sally met her current husband. Although finances are extremely tight, he is able to support the family. Sally worked briefly, but because of the high cost of child care, she now stays home with her son and stepdaughter.

The events that led Sally and her son to a shelter are unique to them but reflect larger patterns. With very limited economic resources, the demands of single parenting (especially of a disabled child) can easily become overwhelming. One more stressor may be enough to tip the balance, catapulting someone onto the streets. Sally struggled to get on her feet despite a traumatic childhood. Although she had a good work history and was able to conquer her alcohol problem, her relationship with an abusive man, child care demands and the loss of her AFDC benefits forced her to turn to a shelter for refuge. As with Sally, violence accompanies poverty in the lives of many women in our study. The interplay of violence and poverty reduces the likelihood of escaping from either.

For a poor family, welfare is often what makes the difference between hav-

PAUL FUSCO *Magnum*

GEORGE COHEN *Impact Visuals*

EUGENE RICHARDS *Magnum*

ing a home or not. Those who had not received assistance, we found, were more likely to be homeless: 24 percent of the homeless women had not been granted AFDC in the past year (compared with 7 percent of the housed). These women had struggled to put together meager annual incomes that averaged $7,637, largely through jobs supplemented with some assistance from family and friends. (According to the Massachusetts Department of Transitional Assistance, the rent and utility burden alone for unsubsidized housing is $7,081 per year.)

Women who had received AFDC were doing somewhat better. AFDC, created in 1935, was a joint state and federal program; states determined their own level of benefits, but all persons who met eligibility requirements were guaranteed assistance. In 1995 the annual AFDC grant for a family of three in Massachusetts was $6,984 (or $582 per month); nationally, the average payment for such a family was $4,464. The women in our study who were on AFDC also obtained other support; together these benefits may have provided the critical margin for the families to stay housed.

At the time of the interviews, the majority of the low-income mothers in our study were on AFDC for short to moderate periods, with about one third having used AFDC more than once. Although the process of cycling on and off welfare is not fully understood, a body of research indicates that women often leave or return to welfare because of work or relationship changes. The median lifetime stay for women in our study was about two years for the homeless and 3.5 years for the housed. About a third of the women had used AFDC for a total of five years or more.

Almost never was AFDC the only source of income. About 30 percent of the women on AFDC worked; others supplemented their income through housing subsidies, food stamps, WIC (a nutritional program for pregnant women and their infants) and child support.

Impossible Lives

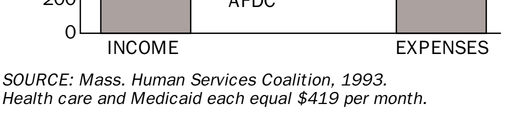
Nationally, only 57 percent of poor mothers have court-awarded child support. In 1989 the average annual award for poor women was only $1,889, but no more than half these women received the full amount. Growing caseloads and varying procedures and laws in each state make child support difficult to enforce. The new law cuts welfare benefits to a mother by at least 25 percent if she does not identify the father of her child. Given the high rate of violence by male partners against both women and children, our study suggests that many women will continue to refuse for fear of physical retaliation.

In addition to the economic hardship and residential instability that the mothers in our study experienced, the study found that most of them had undergone severe traumas. A shocking 91.6 percent of the homeless and 81.8 percent of the housed mothers reported physical or sexual assaults at some point in their lives. Even using a conservative measure—one that excluded spanking, shoves and slaps—almost two thirds of both groups reported violence by parents or other caretakers during childhood. More than 40 percent of both groups had been sexually molested before reaching adulthood. Sixty-three percent reported assaults by intimate male partners—again based on a conservative measure that included being punched, kicked, burned, choked, beaten and threatened or attacked with a knife or gun but excluded being pushed, shoved or slapped fewer than six times. And one quarter reported physical or sexual attacks by nonintimates.

As a result, many mothers in our study were distressed. Low-income housed and homeless mothers reported suffering from at least one emotional disorder in their lifetime at roughly the same rates, 69.3 and 71.7 percent, respective-

DIVERSE FACTORS militate against a poor single-parent family staying housed. Even with AFDC and other benefits, the family cannot make ends meet (*a*). Lack of education ensures that full-time work earns less than the poverty level (*b*); a quarter of the income goes to child care (*c*). Worst of all, pervasive violence (*d*) leaves mothers emotionally and physically battered, impeding their ability to work.

a **INCOME DEFICIT FOR FAMILY OF THREE ON AFDC**



SOURCE: Mass. Human Services Coalition, 1993.
Health care and Medicaid each equal $419 per month.

DAILY LIFE of a poor family includes many hours of waiting in queues, such as this one for lunch vouchers (*far left*) in New York City. Applying for aid (*center left*) may take weeks or months; this Income Maintenance Center is also in N.Y.C. Time spent at home can be barren as well. At a housing project in Chicago, a child watches others playing in a vacant lot (*above*).

ly. (In contrast, 47 percent of women in the general population report at least one lifetime disorder.) The lifetime and current prevalence of major depressive disorder, PTSD and substance abuse was extremely high. But unlike women and men who are on the streets alone, homeless mothers in our sample did not suffer disproportionately from severe disabling conditions such as schizophrenia or anxiety disorder.

PTSD consists of the long-term effects of early physical or sexual abuse as well as other traumas. Its hallmarks include feelings of terror and helplessness. A person suffering from PTSD may have sleep disturbances, irritability, hypervigilance, heightened startle responses and flashbacks of the original trauma. Periods of agitation alternate with emotional numbness. Severe depression, substance abuse and suicide attempts are frequently associated with the disorder. Indeed, 31.2 percent of the homeless and 25.6 percent of the housed mothers reported that they had attempted suicide an average of twice in their lifetime, usually in adolescence.

Together the homeless and housed mothers in our study suffered three times the prevalence of PTSD in their lifetime that women in general do. Because their intimate relationships unfolded within the context of earlier, sometimes profound, betrayal, the women's lives were often characterized by difficulty in maintaining boundaries, as well as by disconnection and distrust. Both groups had few relationships they could count on. Because of the demands of single parenting, histories of family disruption and loss, and the ever present threat of violence in their neighborhoods, many remained socially isolated.

Medically, the well-being of our subjects was greatly compromised as well. Even though most of the women were in their late twenties, a disproportionate number of them were subject to chronic medical problems, such as asthma (22.8 versus 5.4 percent in a national sample of women under age 45), anemia (17.5 versus 2.4 percent), chronic bronchitis (7.8 versus 5.8 percent) and ulcers (5.7 versus 1.4 percent).

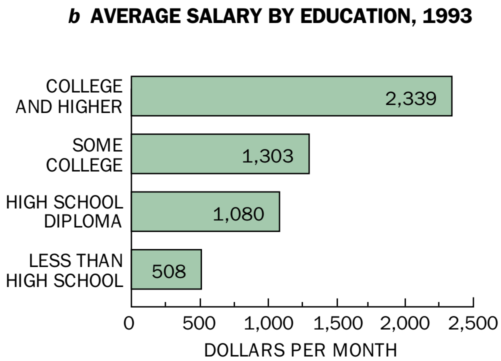
It should be noted, however, that although many mothers in our sample suffered from PTSD and depression or substance abuse, these disorders were equally prevalent in both the homeless and the housed. Despite our initial hypothesis that violence and its aftermath would be strongly associated with homelessness, multivariate modeling of housing status did not bear out this surmise. Economic factors were most salient in predicting the onset of homelessness.

A National Trend

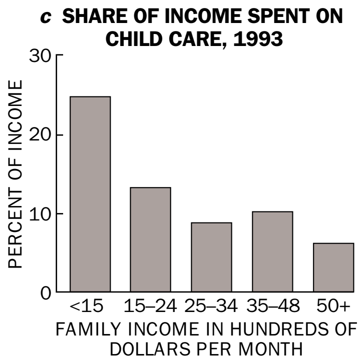
The tale of these mothers and their families is a cautionary one and not specific to Worcester. In most cities with a similarly sized population of between 100,000 and 250,000, 15 percent or so of the citizens are living below the poverty line. During the past decade, as the American economy has slowed and shifted away from manufacturing to service-sector jobs, real wages have declined. Wealth has also been drastically redistributed: in 1993 the top 20 percent of U.S. households received 48.9 percent of the total income, whereas those in the bottom 20 percent shared only 3.6 percent. Between 1991 and 1992, 1.2 million more Americans became poor, for an estimated total of 36.9 million citizens living below the federal poverty level.

At the same time, people are spending more on rent than ever before. According to the Joint Center for Housing Studies, between 1970 and 1994 the median income of renter households fell 16 percent to $15,814, whereas rents increased more than 11 percent to $403 a month. Today 83 percent of renters living below poverty level spend more than the 30 percent of their income on rent that is considered reasonable by standards of the federal housing program.

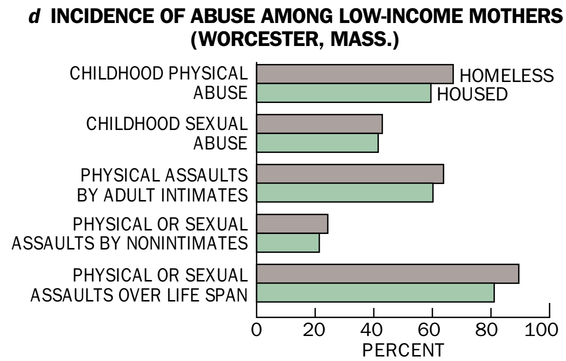
The effects of increased rents and economic shifts can be seen most dramatically in the growing numbers of homeless persons. During the mid-1980s,



SOURCE: Boston Globe, 1996.



SOURCE: Committee on Ways and Means, 1994.



SOURCE: Better Homes Fund, 1996.

JOHNNY JOHNSON

STEVE WEWERKA *Impact Visuals*

VIOLENCE, part of the childhood and daily adult life of most poor women, forms an enormous barrier to their getting on their feet.

many of us reassured ourselves that once affordable housing was provided, homelessness would disappear. Instead it is more prevalent than ever. A 1990 telephone survey led by Bruce G. Link of Columbia University estimated that 13.5 million (or 7.4 percent of) adult Americans have been homeless at some time. But since the early 1980s, federal construction and rehabilitation programs for low- and moderate-income housing have virtually stopped. Many cities have low vacancy rates, and waiting lists for public housing are years long.

The composition of the homeless population has also changed. Approximately 36.5 percent of the nation's homeless now consist of families with dependent children—an increase of 10 percent since 1985. Not since the Great Depression have families in such substantial numbers been among the homeless. An estimated 88 percent of these families are headed by women [see "Homeless Families," by Ellen L. Bassuk; Scientific American, December 1991].

According to the U.S. Conference of Mayors, increasing numbers of low-income families are at risk of becoming homeless. By 1993 nearly 40 percent of all families headed by women lived below the federal poverty level. Among blacks and Hispanics, the rates were 50.2 and 49.3 percent, respectively. Twenty-three percent of children in the U.S. live in poverty; no other industrial nation comes close to this figure. As sole providers and caretakers, women heading households must juggle child care, households and work. Despite the challenge of balancing these tasks, 39.9 percent of poor single mothers and 48.3 percent of poor married mothers do work.

Although the gap between men's and women's incomes has narrowed, women still earn less. The average man without a high school diploma earns 58 percent more than a woman with a similar education. Single mothers, especially those of color or with limited education, are more likely to be working for minimum wage or at part-time, dead-end jobs. One quarter of women workers are employed part-time; 44 percent of these women are working part-time because full-time work is unavailable to them.

For single mothers, the need to care for young children makes consistent employment difficult. In our study, 59 percent cited unavailability of affordable child care as a barrier to work. According to a 1994 General Accounting Office report, the probability of a poor mother working would increase by as much as 158 percent if adequate subsidies for child care were available. Despite the federal allocation of $2.2 billion in 1992 to such programs, however, demand far outweighs supply. Further, programs often do not account for realities of the workplace—some, for example, impose arbitrary time limits. Recent national studies have also raised concerns about the quality of child care programs, suggesting that many threaten the safety, development and well-being of their charges.

The new legislation ends the 60-year-old federal guarantee that families and children living below subsistence levels will receive cash assistance. Through block grants, power has been transferred to the states to set eligibility requirements and benefit levels. In the context of our findings, this legislation seems certain to be devastating to the millions of children currently living in poverty, as well as to single mothers and many low-income working families. There is little doubt that many states will impose even more stringent limitations than those mandated by the new bill. It is also likely that an ensuing "race to the bottom" will occur, in order to discourage potential recipients of welfare from moving between states.

Debates without Data

The federal welfare bill places draconian limits on eligibility for benefits—allowing a maximum of two years for adequate education or training and finding employment that will fully support a family, along with a five-year lifetime limit on welfare. The creation of a corresponding job base, however, has been completely neglected. The new law would necessitate that states quadruple the number of jobs for unskilled and semiskilled labor, a task that will be especially daunting in areas that are already impoverished or lack employment opportunities. And despite increased allocations for child care, demand will quickly outstrip supply given the new work requirement. According to data from the Congressional Budget Office, states will face shortfalls in child care funding in every year after fiscal year 1998.

Even more disturbing is that the legislation reflects a "get tough" attitude that seems to be based on four assumptions that are not supported by empirical findings. The first is that welfare perpetuates dependency rather than serving as a stopgap measure during hard times. Our data confirm other studies indicating that most poor and homeless women use welfare for relatively short periods. Also, two thirds of the mothers in our sample had not grown up in families that were receiving welfare—a fact that debunks the stereotype of intergenerational dependency.

The second fallacy is that welfare compromises the work ethic. Many low-income mothers supplemented their AFDC grants by working at low-paying jobs with no benefits. Because of limited opportunities, many were forced to work part-time. The women most able to maintain jobs had at least a high school education, access to affordable child care and a social network that had some financial resources.

The third ill-conceived argument is that teen mothers and single-parent families are responsible for the growing poverty rate in the U.S. Nationally, however, only 7.6 percent of all mothers who received welfare in 1993 were under 18 years old and unmarried. The median age of our sample was 27.4 years, with 24.5 percent under 21 years and 7.1 percent under 18 years.

And, finally, the fourth myth holds that welfare costs contributed significantly to the growing federal budget and to increased taxes. Taken together, AFDC spending, food stamp benefits and Medicaid for AFDC recipients made up less than 5 percent of all entitlement spending and not quite 3 percent of the total federal outlay. AFDC, Medicaid, Supplemental Security Income and nutrition entitlement programs since 1964 amounted to only about 6.6 percent of total federal spending over the past 30 years. Yet even at painfully low amounts, cash assistance limited the risk of homelessness for poor families.

Shift to States

With the passage of the new law, the onus is now on the states to protect these vulnerable families. An understanding of poor women's experiences and the impact of those experiences on their present circumstances is vital in restructuring antipoverty programs and policies. An effective response should include creating more educational and job opportunities, guaranteeing that basic needs for housing, food, medical care and safety are met, and ensuring that disabled individuals and children are well cared for.

Low-income women with at least a high school diploma are more likely to find gainful employment and support their children. As the Institute for Women's Policy Research has shown, "completing high school increases the chances of escaping poverty to 31 percent." Low-income mothers who continue their education need various kinds of support—such as transportation and child care—to enable regular attendance. To be effective, educational opportunities must also be linked to the realities of the labor market: job training must be aimed at helping these women obtain full-time work that pays a livable wage and offers essential benefits. Once these mothers begin work, health care and child care benefits should be provided for an adequate period.

This legislation seems certain to be devastating to the millions of children currently living in poverty.

At the current minimum wage, a woman working full-time generates $8,840 annually. The new minimum wage is being phased in, and the full amount of $5.15 per hour will not be attained until September 1, 1997. Basic yearly costs of $21,816 for a family of three (unlike the federal poverty level, this figure includes rent, child care, health care and transportation) inevitably force this family into debt. Health care insurance, subsidies for child care and expansion of the earned income tax credit would improve the economic status of these parents and make work a more realistic option than welfare.

Moreover, violence at the hands of male partners is a major barrier to building a successful work history for many women. Effective back-to-work policies must take into account the long-term, devastating effects of childhood and adult victimization, as well as the extremely high rates of violent assaults faced by women living in poverty. Given the pervasiveness of this violence, communities should create comprehensive services to address the emotional and behavioral effects experienced by both women and children.

If a low-income parent is faced with an economic crisis or is unable to work—for example, because of a disability—it is essential that some income guarantees exist to protect his or her well-being, and also that of the children. The new welfare bill eliminates the federal government's role in establishing a safety net. Previously, the federal government set basic eligibility criteria and ensured minimal funding levels for cash assistance to the poor. With the shift in responsibility to the states, these guarantees will be gone. Will the states continue to protect those who are disadvantaged—by poverty or disability, or both?

In a society as affluent as ours, the possibility that large numbers of families will be cast aside raises troublesome questions about our moral values. We pride ourselves on being family-oriented, particularly treasuring the future of our children. But the new legislation suggests that low-income families headed by women are expendable. Creating realistic state programs is far more cost-effective than the financial and social burden that will result if thousands of families and children are left destitute. That situation is inevitable if jobs and child care are not available by the time a woman's eligibility for assistance expires. The future of our country depends on how we usher children through critical developmental years. Without adequate support of mothers in their challenging roles, all of society will suffer. SA

The Authors

ELLEN L. BASSUK, ANGELA BROWNE and JOHN C. BUCKNER study different aspects of poverty and homelessness at the Better Homes Fund in Newton, Mass. Its co-founder and president, Bassuk is associate professor of psychiatry at Harvard Medical School and a staff member at Cambridge Hospital. She has worked extensively on issues of managed care. Browne specializes in family violence. She is affiliated with the New York State Research Institute on Addictions and is a consulting psychologist to Bedford Hills Correctional Facility for women. Buckner, who directs research at the Better Homes Fund, lectures at Harvard Medical School and is conducting a study on stress among poor children for the National Institute of Mental Health.

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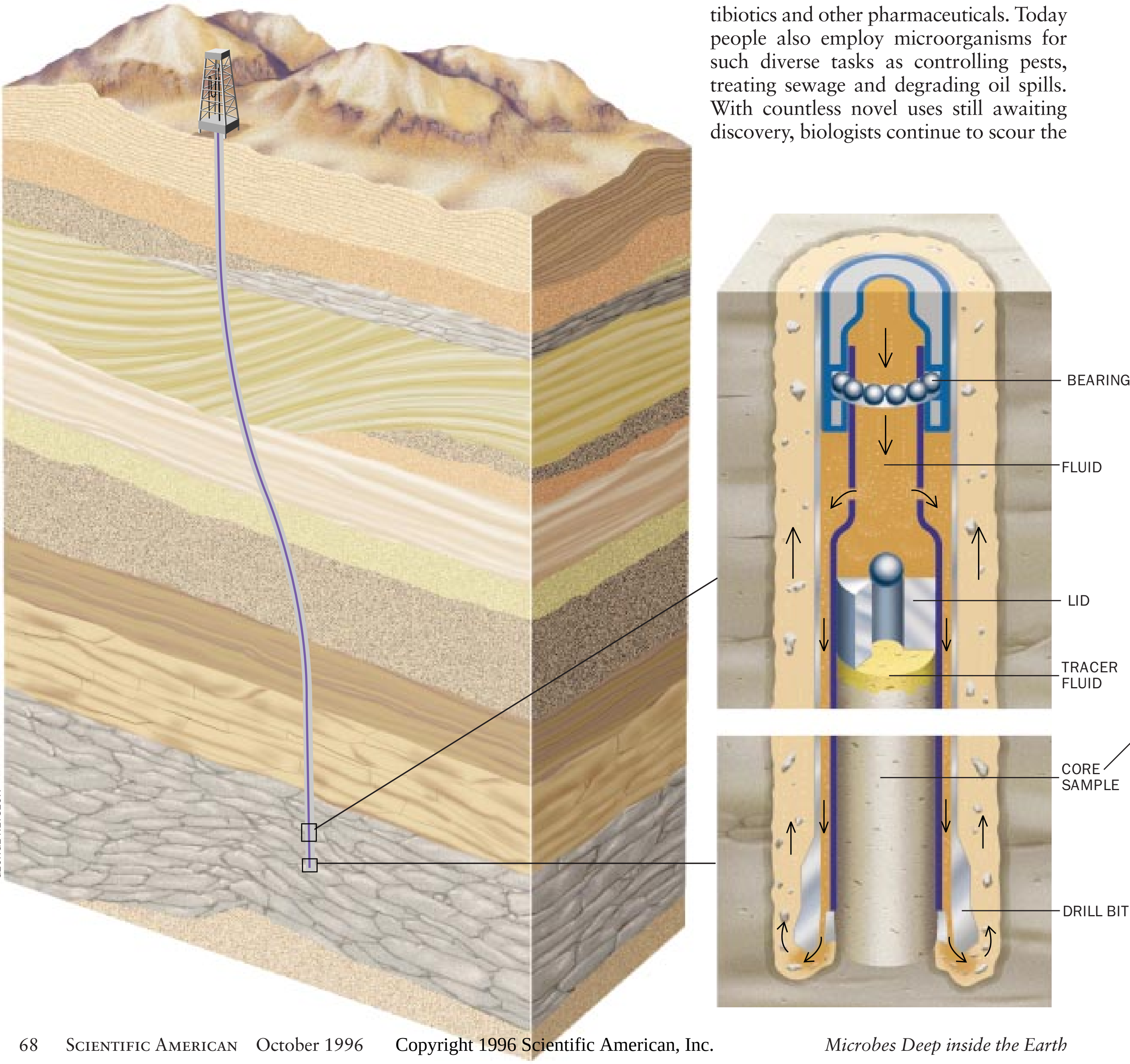
Microbes Deep inside the Earth

Recently discovered microorganisms that dwell within the earth's crust could reveal clues to the origin of life

by James K. Fredrickson and Tullis C. Onstott

Single-celled organisms—bacteria, fungi and protozoa—thrive on all parts of the earth's surface. Their habitats range from the boiling hot waters of thermal springs to the pleasantly cool soils of backyard gardens. Microorganisms provide essential services to other creatures by decomposing waste products and forming nutrients. Some microbes also inflict harm by infecting higher organisms and causing disease. Fortunately, scientists have learned to control many of those damaging effects and to expand on the ways microorganisms benefit humankind.

Although people have used the metabolic activities of microorganisms for thousands of years to produce cheese, wine and bread, it was not until the mid-20th century that scientists harnessed microbes to create antibiotics and other pharmaceuticals. Today people also employ microorganisms for such diverse tasks as controlling pests, treating sewage and degrading oil spills. With countless novel uses still awaiting discovery, biologists continue to scour the



GEORGE RETSECK

surface of the earth in search of microbes that might prove valuable in formulating new drugs or improving industrial processes. But until recently, few such bio-prospectors thought to look deep inside the earth. Long-standing scientific dogma held that this realm was essentially sterile. But that belief, as it turns out, was wrong.

It's Alive!

The first hints that microorganisms lived in the deep subsurface—hundreds to thousands of meters below ground—emerged in the 1920s from the studies of Edson S. Bastin, a geologist at the University of Chicago. Bastin questioned why water extracted from oil fields contained hydrogen sulfide and bicarbonate. After puzzling for some time, Bastin ventured an explanation. He knew that so-called sulfate-reducing bacteria can exploit sulfate for respiration in places on the surface where no oxygen is present. So Bastin reasoned that such bacteria must also live in underground oil reservoirs and produce hydrogen sulfide and bicarbonate when they degrade organic components in oil. By 1926 Bastin and Frank E. Greer, a colleague at the University of Chicago who specialized in microbiology, had succeeded in culturing sulfate-reducing bacteria from groundwater samples extracted from an oil deposit that was hundreds of meters below the surface.

Bastin and Greer speculated that these microbes might have been descendants of organisms buried more than 300 million years ago when the sediments that constituted the oil reservoir were deposited. But they had no way to test this intriguing hypothesis. At the time, many scientists viewed with skepticism the very idea of microorganisms living deep underground, noting that oil-drilling techniques were not designed to obtain samples uncontaminated by microorganisms from the surface. With little acceptance or support in the scientific community, the views of Bastin and Greer languished.

Interest in the microbiology of petroleum deposits temporarily revived during the late 1940s and 1950s, when Claude E. Zobell of the Scripps Institution of Oceanography and his colleagues investigated microbial processes in sediments buried far below the seabed. But research into subsurface microbiology again fell into dormancy during the 1960s and 1970s. Despite the importance of rock formations as reservoirs and conduits for water supplies, few considered the possibility of microbial activity deep underground. Most researchers believed that water underwent predominantly inorganic chemical alterations as it passed through the earth and that biological influences were restricted to near-surface soil layers. These scientists routinely assumed that any microbes found in groundwater samples taken from great depths were surface contaminants.

Then, during the late 1970s and early 1980s, concerns about the quality of groundwater stimulated some investigators at the U.S. Geological Survey and the Environmental Protection Agency to reevaluate their understanding of groundwater chemistry. This work spurred them to reconsider the possibility that microorganisms could inhabit water-yielding rock formations. At the same time, the U.S. Department of Energy (DOE) faced the daunting task of cleaning up the industrial facilities where nuclear materials had been produced. (As a cold war expedient, the DOE had dumped vast quantities of waste—including organic-rich solutions, metals and radioactive materials—into the subsurface at these sites.) DOE scientists were also studying how to build underground repositories that could isolate high-level radioactive wastes for thousands of years.

During this period, Frank J. Wobber, a geologist and manager at the DOE, reasoned that if microorganisms were present well below the earth's surface, they might helpfully degrade buried organic pollutants or dangerously disrupt the integrity of closed chambers containing radioactive waste. But a great deal of fundamental research needed to be done before such practical concerns could be addressed. And so he began a special effort, called the Subsurface Science Program, within the DOE. His idea was to sponsor a diverse group of biologists, geologists and chemists to search systematically for deep-seated life-forms and examine their activities.

Because water brought up from deep drill holes is easily contaminated with organisms living near the surface, the team assembled by Wobber decided to study pieces of rock instead. But first the group needed a way to collect clean, intact samples of rock (cores) from deep in the crust.

Tommy J. Phelps of Oak Ridge National Laboratory and W. Timothy Griffin of Golder Associates rose to the challenge by designing a special drilling apparatus that minimized contact of the core samples with the drilling fluid needed to provide lubrication in a borehole. And James P. McKinley of Battelle, Pacific Northwest National Laboratory, along with F. S. (Rick) Colwell of Idaho

DAVID BOONE *Oregon Graduate Institute*

SUBSURFACE EXPLORATION (*far left*) requires a great length of rotating steel pipe to snake downward from a drilling derrick to an underground target. As the pipe rotates, a diamond-studded drill bit at the bottom of the borehole (*detail, bottom left*) cuts away at the underlying rock and surrounds a cylindrical sample that is later extracted when the pipe is withdrawn. Lubricating fluid with a special tracer substance is pumped down the center of the pipe (*detail, top left*) and out through holes in the bit (*arrows*). The cylindrical rock sample remains in place as the pipe and bit rotate because it sits within a stationary inner barrel that is supported by a bearing. As a core of rock fills the inner barrel, a bag of concentrated tracer material above it breaks open and coats the outer surface of the sample (*yellow*). Cores recovered in this way are cut into short segments from which the outer rind marked by the tracer is removed to avoid contamination (*above, left*). Within pristine inner core samples, deep-living bacteria (*above, right*) can be found.

National Engineering Laboratory, formulated special "tracers"—additives that could be mixed with the drilling fluid to indicate whether this liquid (and any microorganisms carried inside it) could have penetrated the core samples.

Striking It Rich

The search for subsurface microbes began in 1987, when the DOE arranged to drill several deep boreholes in South Carolina near the Savannah River nuclear materials processing facility. With the operators of the drilling rig there, a field team of scientists labored to avoid microbial contamination. Researchers diligently added tracers and monitored procedures around the clock as drilling proceeded. When the drillers brought a core to the surface, a member of the team quickly encapsulated the sample and placed it in a "glove bag" for processing. Those plastic containers provided a sterile environment filled with an unreactive gas (nitrogen) as a precaution to protect any so-called obligatory anaerobes—bacteria that would be quickly poisoned by the oxygen in the air.

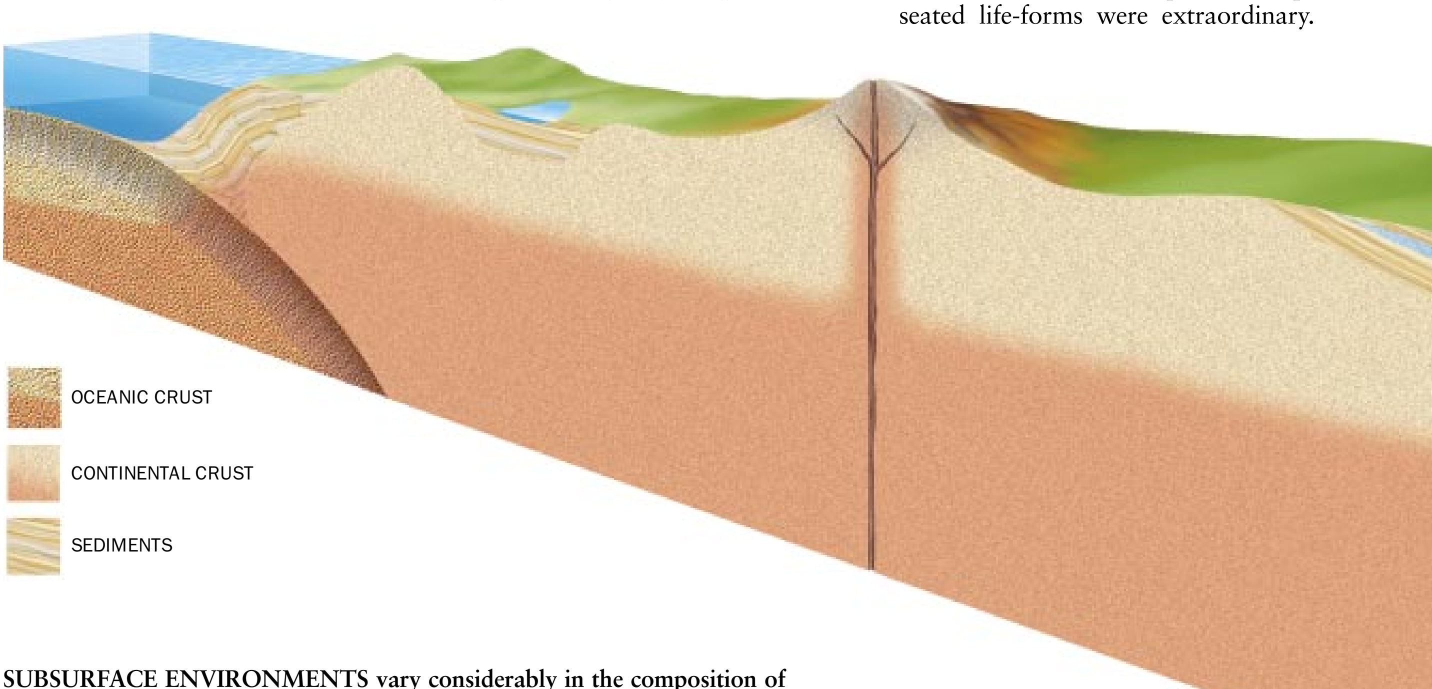
Using surgical rubber gloves attached to the interior of these bags, members of the team used sterile tools to pare away the outermost rind of each core sample, leaving only the part that was least likely to have been exposed to bacterial contaminants in the drilling fluid. If seepage of the tracer chemical indicated that a particular specimen might have been tainted, the scientist dissecting it noted that the core from which it came was very possibly contaminated.

Pristine inner core samples recovered in this way were then placed in sterile containers filled with nitrogen, which were packed in ice and shipped to research laboratories across North America. Within 72 hours after the removal of the rocks from the subsurface, other members of the research group based at many different institutions were subjecting the samples to a battery of tests designed to evaluate the rocks and the microorganisms they harbored. After these initial experiments, researchers sent the microbes they had extracted from the subsurface samples to special repositories in Florida and Oregon to be stored in liquid nitrogen at -96 degrees Celsius.

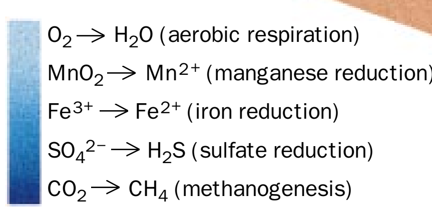
The first results of this quest for deep-seated life-forms were extraordinary.

PHIL LONG *Battelle, Pacific Northwest National Laboratory*

GLOVE BOX, with its rubber gloves protruding inward, allows scientists working near the drill sites to manipulate solid samples extracted from the subsurface. These plastic enclosures are filled with an unreactive gas to prevent oxygen from damaging delicate microbes within the recovered cores of rock.



GEORGE RETSECK



SUBSURFACE ENVIRONMENTS vary considerably in the composition of the surrounding rock. Deep-living microbes pervade both oceanic and continental crust and are especially abundant in sedimentary formations. Such microorganisms fail to survive only where the temperature exceeds about 110 degrees Celsius (*orange areas*). The nature of the population does, however, change from place to place. For example, a porous sedimentary layer that acts as a conduit for groundwater may contain both oxygen-rich (*light blue*) and oxygen-poor (*dark blue*) zones, and the bacteria found within its different regimes will vary according to the chemical reactions they use for energy (*bar, right*).

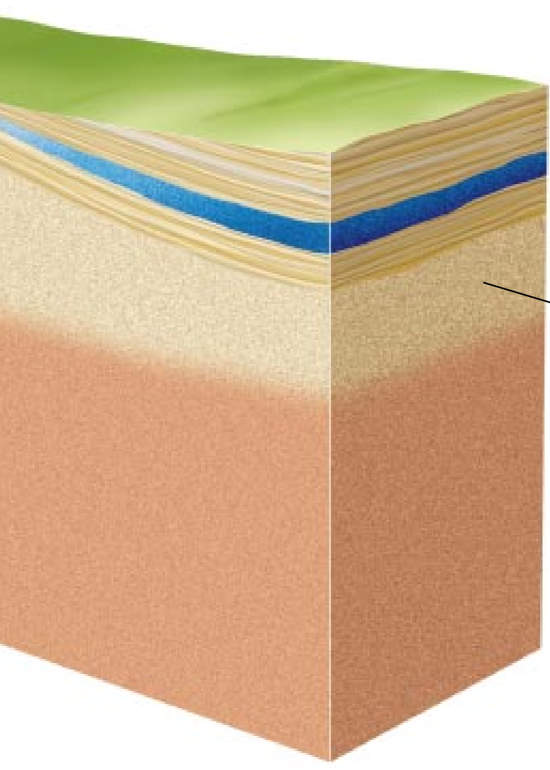
The scientists involved quickly learned that diverse types of microorganisms lived beneath the Savannah River site at depths extending at least as far as 500 meters beneath the surface, the deepest core taken. We and our many colleagues working under the aegis of the DOE's Subsurface Science Program have since examined many other geologic settings. Although we are still unsure of the extent of fungi or protozoa, the results clearly indicate that subsurface bacteria are ubiquitous. We have now recovered these organisms from formations with temperatures as high as 75 degrees C (167 degrees Fahrenheit) and from depths extending to 2.8 kilometers (1.7 miles) below the surface.

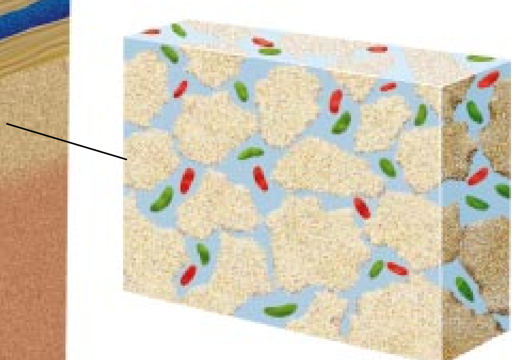
What determines the maximum depth at which subsurface microbes can exist? Mounting pressure exerts little direct effect on microorganisms even several kilometers below ground level. It is the increasing temperature that limits the depth of subsurface life. The maximum temperature that such organisms can tolerate remains something of a mystery, but biological oceanographers have found bacteria that are capable of growing at 110 degrees C in deep-sea volcanic vents, and some scientists estimate that subsurface microorganisms might be able to withstand temperatures as high as 140 degrees C, at least for short periods.

For oceanic crust, where the temperature rises about 15 degrees C per kilometer of depth, tolerance of 110 degrees allows microbial life to extend (on average) about seven kilometers below the seafloor. For continental crust, where the temperature is often near 20 degrees C at the surface and typically increases by about 25 degrees per kilometer, microscopic life should, on average, reach almost four kilometers downward into the earth.

The abundance of microbes will, however, vary considerably from place to place, even at the same depth in the earth. For example, we have discovered that samples obtained from 400 meters below the surface of the ground can contain as few as 100 to as many as 10 million bacteria in each gram of rock. John R. Parkes and his colleagues at the University of Bristol have found somewhat higher concentrations of microorganisms living in sediments beneath the ocean floor. In comparison, agricultural topsoil typically contains more than one billion bacteria in each gram of dirt.

It seems that the richness of life in the deep subsurface depends not only on tolerable temperatures but also on the capacity of the local environment to support growth and proliferation. Crucial prerequisites include the presence of water and the sheer availability of space in the pores of the rock. The region hosting the microbes must also contain the nutrients—such as carbon, nitrogen, phosphorous and various trace metals—that microorganisms need to synthesize their cellular constituents, including DNA and proteins. The environment also has to offer some form of fuel to provide the energy required for this ongoing activity.





SLIMES, or subsurface lithoautotrophic microbial ecosystems, exist in the pores between interlocking mineral grains of many igneous rocks. Autotrophic microbes (*green*) derive nutrients and energy from inorganic chemicals in their surroundings, and many other microbes (*red*), in turn, feed on organics created by autotrophs.

From Sandstone to SLiMEs

The types of microbes found in the earth's deep realms depend on the particulars of the local subsurface environment. Diverse bacterial communities thrive in most sedimentary rocks, which commonly contain a rich supply of organic compounds to nourish microorganisms. These nutrients were originally produced by plants at the earth's surface before the loose sands, silts or clays that constitute most sedimentary formations were buried and consolidated into solid rock. As long as these nutrients remain available, microorganisms living within the pores of the sediments can continue to survive and grow. Sedimentary rocks also supply oxidized forms of sulfur, iron and manganese that can provide the energy these microbes need. The chemical power sources here are so-called reduction reactions (processes that involve the gain of electrons).

As sediments become more deeply buried over geologic time, they are increasingly compacted. Much of the dwindling pore space eventually becomes cemented with minerals that precipitate from fluids passing through the rock. Consequently, as depth and pressure increase, the opportunity for obtaining life-sustaining materials declines, and the overall rate of metabolism of microbial communities gradually diminishes, except in those spots that directly surround rich concentrations of nutrients. The distribution of microorganisms in sediments ultimately becomes quite patchy. Small colonies—or even individual cells—live well separated from one another within the rock. Not surprisingly, then, searching for microorganisms living in these settings proves to be a hit-or-miss affair. Todd O. Stevens of Battelle, Pacific Northwest National Laboratory has found, for example, that with sediment collected near the DOE's Hanford facility in Washington State, the larger the sample tested, the better the chances of finding microbial activity.

Although quite inhospitable, such hardened sedimentary rock is not the most challenging environment for subsurface microbes: some environments appear far more hostile. The bulk of the continental crust is composed of igneous rock (that is, rock solidified from molten magma), which contains little organic carbon. Nevertheless, Stevens and McKinley discovered bacteria living within igneous formations that are composed of layers of basalt (a dark, fine-grained type of rock).

Microorganisms thrive in other igneous rock as well. Karsten Pedersen of the University of Göteborg in Sweden detected bacteria in water flowing through deep fractures in granite—a light-colored, coarse-grained variety of igneous rock. Because igneous rock is too hot to support life when it is first formed, the microbes found within such rock must have been carried there by the flow of groundwater sometime after the parent magma cooled and solidified.

Little buried organic matter is available within igneous formations, and so Stevens and McKinley were surprised to find that microbes could flourish in basalt. They eventually discovered the secret. The bacterial communities living there include so-called autotrophs, organisms that synthesize organic compounds (proteins, fats and other biological molecules rich in carbon) from inorganic sources. Many types of autotrophic bacteria capture energy from inorganic chemical reactions involving iron or sulfur. The autotrophs living in these basalts use hydrogen gas for energy and derive carbon from inorganic carbon dioxide. These "acetogens" then excrete simple organic compounds that other bacteria can in turn consume. In these basalts the hydrogen gas is produced by the reaction of oxygen-poor water with iron-bearing minerals. Many of us call such environments "SLiMEs," for subsurface lithoautotrophic microbial ecosystems. Amazingly, SLiME microorganisms can persist indefinitely without any supply of carbon from the surface.

Old as the Hills?

Like Bastin and Greer working decades before us, we wondered whether subsurface bacterial colonies might survive for as long as the rocks that host them. Such longevity is clearly not always possible. The continuing burial of sediments can ultimately raise temperatures sufficiently to purge an entire rock formation of live bacteria. More local sterilization may also occur where fiery hot magma impinges on sedimentary strata, leaving a body of igneous rock with some well-baked sediments surrounding it. Once such newly solidified rock cools, or tectonic forces lift hot, deeply buried sedimentary layers to a cooler position closer to the surface, bacteria carried by groundwater will then colonize the formerly sterile zones.

Yet that process of infiltration can be exceedingly slow. Ellyn M. Murphy of Battelle, Pacific Northwest National Laboratory has determined, for example, that the groundwater now present deep beneath the Savannah River facility has not been in contact with the surface for thousands of years. In the deepest sites we have examined, our measurements and computer modeling indicate that the groundwater has been isolated from the surface for millions of years. Because microorganisms could not have traveled downward from the surface faster than the groundwater descended, some subsurface microbial communities must be at least several million years old.

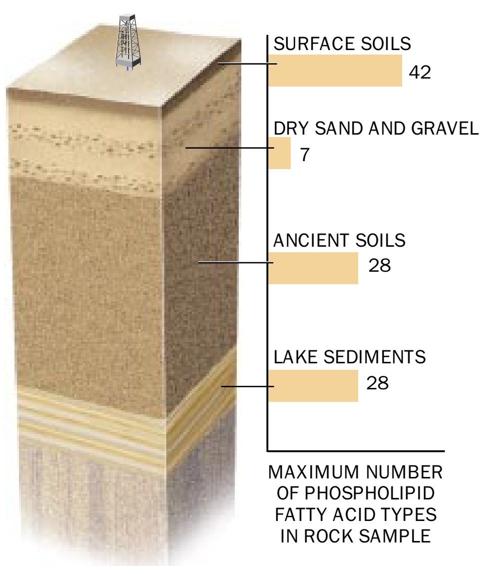
How do microorganisms manage to persevere for so long? In some cases (for example, SLiMEs), bacteria can survive because the essential nutrients are constantly renewed; although in most other sorts of formations, food and energy sources are relatively scarce. Neverthe-

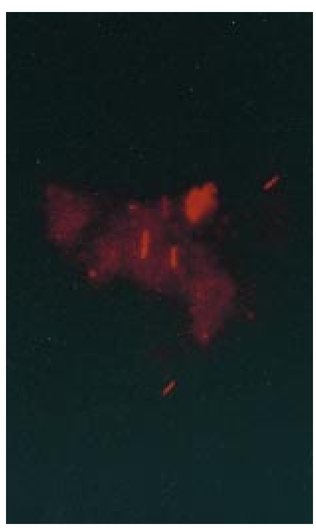
Biodiversity in the Subsurface

Just as countless kinds of life-forms cover the surface of the earth, many different types of bacteria live deep inside the crust. But because different microbes often look very much alike under the microscope, scientists have to resort to creative methods to gauge the extent of this bacterial diversity.

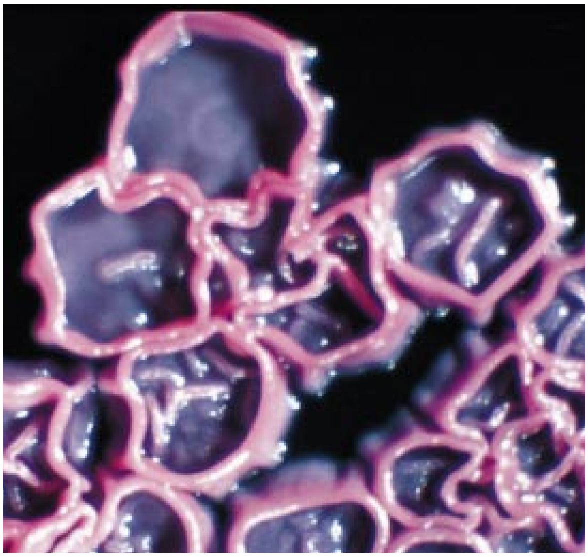
Certain methods allow researchers to avoid having to culture the microbes first. Biologists can, for example, apply a procedure called epifluorescence microscopy to visualize bacteria living within rock samples. This technique takes advantage of the unique makeup of the ribosomal RNA found in different types of bacteria (ribosomes are structures used by the cells to construct protein molecules). By first fashioning short strands of DNA so that they bind to particular kinds of ribosomal RNA, one can rapidly determine the variety of bacterial families in a sample. These DNA probes include a fluorescent dye so that when bacteria accumulate this substance, they seem to glow when viewed in an epifluorescence microscope (*micrograph*).

Another way to assess bacterial communities is to analyze samples for distinctive organic molecules called phospholipid fatty acids. These long carbon chains are the building blocks of bacterial cell membranes. Their molecular structure (which can be ascertained using modern laboratory instrumentation) provides a fingerprint for different bacterial families. If many different types of the fatty acid chains are found within a given sample, a diverse bacterial community exists within it. In contrast, finding a small number of distinct fatty acid molecules indicates a community of limited variety. At a site near the Department of Energy's Hanford facility in Washington State, drilling revealed striking variation in the bacterial diversity of different subsurface environments.





SANDRA A. NIERWICKI-BAUR *Rensselaer Polytechnic Institute* (*micrograph*); SOURCE: DAVID C. WHITE AND DAVID B. RINGELBERG *University of Tennessee*; GEORGE RETSECK (*diagram*) less, the resident bacteria appear to have adapted to these rather spartan living conditions. Bacteria must rely on internal reserves during periods of long-term starvation (as do higher organisms), and most types of bacteria shrink from a healthy size of a few microns to less than a thousandth of their normal volume as they use up their stores. Thomas L. Kieft of the New Mexico Institute of Mining and Technology has found that such tiny, starved microbes (called dwarf bacteria or "ultramicro-bacteria") commonly inhabit the subsurface.



JAMES K. FREDRICKSON

PIGMENTED BACTERIA inhabit parts of the subsurface near Idaho Falls, Idaho. Cultures of these microorganisms vary in appearance from purple to red because they produce copious amounts of a brightly colored substance that shifts in hue according to the ambient acidity.

The metabolic rate of such starved bacteria is probably much lower than when they are well fed. As a result, the average frequency of cell division for a subsurface microbe may be once a century, or even less, whereas surface microorganisms reproduce in a matter of minutes, hours, days or, at most, months. Microorganisms living in the deep subsurface limit their metabolism in order to endure starvation for geologically significant lengths of time. These bacteria can remain viable at little or no metabolic cost.

The sluggish pace of microbial metabolism in the subsurface makes it difficult to define just how many of the bacteria found entombed in these rocks are truly alive. One approach is to count only those microbes that can be grown in the laboratory. More than 10 percent of the cells extracted from sandy sediments where water and nutrients can generally flow freely will proliferate when given a supply of nutrients in the laboratory. In contrast, less than one tenth of 1 percent of the cells drawn from sediments in the arid western U.S. (where the flux of water is minimal) will grow in a culture dish.

It may be that failure to culture most subsurface bacteria is a result of our inability to properly reproduce necessary conditions in the laboratory. Or perhaps these organisms are simply no longer alive. In rocks where the flux of nutrients and water is low, dead cells decompose exceedingly slowly, and so some of our biochemical assays would count them along with the few living cells. Alternatively, most of the organisms could be functioning but may have lost the ability to replicate.

The Prospects Underground

So far our colleague David L. Bulkwill of Florida State University has catalogued and preserved more than 9,000 strains of microorganisms from diverse subsurface environments. These isolates—containing a vast assortment of bacteria and about 100 types of fungi—are a source of novel microbial life that have not yet been fully tested for commercially applicable properties.

Of the small percentage of the collection that researchers have examined in detail, a surprisingly high proportion show potentially valuable capabilities. Examples of such traits include the ability to degrade toxic organic compounds as well as to produce antibiotics, heat-stable enzymes and even novel pigments. Pfizer is now screening 3,200 kinds of subsurface bacteria for the production of new antimicrobial products, and ZymoGenetics, a biotechnology company, is currently examining at least 800 isolates from this archive for production of other useful substances.

Perhaps many commercial products will result from these investigations. But even without such quick practical returns, the effort to probe the earth's interior for microorganisms will surely reward scientists with a fuller understanding of how life can exist in isolation from the surface. More study of subsurface communities may, for instance, indicate how life functioned on the early earth, before photosynthesis evolved. It may also provide insight into whether microbes might be living even now under the surface of Mars or below the icy exterior of some of the larger moons of the outer solar system. Seeing how microbes survive the rigors of deep burial on the earth, we are more inclined to believe tiny extraterrestrials might indeed be lurking out there. SA

The Authors

JAMES K. FREDRICKSON and TULLIS C. ONSTOTT conduct research for the Department of Energy's Subsurface Science Program. Fredrickson is an environmental microbiologist at Battelle, Pacific Northwest National Laboratory and also serves as editor in chief of the journal *Microbial Ecology*. He has specialized in applying molecular and isotopic methods to investigations of subsurface bacteria (including some obtained from his wine cellar). Onstott is a professor in the department of geological and geophysical sciences at Princeton University. His expertise is in studying the history of fluid and heat flow within the earth's crust. He began working with members of the Subsurface Science Program in 1993 to help determine the age of deeply buried microbial communities, and he quickly caught the mysterious subsurface bug that has infected this large group of scientists with a peculiar enthusiasm for their joint research.

Further Reading

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Information on the U.S. Department of Energy Subsurface Science Program is available on the World Wide Web at http://www.er.doe.gov/production/oher/EPR/subprog.html

Friction at the Atomic Scale

Long neglected by physicists, the study of friction's atomic-level origins, or nanotribology, indicates that the force stems from various unexpected sources, including sound energy

by Jacqueline Krim

I used to dread the first week of December. It wasn't the darkness or Boston's pre-snow drizzle that made me gloomy, and it wasn't the nonexistent parking at holiday-frenzied shopping malls. This was the week when abstracts were due for the annual March meeting of the American Physical Society, *the* meeting of condensed-matter physicists. In 1986 my colleague Allan Widom and I had developed an experimental technique that could measure the frictional force of one-atom-thick films sliding along flat solid surfaces. The problem was, I could find nowhere to classify my atomic-scale friction abstract within a myriad of March meeting subject categories.

It was not that research on friction did not exist. I had always been welcomed by the multidisciplinary American Vacuum Society, in sessions on macroscopic-scale friction or nanometer-scale science. But mainstream physicists seemed to have no interest in the topic. With near unanimity, they would attribute the origins of friction as something to do with surface roughness. Given the everyday familiarity and economic impact of friction, one would have thought that they might have been more interested. (By most estimates, improved attention to friction and wear would save developed countries up to 1.6 percent of their gross national product, a whopping $116 billion for the U.S. alone in 1995.)

In fact, I wasn't really alone in my research interests. The late 1980s marked the advent of many new techniques, including my own, that could study the force of friction, either experimentally, by sliding atoms on crystalline substrates, or theoretically, using new computer models. I first referred to the field as "nanotribology"—friction, or tribology, studied in well-defined geometries on the nanometer scale—in a January

GRINDING wears away sliding surfaces. Such instances of friction had always been associated with permanent damage to the surfaces. But new studies have shown that friction can persist at high levels even in the absence of wear or damage.

1991 publication, and others began using the term as well. What was once a grassroots community of isolated researchers was progressively becoming an accepted scientific field in its own right.

Since then, nanotribologists have been regularly discovering that atomic-scale friction can differ significantly from what is observed at the macroscopic level. Friction has very little to do with microscopic surface roughness, and in some instances, dry surfaces are actually slicker than wet ones. The force is complex enough that, even if we can perfectly characterize a sliding interface, we cannot accurately predict the friction that will occur at that interface. If the precise nature between microscopic contacts and macroscopic materials could be determined, then better understanding of friction could lead to such industrial innovations as improved lubricants and wear-resistant machine parts.

Such technological considerations have driven humans to attempt to understand friction since prehistoric times. More than 400,000 years ago, our hominid ancestors in Algeria, China and Java were making use of friction when they chipped stone tools. By 200,000 B.C.E., Neanderthals had achieved a clear mastery of friction, generating fire by the rubbing of wood on wood and by the striking of flint stones. Significant developments also occurred 5,000 years ago in Egypt, where the transportation of large stone statues and blocks for the construction of the pyramids demanded tribological advances in the form of lubricated wooden sledges.

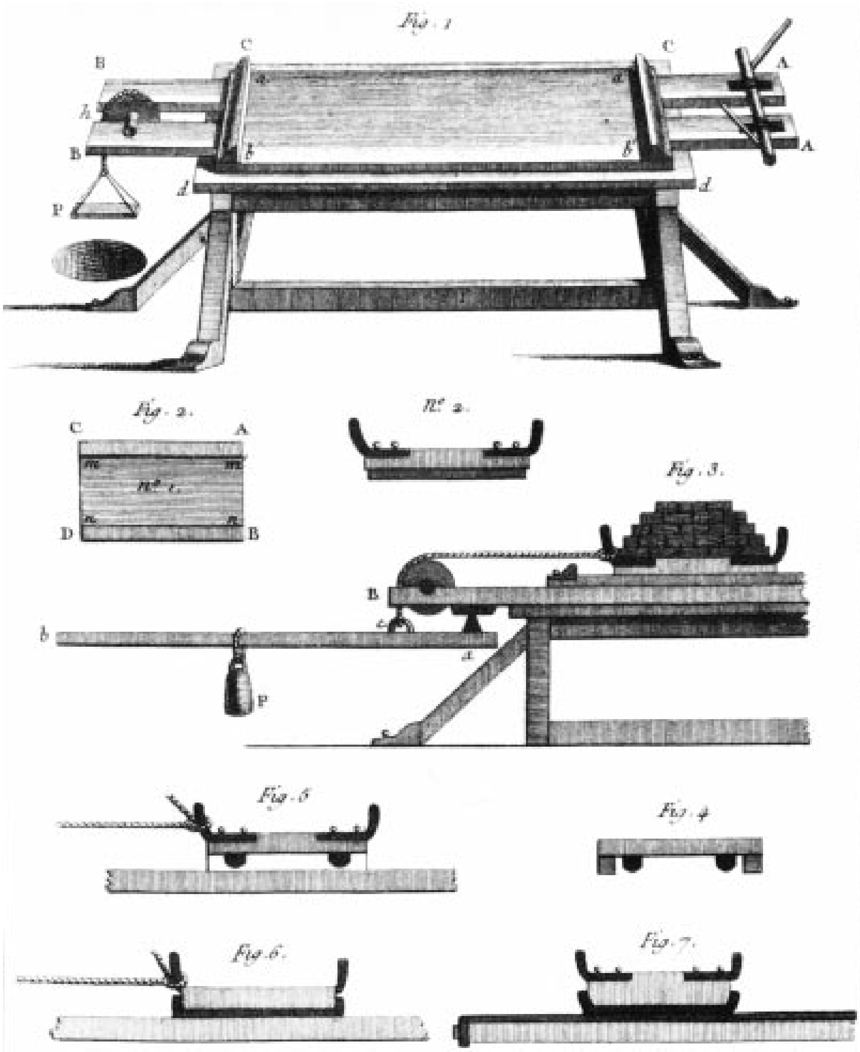

FPG INTERNATIONAL

Writing the Classics

Modern tribology began perhaps 500 years ago, when Leonardo da Vinci deduced the laws governing the motion of a rectangular block sliding over a flat surface. (Da Vinci's work had no historical influence, however, because his notebooks remained unpublished for hundreds of years.) In the 17th century the French physicist Guillaume Amontons rediscovered the laws of friction after he studied dry sliding between two flat surfaces.

Amontons's conclusions now help to constitute the classic laws of friction. First, the friction force that resists sliding at an interface is proportional to the "normal load," or the force that squeezes the surfaces together. Second, and perhaps counterintuitively, the amount of friction force does not depend on the apparent area of contact. A small block sliding on a surface experiences as much friction as does a large block of the same weight. To these rules is sometimes added a third law, attributed to the 18th-century French physicist Charles-Augustin de Coulomb (better known for his work in electrostatics): the friction force is independent of velocity once motion starts. No matter how fast you push a block, it will experience nearly the same amount of resistance.

Amontons's and Coulomb's classical friction laws have far outlived a variety of attempts to explain them on a fundamental basis in terms of, say, surface roughness or molecular adhesion (attraction between particles in the opposing surfaces). By the mid-1950s, surface roughness had been ruled out as a viable mechanism for most everyday friction. Automobile makers and others had found, surprisingly, that the friction between two surfaces is sometimes less if one of the surfaces is rougher than the other [see "Friction," by Frederic Palmer; SCIENTIFIC AMERICAN, February 1951]. Furthermore, friction can in-



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EARLY STUDIES OF FRICTION, such as those done in the 18th century by the French physicist Charles-Augustin de Coulomb, helped to define the classical laws of friction and attempted to explain the force in terms of surface roughness, a feature that has now been ruled out as a significant source.

crease when two surfaces are made smoother. In cold welding, for instance, highly polished metals stick together quite firmly.

Molecular adhesion, though, was a strong possibility, a conclusion reached in large part because of the ingenious work of F. P. Bowden, David Tabor and their co-workers at the University of Cambridge. They also found that friction, though independent of apparent macroscopic contact area, as Amontons had stated, is in fact proportional to the true contact area. That is, the microscopic irregularities of the surfaces touch and push into one another. The sum of all these contact points constitutes the true contact area. Having established that some kind of intimate link existed between friction and adhesion, the Cambridge group presumed that friction resulted primarily from adhesive bonding at true contact points that was so strong that tiny fragments were continually being worn away.

But this explanation was wrong. It simply could not explain the fact that substantial friction exists even in cases in which wear is negligible. Indeed, under Tabor's own supervision in the 1970s, a gifted Ph.D. candidate, Jacob N. Israelachvili, developed a "surface-forces apparatus" for atomic-scale friction measurements and found clear evidence of wear-free friction. The measurement left Tabor to puzzle over where that friction might be coming from.

Israelachvili's apparatus explores the lubricated contacts between uniform mica surfaces. It takes advantage of the fact that mica is atomically smooth: cleaving a piece of mica leaves a surface that has atomically flat areas spanning as much as one square centimeter, a distance of more than 10 million atoms. (In contrast, typical surfaces might stay flat for a distance of 20 atoms, whereas smooth metals might go on for 300 atoms.) When two mica surfaces touch, an interface free of atomic pits or mountains ("asperities") is formed. In the device the backs of the mica surfaces are generally glued onto crossed half-cylinders that can be moved in two directions in the horizontal plane. To measure the contact area and separation, researchers shine a coherent light beam across the gap and look at a resulting optical effect called an interference pattern, a series of dark and light bands. Deflections of springs connected to the half-cylinders indicate the frictional force.

Early on, the surface-forces apparatus allowed atomic-scale verification of the macroscopic deduction that friction is proportional to the true contact area. But it would be nearly two decades before Israelachvili, now a full professor at the University of California at Santa Barbara, and his colleagues would establish the elusive link between friction and adhesion. They discovered that friction did not correlate with the strength of the adhesive bond itself. Rather friction was connected to adhesive "irreversibility," or how differently surfaces behave when they stick together as compared with when they are in the process of becoming unstuck. But in their triumph, the investigators could not address the explicit physical mechanism that gave rise to the friction they were measuring.

James A. Greenwood of the University of Cambridge, a world authority on tribological contact between rough surfaces, summed up the situation in 1992 when he wrote, "If some clever person would explain why friction exists, and is proportional to the [true] area of contact, our problem would be solved."

Good Vibrations

A leading candidate for that clever person is Gary M. McClelland of the IBM Almaden Research Center. In the 1980s he derived a very simple model for wear-free friction based on vibrations of atomic lattices. Unknown to McClelland, the model had been published by G. A. Tomlinson of the British National Physical Laboratory in 1929, as had a far more sophisticated treatment by Jeffrey B. Sokoloff and his co-workers at Northeastern University in 1978. But these works had received little attention.

Friction arising from atomic-lattice vibrations occurs when atoms close to one surface are set into motion by the sliding action of atoms in the opposing surface. (The vibrations, which are really just sound waves, are technically called phonons.) In this way, some of the mechanical energy needed to slide one surface over the other is converted to sound energy, which is eventually transformed into heat. To maintain the sliding, more mechanical energy must be added, and, hence, one has to push harder.

The amount of mechanical energy transformed into sound waves depends on the nature of the sliding substances. Solids are much like musical instruments in that they can vibrate only at certain distinct frequencies, so the amount of mechanical energy consumed will depend on the frequencies actually excited. If the "plucking" action of the atoms in an opposing surface resonates with one of the frequencies of the other, then friction arises. But if it is not resonant with any of the other surface's own frequencies, then sound waves are effectively not generated. This feature opens the exciting possibility that sufficiently small solids, which have relatively few resonant frequencies, might exhibit nearly frictionless sliding.

In any case, McClelland, excited by the fact that not only wear-free but also nearly friction-free sliding was a theoretical possibility, proceeded to collaborate with his colleague C. Mathew Mate and others. To measure nanometer-scale friction, they adapted a newly invented instrument: the atomic-force microscope. With it, they published their first observations of friction, measured atom by atom, in a landmark 1987 paper.

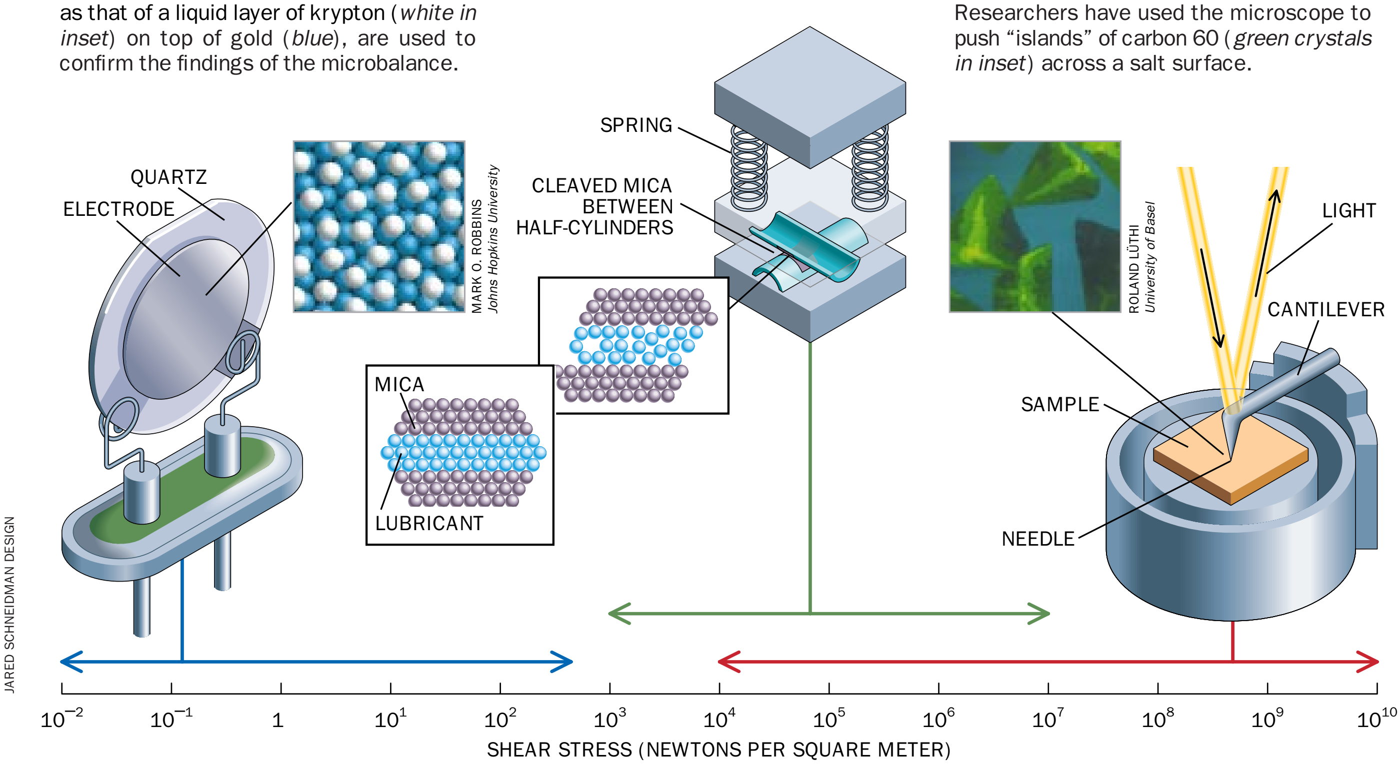
An atomic-force microscope consists of a sharp tip mounted at the end of a compliant cantilever. As the tip is scanned over a sample surface, forces that act on the tip deflect the cantilever. Various electrical and optical means (such as capacitance and interference) quantify the horizontal and vertical deflections. The microscope can detect friction, adhesion and external loading forces as small as a piconewton, or 10^{-12} newton. (Loosely speaking, a piconewton is to a fly's weight as a fly's weight is to an average person's.) By the early 1990s, the IBM researchers had set up their friction-force microscope in ultrahigh vacuums, allowing them to study the sliding of a diamond tip over a crystalline diamond surface with a contact area estimated to be less than 20 atoms in extent.

McClelland and his colleagues' measurements yielded a friction force that exhibited no dependence on normal load. According to the classical friction laws, this result would have implied zero friction. But not only was friction evident, the shear stress, or force per area required to maintain the sliding, was

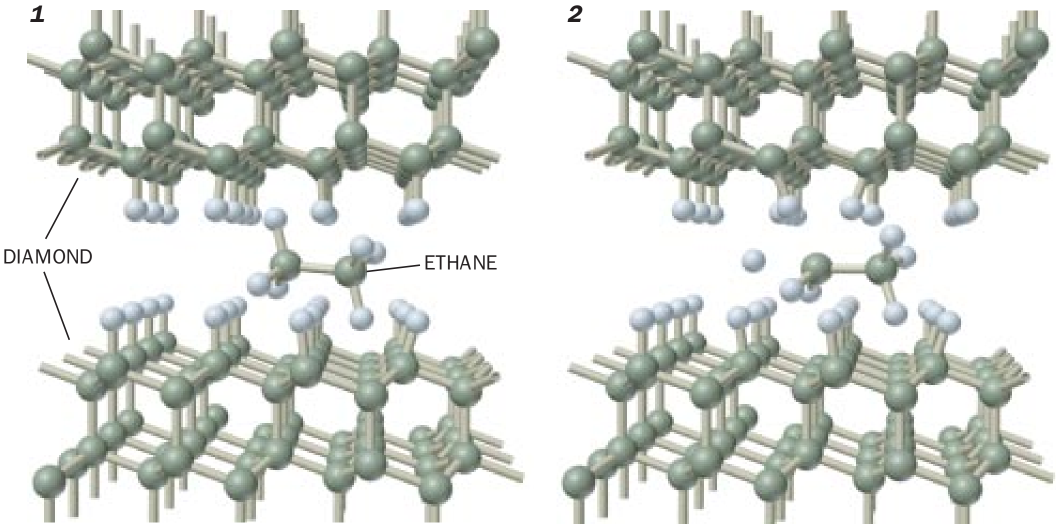
QUARTZ-CRYSTAL MICROBALANCE can measure friction between its electrode and a layer of material only one or two atoms thick deposited on the electrode. Changes in the vibrational properties of the quartz indicate how much the deposited layer slips on the underlying surface. Computer simulations of the sliding layers, such as that of a liquid layer of krypton (*white in inset*) on top of gold (*blue*), are used to confirm the findings of the microbalance.

SURFACE-FORCES APPARATUS makes use of two cleaved mica surfaces, which are the smoothest surfaces known. Investigators can place lubricant films, which can be as thin as a few molecules, between the mica surfaces and slide them about, to see how the films affect the sliding (*insets*).

LATERAL-FORCE MICROSCOPE is a variation of the atomic-force microscope. It employs a fine needle mounted on a cantilever. The tip deflects as it drags along the sample's surface. Light reflecting off the tip indicates the degree of deflection, thus providing a measure of the friction between the tip and the surface. Researchers have used the microscope to push "islands" of carbon 60 (*green crystals in inset*) across a salt surface.



SHEAR STRESS, the amount of force per unit of true contact area needed to maintain the sliding of one object on another, is one measure of friction that has been explored with several instruments. Collectively, they have recorded a range of stress spanning 12 orders of magnitude, all in experimental geometries free of wear, surface damage and roughness.



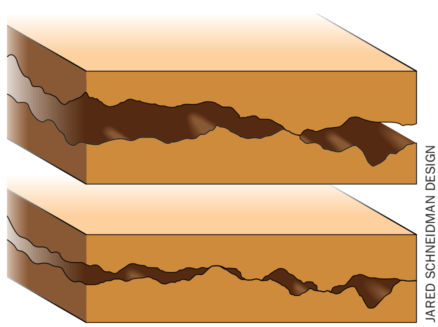
CHEMICAL REACTIONS can occur between two sliding interfaces. In this setup, an ethane molecule, composed of two carbon atoms (*green*) and six hydrogen atoms (*blue*), is sandwiched between two diamond surfaces, which are terminated with hydrogen atoms (*1*). As the surfaces slide, the ethane loses a hydrogen atom (*2*), becoming an ethyl radical. The free

enormous: one billion newtons per square meter, or 150,000 pounds per square inch. That force is large enough to fracture top-grade steel. It was becoming clear that even if the atomic nature of the sliding contact was completely known, our ability to predict the friction force occurring at that contact was virtually nonexistent.

To date, nanotribologists have collectively observed a remarkable range of shear stresses, from 0.01 newton to 10 billion newtons per square meter. For example, Roland Lüthi, Ernst Meyer and coworkers at the Institute of Physics at the University of Basel have pushed “islands” of one-molecule-thick buckminsterfullerene (“buckyballs,” or carbon 60) along a crystalline salt surface with a modified atomic-force microscope tip approaching single-atom dimensions. They found shear stresses of 10,000 to 100,000 newtons per square meter, orders of magnitude lower than those associated with typical macroscopic-scale solid lubricants, such as graphite powder. (The shear stress appears high only because it is measured over a square meter of true—not apparent—contact area, which in general is orders of magnitude smaller than the apparent contact area. When graphite is used, say, to lubricate a lock cylinder, even the apparent contact area is quite small, so the actual friction encountered can be rather low.) The researchers also measured the force needed to slide the tip over the top of the buckyball island and found it to be “stickier” than the salt.

Shear stresses orders of magnitude lower have been observed in my own laboratory by means of a quartz crystal microbalance, a device that for decades has been used to weigh samples as light as a few nanograms. It consists of a single crystal of quartz that stably oscillates at high frequency (five to 10 million times a second). We deposit metal-film electrodes onto its surfaces and then condense single-atom-thick films of a different material onto the electrodes. The condensation onto the microbalance lowers the frequency, providing a measure of how well the film particles can track the shaking of the underlying quartz substrate. The smaller the resulting amplitude of vibration, the greater the friction from the “rubbing” action of the film sliding about on the substrate.

The quartz microbalance is currently the only experimental apparatus operating on a timescale short enough to see how atomic-scale friction depends on velocity. Although the third classic law of friction states that friction is independent of velocity, researchers later found this rule to be untrue. (Coulomb himself suspected as much but could not prove it.) For example, to decelerate an automobile uniformly and stop it without a jerk, the driver must ease up on the brake in the final moments, demonstrating that friction increases with slower speeds. Such macroscopic velocity dependencies are almost always attributed to changes at the microscopic contact points (which can melt at high sliding speeds and can increase in area at low speeds, where they “tear apart”



CONTACT POINTS are the places where friction occurs between two rough surfaces sliding past each other (*top*). If the “normal load”—the force that squeezes the two together—rises, the total area of contact increases (*bottom*). That increase, and not the surface roughness, governs the degree of friction.

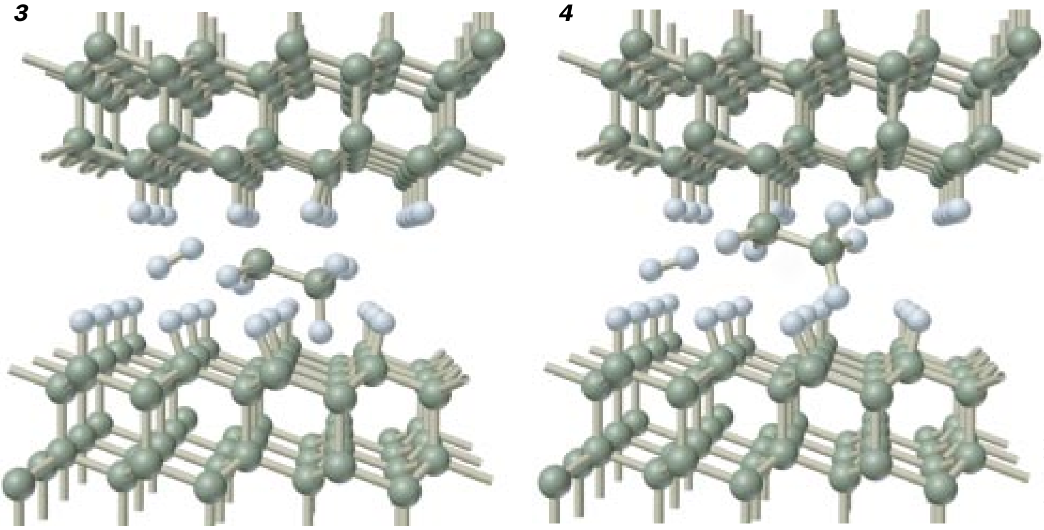
more slowly and hence have more time to form bonds). But for a geometry in which the contact area remains fixed, such as that of our quartz microbalance, friction is in fact predicted to exhibit just the opposite behavior, increasing in direct proportion to the sliding speed. We recently confirmed this observation for one-atom-thick solid films sliding over crystalline silver and gold surfaces.

Slippery when Dry

But analytic theories did not predict our surprising discovery in 1989 that krypton films sliding on crystalline gold surfaces were slipperier when dry. We observed that friction forces for liquid films were about five times higher than for solid films, with shear stresses for the solid films being a minuscule 0.5 newton per square meter for sliding speeds of one centimeter per second. The effect was so counterintuitive to me that I held off publishing the result for more than a year after discovering it.

Why should a liquid layer cause more friction on the atomic scale when in most situations in everyday life it lubricates two surfaces? Computational studies have supplied the crucial link, for they open a rare window into molecu-

3 4



MICHAEL GOODMAN

hydrogen subsequently removes a hydrogen atom from the diamond and bonds with it to form a molecule of hydrogen gas (*3*). The ethyl radical eventually becomes chemically bound to one of the diamond surfaces (*4*). The diagram is based on computer simulations conducted by Judith A. Harrison and her co-workers at the U.S. Naval Academy.

lar behavior that is unattainable by any other means. Several researchers have broken new nanotribological ground with the computer. They include Uzi Landman of the Georgia Institute of Technology, who pioneered simulations of point contacts; Judith A. Harrison of the U.S. Naval Academy, who modeled interfacial chemical effects; and James Belak of Lawrence Livermore National Laboratory, who analyzed machining and wear.

It was Mark O. Robbins and his co-workers at Johns Hopkins University, though, who answered the question of liquid friction when they simulated one-atom-thick krypton films sliding on crystalline gold surfaces. They demonstrated that liquid krypton atoms, being more mobile than solid krypton, could "get stuck" more easily in the gaps between the solid gold atoms. Note that the shearing takes place between a solid and a liquid surface, a situation different from macroscopic cases of liquid lubrication. In those instances, the shearing takes place within the bulk of the liquid (that is, at a liquid-liquid interface), which usually offers less resistance to shearing than does a solid-liquid interface.

The near-perfect agreement between Robbins's model and our experimental result is both surprising and revealing, because all the friction in his calculations was attributed to lattice vibrations (sound waves). His model neglected friction from electrical effects. For insulating surfaces, such friction arises from the attraction of positive and negative charges that have separated at the interface. (A similar attraction is achieved when a balloon is rubbed on hair and left to cling to a wall.) When one or both of the surfaces in contact are metal, however, then the buildup of charge should not be significant. Rather another type of electronic friction may occur, as suggested by Mats Persson of Chalmers University of Technology in Göteborg, Sweden, and extensively investigated by theorist Bo N. J. Persson of the Jülich Research Center in Germany. That friction is related to resistance felt by mobile electrons within the metallic material as they are dragged along by the opposing surface.

Physicists know that such friction exists but not how important it is (which is why small solids might exhibit nearly frictionless, instead of completely frictionless, sliding). The success of the model calculated by Robbins and his colleagues seemed to imply that electronic effects play no significant role in friction.

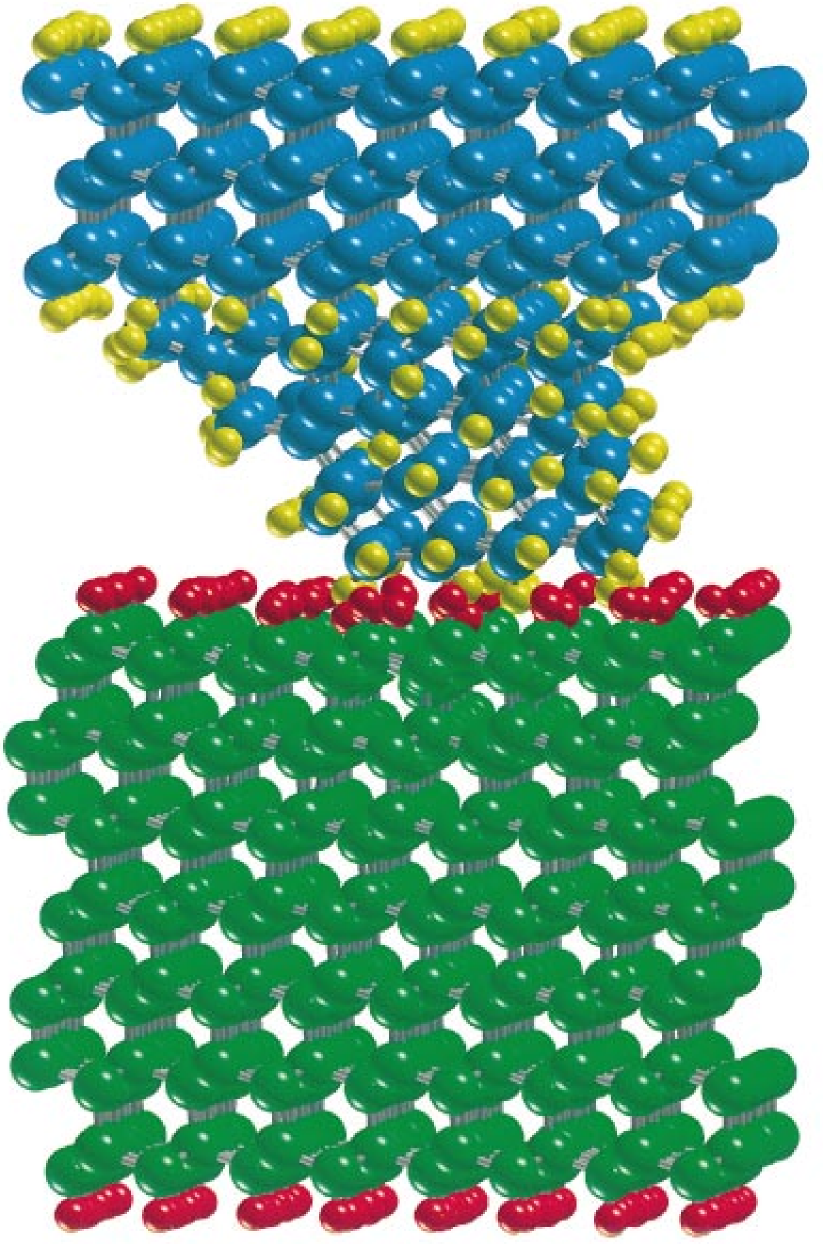
To investigate this issue further, we recently measured the force needed to slide one- and two-atom-thick solid films of xenon along a crystalline silver surface, and we observed that friction increased by approximately 25 percent for the two-atom-thick xenon film.

Did this 25 percent increase stem from electronic effects? Probably not. Bo Persson, Robbins and Sokoloff have performed independent computer simulations of the xenon-silver system, and their preliminary computational results indicate that the friction associated with sound waves is much greater for two layers than for one. Basically, two layers make for a more elaborate "musical instrument," so there are more resonant frequencies to excite and hence more friction. Electronic friction undoubtedly exists, but its strength may be determined in large part by only those atoms immediately adjacent to the interface. The parameters selected to represent metal surfaces in a simulation could easily mask it. But as theoretical and simulational efforts become increasingly sophisticated, we should eventually be able to estimate with precision the proportion of energy loss that is associated with electronic effects and lattice vibration.

Rewriting the Rules

The recent progress in nanotribology clearly demonstrates that the laws of macroscopic friction are inapplicable at the atomic scale. We can now rewrite the laws of friction in a more general way. First, the friction force depends on how easily two surfaces become stuck relative to becoming unstuck: it is proportional to the degree of irreversibility of the force that squeezes the two surfaces together, rather than the outright strength of the force. Second, the friction force is proportional to the actual, rather than apparent, area of contact. Finally, the friction force is directly proportional to the sliding speed of the interface at the true contact points, so long as the surfaces are not allowed to heat up and the sliding speed remains well below the speed of sound. (Near that speed, it levels off because the lattice vibrations cannot carry away the sound energy rapidly enough.)

The discrepancy between microscopic and macroscopic frictional phenomena greatly diminishes if one notes that the true area of contact between macroscopic objects is likely to be proportional to the squeezing force. The harder you squeeze, the more area comes into con-



JUDITH A. HARRISON *U.S. Naval Academy*

DIAMONDLIKE TIP made of carbon (*blue*) and hydrogen (*yellow*) slides across the face of a similar material, a diamond surface made of carbon (*green*) and terminated with hydrogen atoms (*red*). Such computer simulations help in tribochemistry, or the study of friction-induced reactions. In this particular computation, the tip and surface deformed, but no chemical reactions occurred.

tact. So friction appears to be proportional to the normal load, as Amontons stated.

And what ever became of surface roughness? Alas, its importance seems to shrink. Physicists had presumed that surface irregularities played a role in stick-slip friction, in which surfaces gliding past one another momentarily cling and then let go. Notable examples include screeching train brakes and fingernails on blackboards. Roughness was thought to cause the random nature of the sticking and the slipping. But Steve Granick and his colleagues at the University of Illinois recently observed stick-slip friction in lubricated contacts between nominally "perfect" mica surfaces. They applied millions of repetitive cycles of a sinusoidal force to confined liquids without wear and observed results suggesting that randomness (specifically, so-called 1/*f* noise) may be intrinsic to the stick-slip friction itself.

Considering the current race to manufacture machine components with astoundingly small dimensions, what is today considered fundamental research on the atomic scale may give way tomorrow to direct application. For instance, we now know why substances made of branched-chain molecules make better lubricants than straight-chain molecules, even though the branched-chain ones are, in bulk form, more viscous. (They remain as a liquid under greater forces than do the straight-chained molecules and thus are better able to keep two solid surfaces from touching.) Nanotribologists working with known contact geometries may one day help chemists understand friction-induced reactions taking place on surfaces or aid materials scientists in designing substances that resist wear. As the need to conserve both energy and raw materials becomes more urgent, physicists' rush to understand basic frictional processes can be expected only to accelerate. SA

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The Author

JACQUELINE KRIM, a professor of physics at Northeastern University and a member of its Center for Interdisciplinary Research on Complex Systems, received her B.A. from the University of Montana and her Ph.D. from the University of Washington. She received a National Science Foundation Presidential Young Investigator Award in 1987 and a creativity award in materials research in 1992. She has chaired the national board of trustees of the American Vacuum Society and currently serves on the executive board of its surface science division. She thanks the NSF for its continued research support.

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Controlling Computers with Neural Signals

Electrical impulses from nerves and muscles can command computers directly, a method that aids people with physical disabilities

by Hugh S. Lusted and R. Benjamin Knapp

In the classic science-fiction movie *Forbidden Planet,* space travelers from Earth land on a distant world, where they encounter the remnants of a technologically advanced civilization. Remarkably, the human visitors are able to communicate with one of the alien computers that is still functioning. Connected through glowing head probes, the men's thoughts and feelings are directly conveyed to the machine over a neural link.

Many similar examples of people having their minds coupled to computers have appeared in other works of fiction. As often depicted, a person simply thinks of a command, and the computer immediately responds—a scheme analogous to the computer voice recognition in use today. Thought recognition would be the ultimate computer interface, the machine acting as an extension of the human nervous system itself.

Computer technology has advanced markedly in the 40 years since *Forbidden Planet* was released, but constructing a versatile neural junction between a human brain and an electronic one remains a formidable challenge. Attempts to tie the nervous system to external electronic circuits are, however, well worth pursuing because the results may provide the means for effortless communication with computers. This work is already extremely valuable to people with devastating neuromuscular handicaps—a group usually without access to computers or indeed much opportunity to influence the world.

Our work over the past decade has helped make such "hands free" control of computers a reality. Neural linkages with computers can now satisfy a variety of needs, and we expect that enterprising people will soon find additional ways to harness this technique. A view of what the future holds in store requires only some imagination—and a clear understanding of how past work has led to today's accomplishments.

The Body Electric

The electrical nature of the human nervous system—the basis for direct neural control of computers—has been recognized for more than a century. In 1849 the German physiologist Emil Heinrich Du Bois-Reymond first reported the detection of minute electrical discharges created by the contraction of the muscles in his arms. He made these observations using a primitive device for measuring voltages called a galvanometer. Du Bois-Reymond attached the wires of this instrument to his body using pieces of saline-soaked blotting paper to keep electrical resistance in the connection to a minimum. But he soon realized that the skin acted as a barrier to the underlying muscle signals. So this dedicated researcher induced a blister on each arm, removed the skin and placed the paper electrodes within the wounds. Du Bois-Reymond was then able to capture electrical signals that were about 30 times stronger than those he could obtain with the skin intact.

These early investigations built the foundation for a technique that serves well today to monitor muscle contractions. With modern silver chloride electrodes and sensitive electronic amplifiers, tiny muscle impulses—even those muted by passage through the skin—provide easily registered voltages. Medical researchers first exploited this phenomenon during the 1970s to devise mechanized prostheses that could operate by sensing muscle contractions. Other scientists realized that electrical impulses from active muscle fibers could also help people who suffered from diseases or injuries that left them too weak to move any of their limbs: they needed only to have electrodes placed near unimpaired muscles. Following that strategy, even profoundly handicapped individuals can

STEPHEN FERRY

SELECTION FROM A MENU on a personal computer usually requires manipulation of a keyboard or mouse. Yet physically handicapped people, using their body's electrical signals, can also command a computer. For example, Heather Black has severe cerebral palsy, but she can operate a computer by fixing her gaze on one of many flashing squares on the screen. Electrodes on the back of her head pick up the signals evoked by the flashes, and the timing of these impulses identifies her choice.

manipulate electronic equipment with the electrical signal from muscles (called an electromyographic signal, or EMG, a name borrowed from the term for a paper tracing of such impulses).

But one cannot simply attach EMG sensors to a person's skin and plug the wires into the back of a conventional computer. The task requires specialized circuits and software to analyze and interpret the pattern of muscle impulses. To aid others involved in these efforts, we have designed equipment to serve as a general-purpose interface between a computer and the body's various electrical signals. We dubbed our creation the Biomuse.

The work of translating muscle impulses to a form more appropriate for a digital computer begins with the amplification of the raw signals sensed by the electrodes, which increases these voltages by a factor of about 10,000. Other circuits then convert the amplified EMG signals to digital form. After much additional processing of these digitized measurements, a computer can determine when muscle fibers near the electrodes are contracting and by how much. In this way, the muscle activity can direct the operation of a personal computer—just as one might employ a computer mouse or trackball.

Some arrangements to control computers using muscle signals have proved particularly valuable to handicapped people. For instance, in 1993 David J. Warner, a neuroscientist at Loma Linda University Medical Center in California, connected the electrodes from our EMG apparatus to the face of a 10-year-old boy who had been completely paralyzed below the neck in an automobile accident. By tensing certain facial muscles, the young patient could move objects

STEPHEN FERRY

ARM MUSCLES of a woman with cerebral palsy, Dawn Parkot (*foreground*), generate electrical signals that a computer can sense. Electrodes underneath the black band on her left arm pick up tiny voltage fluctuations that change when groups of muscle fibers begin contracting. With the computer displaying these biological signals, this engineering graduate student at the University of Notre Dame learns to vary muscle activity in her forearm from low (*left*) to high (*right*).

on the computer screen—the first time since his injury that the child could manipulate a part of his environment without aid.

But people do not have to be physically impaired to benefit from the ability of muscle signals to control a computer. We are, for example, now experimenting with a hands-free EMG mouse. With it, a person can adjust the position of a cursor on the screen using, for example, forearm muscles. Such a device allows someone to move the cursor without having to lift a hand from the keyboard.

Unrecognized Potential

Another approach to controlling computers with biological signals depends on a completely different electrical phenomenon of the human body: the corneal-retinal potential. This signal arises because the retina, the site of most metabolic activity within the eye, exhibits a slight negative voltage compared with the cornea. In a sense, the eye acts as a weak electric battery. Electronic circuits can detect the tiny voltage fluctuations on a person's face that arise when the eyes shift in orientation. These impulses are called an electrooculographic signal, or EOG (the name for recordings made of them).

Measurement of EOG signals has served researchers for decades as a convenient indicator of eye movement in various physiological studies. In 1953, for example, Nathaniel Kleitman of the University of Chicago and Eugene Aserinsky of Jefferson Medical College in Philadelphia used EOG recordings to document eye movement during certain periods of sleep. These particular intervals were accompanied by intense brain activity similar to that of the awake state, and so the investigators distinguished this curious type of slumber by calling it rapid-eye-movement, or REM, sleep.

Although investigators had previously used the EOG merely to record the overall motion of the eyes, by the late 1980s it seemed feasible that measurements of the corneal-retinal potential could also indicate the direction of a person's gaze. With the proper arrangement of electrodes, EOG voltages will vary proportionally with eye rotations over a range of about 30 degrees from center. By 1990 several research groups had reported some success in using this method to move a computer cursor. Still, skeptics continued to believe that electrical "noise" in the form of gradual changes in the voltage across the electrodes ("electrode drift") would render this approach unworkable for anything other than a laboratory demonstration.

Our efforts did, however, uncover a way to eliminate the interference and construct a practical device for controlling computers. To accomplish that result, we employed the same system we had used for detecting muscle signals but this time configured the apparatus as an EOG monitor. As with EMG processing, the EOG analyzer begins by amplifying and digitizing the voltages obtained from several electrodes (one pair of electrodes serves to detect vertical eye displacements; another set indicates horizontal eye movements). The system then applies so-called fuzzy logic to discriminate between true eye movement and electrode drift [see "Fuzzy Logic," by Bart Kosko and Satoru Isaka; Scientific American, July 1993].

With this equipment, a person can reliably operate a computer with eye movements—for instance, by positioning the cursor at various points on the screen. There are other techniques for tracking a person's gaze that utilize infrared beams or video cameras. But EOG equipment proves much less costly than alternative strategies, making it possible for more people to consider using eye motion to operate computers—in particular, as an aid for the disabled.

At Loma Linda in 1991, Warner tried our eye-tracking system to help a youngster who had sustained a serious injury to her spinal cord as an infant. Because of her age at the time of her accident, the doctors at the center were concerned that the girl's physical restrictions would compromise the development of her brain. Fitted with a special EOG headband and placed in front of a video monitor, the 18-month-old girl quickly discovered that she could move an icon (a smiling face) about the screen with just her eyes. She understood intuitively how to control the display without having been told how the system worked.

Other institutions dedicated to the rehabilitation of paralysis victims have used similar equipment in conjunction with "visual keyboard" software that displays a standard typewriter keyboard. Using eye movements alone, an operator can select letters from the keys presented on the screen. Although the process of forming words in this way is slow, with practice (and some clever software aids) people can complete multiple sentences, even whole documents, by a continuous succession of glances.

Tracking a person's gaze with EOG signals can be done so reliably that a number of groups are also attempting to integrate this mechanism in other settings. For instance, we have collaborated with physicians from Stanford University to develop a way to adjust the fiber-optic cameras used during endoscopic surgery (procedures performed remotely, inside the body). Our EOG device allows a doctor to change the camera's view with eye movements, while his or her hands are engaged in manipulating other surgical instruments.

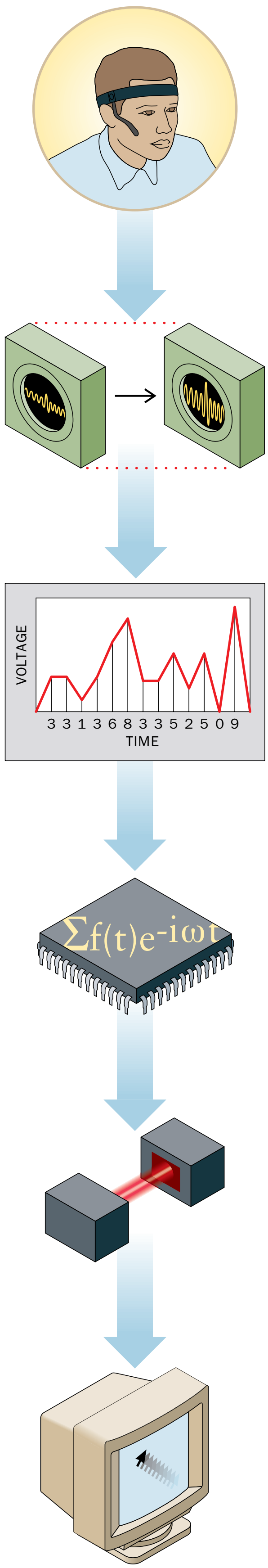
Mind Control

Devices that detect EMG or EOG signals have successfully linked humans to computers for a wide variety of applications, but in each case the process relies on tiny biological voltages from muscles or eyes. Is it possible to make a neural connection without those intermediaries? Indeed, some people have operated computers in a rudimentary fashion using the underlying electrical activity of the brain itself.

That the human mind produces measurable electrical signals is no surprise. In 1929 the German psychiatrist Hans Berger coined the term "electroencephalogram," commonly known as EEG, to describe recordings of voltage fluctuations of the brain that can be detected using electrodes attached to the scalp. These EEG signals arise from the cerebral cortex, a several-centimeter-thick layer of highly convoluted neuronal tissue. Neurophysiologists believe that the pyramidal cells of the cerebral cortex are the source of EEG voltages. Each of these nerve cells constitutes a tiny current dipole, with a polarity that depends on whether the net input to the cell is inhibitory or excitatory. Hence, the layer of densely packed pyramidal cells in the brain produces a constantly shifting configuration of electrical activity as the nerve impulses change. Measurements on the scalp can detect the underlying electrical patterns, albeit in a form that is attenuated and unfocused by passage through the skull.

For decades, researchers have sought to correlate various EEG signals with particular behaviors or sensations, and the results of these studies have slowly

Components of the Biomuse System



JARED SCHNEIDMAN DESIGN

USER
A person using the system to translate biological impulses into commands for an ordinary computer must wear a specially designed headband or armband. Within the band are several electrodes that can detect electrical signals that emanate from eyes or muscles and pass through the skin.

AMPLIFIER
The tiny signals detected by the electrodes first need to be amplified so that they are many thousands of times stronger. The chief technical difficulty is that small amounts of electrical noise can easily become amplified as well—unless certain precautions are taken. One common strategy is to use a so-called differential amplifier, a device that amplifies only the difference in voltage between two points. This tactic works because most sources of electrical noise tend to affect all signals equally. Hence, the difference in electrode voltages will remain uncontaminated.

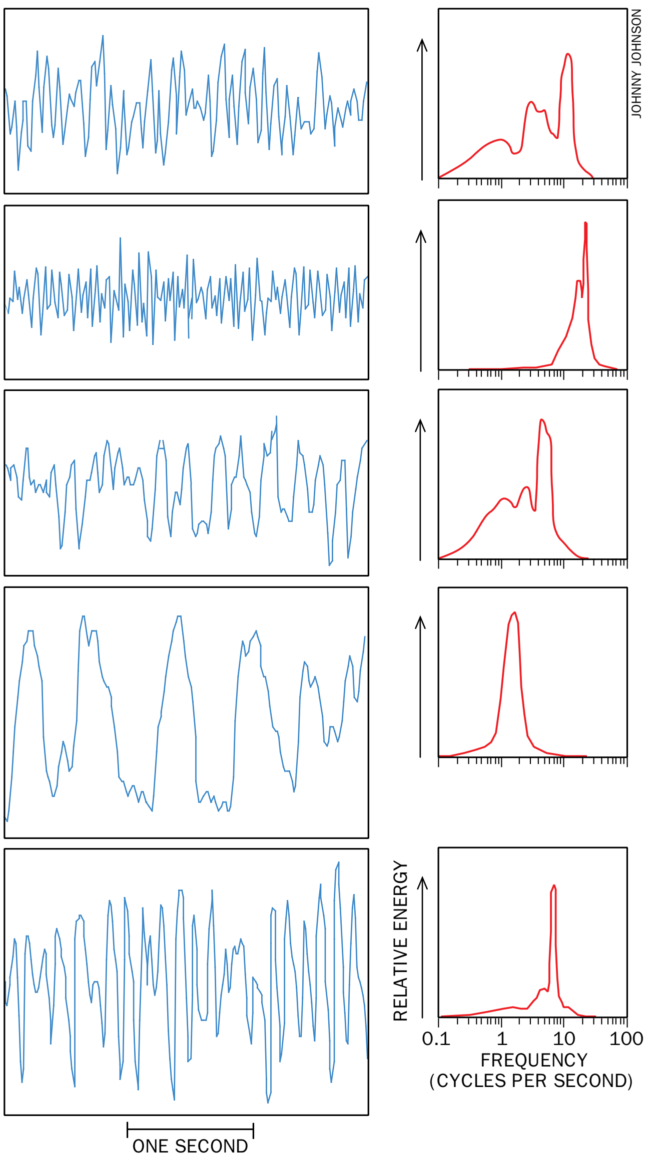
ANALOG-TO-DIGITAL CONVERTER
The amplified voltages need to be translated to a form that a computer can understand. To accomplish this task, a specialized circuit called an analog-to-digital converter repeatedly samples the incoming signal—doing so as rapidly as 4,000 times a second. This circuitry then converts the voltage levels to a series of numbers. The precision of this conversion is such that the error introduced by translation to digital form is limited to a small fraction of a percent of typical signal levels.

DIGITAL-SIGNAL PROCESSOR
The digital-signal processor is a computer "chip" that is similar in many ways to the integrated circuits that serve as central processing units in personal computers. A digital-signal processor is, however, designed to perform certain numerical calculations swiftly and efficiently. In this system it acts to extract important features in the sequence of numbers it receives from the analog-to-digital converter and to recognize particular patterns in this data stream. Then, using these results, it recognizes which muscles generated the original electrical signals.

OPTICAL ISOLATION
Because electric shock can occur whenever electrodes on the skin are connected to a high-voltage appliance (in this case, a computer), precautions have to be taken to avoid injury. In this system the electrical signal is interrupted at one point and transformed to an optical signal that is transmitted over a short distance. By breaking the electrical path with an optical link, the signal can pass unimpeded, but the possibility of electric shock is greatly reduced.

PERSONAL COMPUTER
A personal computer displays the signals detected and processed by the other components of the system. Depending on the electrical signals generated initially by eye movements or muscle contractions, the computer can operate another computer or a separate electronic device. The computer also allows easy adjustment of the system's controls, including the overall level of amplification and the specific actions of the digital-signal processor.

A Sampling of Brain Waves



ALPHA WAVES, brought on by unfocusing one's attention, have relatively large amplitude and moderate frequencies.

BETA WAVES, the result of heightened mental activity, typically show rapid oscillations with small amplitudes.

THETA WAVES, which can accompany feelings of emotional stress, are characterized by moderately low frequencies.

DELTA WAVES result from an extremely low frequency oscillation that occurs during periods of deep sleep.

MU WAVES, which resemble croquet wickets in shape, are associated with physical movements or the intention to move.

outlined a functional map of the human cerebral cortex. Scientists can now tailor their EEG experiments by placing electrodes on one part of the scalp, directly over the source of activity they desire to monitor. In order to use this electrical activity to operate a computer, some workers have attempted to isolate specific EEG signals that people can adjust at will. Unfortunately, the electrical output of the brain is not easily controlled. A common strategy calls for measuring a variety of EEG signals continuously and filtering out the unwanted components.

The analysis of continuous EEG signals, or brain waves, is something of a science in itself, complete with its own set of perplexing nomenclature. Different waves, like so many radio stations, are categorized by the frequency of their emanations or, in some cases, by the shape of their waveforms. Five types are particularly important.

Alpha waves (those in the frequency band between eight and 13 hertz) can be brought on easily by actions as simple as closing one's eyes; these waves are usually quite strong, but they diminish in amplitude when a person is stimulated by light, concentrates on vivid imagery or attempts other mental efforts. Beta waves (typically from 14 to 30 hertz) are associated with an alert state of mind and can reach frequencies near 50 hertz during intense mental activity. Theta waves (four to seven hertz) arise from emotional stress, especially frustration or disappointment. Delta waves (below 3.5 hertz) occur during deep sleep. Mu waves (also known as the wicket rhythm because the rounded EEG traces resemble the wickets used in the lawn game croquet) appear to be associated with the motor cortex: they diminish with movement or the intention to move.

Most attempts to control a computer with continuous EEG measurements work by monitoring alpha or mu waves, because people can learn to change the amplitude of these two rhythms by making the appropriate mental effort. A person might accomplish this result, for instance, by recalling some strongly stimulating image or by raising his or her level of attention.

Over the past decade Jonathan R. Wolpaw and Dennis J. MacFarland of the New York State Department of Health Wadsworth Center in Albany have taught patients to control the amplitude of their mu waves by visualizing various motor activities, such as smiling, chewing or swallowing. With enough practice, the trainees could learn to manipulate a computer cursor that was programmed to shift with changes in the amplitude of the measured mu waves.

We have also experimented with brain waves. In 1987 we first configured one of our Biomuse devices to act as an EEG monitor and set it to adjust a music synthesizer. That exercise provided a dramatic demonstration of the power of this technique. We arranged the system to detect bursts of alpha-wave activity, which can be brought on at will, for example, by unfocusing one's attention. Such equipment constitutes a brain-activated electronic switch, a device that even a person with severe physical disabilities can trigger.

For example, we have developed similar equipment for a Brazilian patient immobilized with advanced amyotrophic lateral sclerosis (also known as Lou Gehrig's disease). To type words, he employs our alpha-wave switch and a personal computer using special visual keyboard software. It is a laborious process because he can make only yes or no responses and must go through as many as six iterations before he can narrow the search to a single key. Still, he now has an electronic aid that allows him to communicate, a vital ability that had previously been completely lost to him.

Other handicapped people have benefited from a second type of brain-wave-measuring apparatus, one that monitors what is called the evoked potential, or EP, action of the brain. The EP signal arises in response to certain stimuli—such as a loud noise or a flash of light—a tiny fraction of a second after it is provoked. The method of EP detection has been used by a number of researchers for controlling computers with the brain's electrical activity. In particular, Erich E. Sutter of the Smith-Kettlewell Eye Research Institute in San Francisco has developed a system that allows physically handicapped people to select words or phrases from a menu of flashing squares on a computer monitor. By keeping a gaze fixed on the appropriate square for a second or two, a person wired with scalp electrodes can convey a choice to the computer. The machine monitors the form and timing of the EP response and so can discriminate which of the coded flashes caused the evoked electrical activity in the brain. The computer can then pick out the one item chosen from the group of words or phrases presented on the screen.

Like Sutter, Grant McMillan and his colleagues at the Alternative Control Technology Laboratory of Wright-Patterson Air Force Base in Dayton, Ohio, are similarly experimenting with EP signals. They hope to help military pilots by teaching them how to modify the magnitude of EP signals at will. This mechanism provides a coarse auxiliary control—one that pilots can operate even when their hands and feet are busy flying the airplane.

Future Shocks

Although it is clear that an immense amount of electrical activity accompanies the thought processes of the human brain, researchers can recognize only a few of these underlying patterns from voltage fluctuations on a person's scalp. There has been little success, for example, in pinpointing which particular set of brain waves will consistently arise when a person thinks of something as specific as a single word or letter of the alphabet. But more advanced systems for unraveling complex brain waves might yet succeed in accomplishing this feat.

The prospects for controlling computers through neural signals are indeed difficult to judge because the field of research is still in its infancy. Much progress has been made in taking advantage of the power of personal computers to perform the rapid-fire operations needed to recognize patterns in biological impulses, and the search continues for new signals that may be even more useful than those tapped so far. Newly developed software is also just now being distributed that can use the existing speed and sophistication of modern computer hardware most effectively.

If the advances of the next century match the strides of the past few decades, direct neural communication between humans and computers may ultimately mature and find widespread use. Perhaps newly purchased computers will one day arrive with biological signal sensors and thought-recognition software built in, just as keyboard and mouse are commonly found on today's units. If so, computer buffs of the 21st century may be surprised to find that this method of directing their machines had first been developed in the 1990s through the efforts of a handful of academic researchers and a determined group of physically handicapped pioneers. SA

STEVE MUREZ *Black Star*

MUSICAL COMPOSITIONS that depend only on muscle signals have been performed by Atau Tanaka. The signals sensed by electrodes within the composer's two armbands operate a computer that in turn controls various electronic instruments.

The Authors

HUGH S. LUSTED and R. BENJAMIN KNAPP have worked together for a decade. Lusted received a doctoral degree from the Stanford University School of Medicine in 1980 before spending a year studying nerve regeneration at the University of London. He then returned to Stanford to help develop an electronic cochlear implant—a device he and his colleagues casually referred to as a "bionic ear." It was during this time that he met Knapp, who had come to Stanford after completing a bachelor's degree in electrical engineering at North Carolina State University. In 1989 Knapp earned his doctorate in electrical engineering at Stanford, and he now serves on the faculty at San Jose State University. Lusted and Knapp founded Biocontrol Systems in 1989. They each have an interest in music (particularly, electronically generated forms), and both maintain affiliations with the Center for Computer Research in Music and Acoustics at Stanford.

Further Reading

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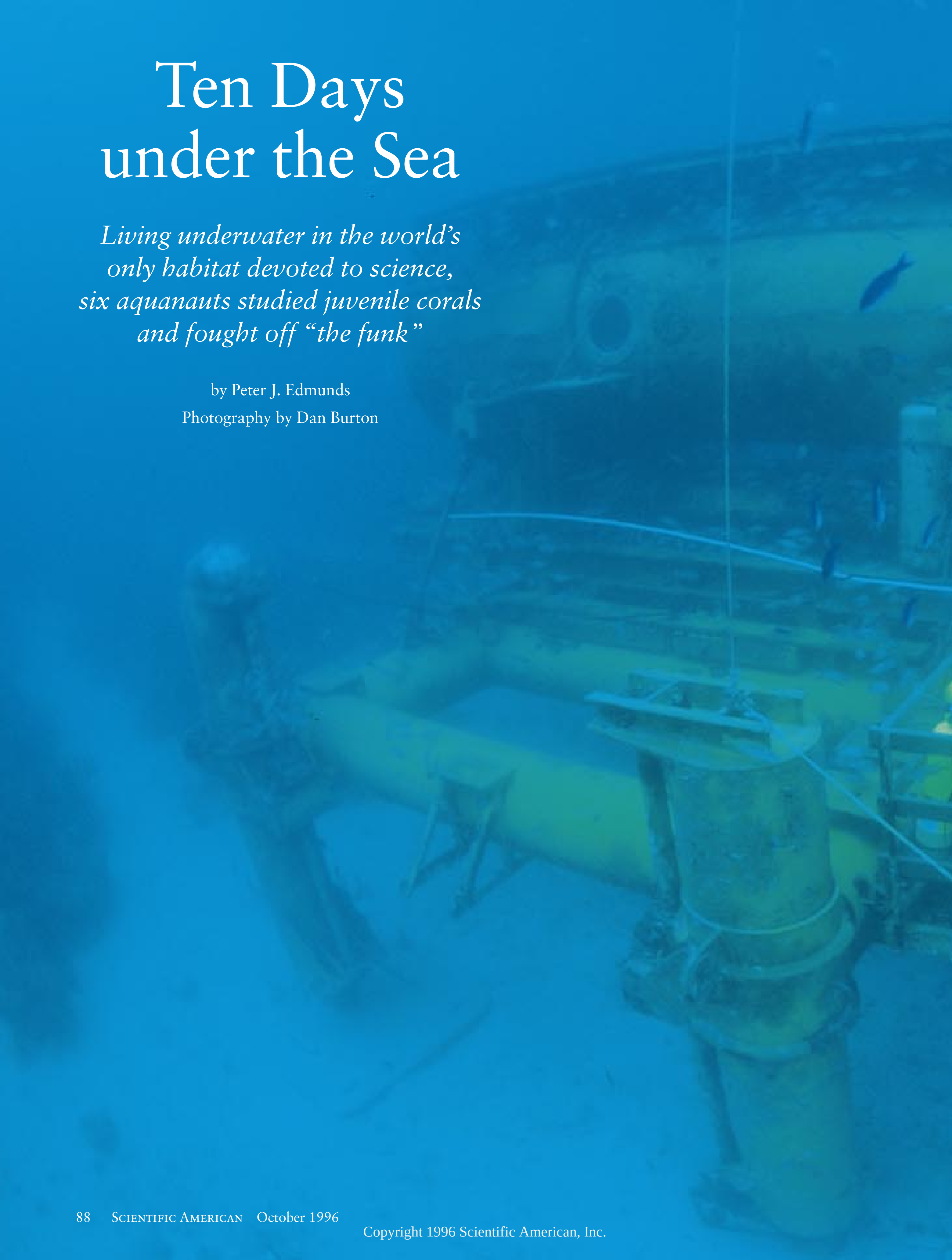
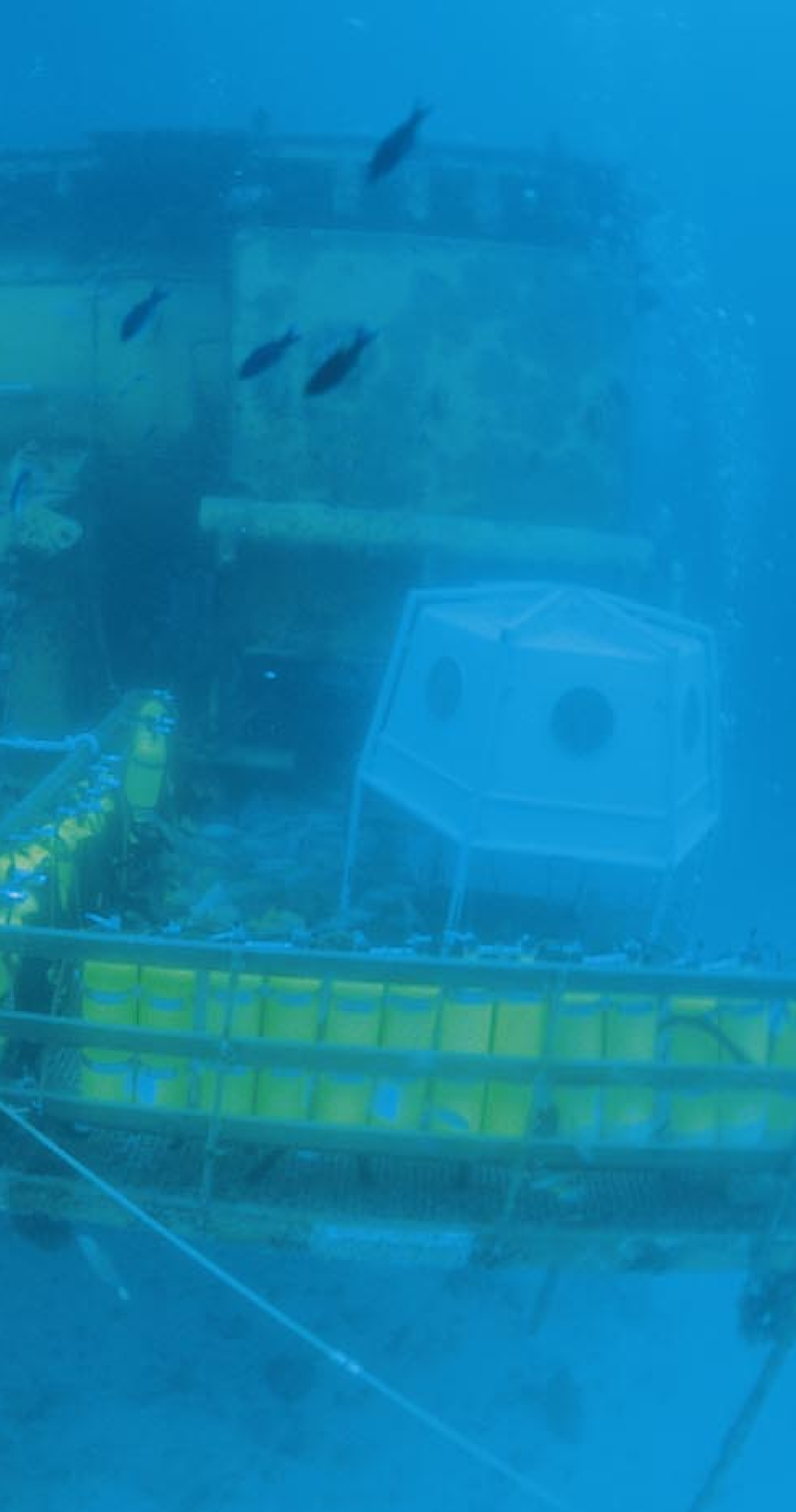
Ten Days under the Sea

Living underwater in the world's only habitat devoted to science, six aquanauts studied juvenile corals and fought off "the funk"

by Peter J. Edmunds
Photography by Dan Burton





It was an overcast July morning as we hopped on board the motorboat that would take us away from open spaces, dry land and summer breezes for a week and a half. We were about to begin an underwater mission in the *Aquarius* habitat, a six-person research station situated 6.5 kilometers off Key Largo, Fla., and 15 meters beneath the waves.

Behind us were four days of training, a year of preparation and, in my case, a lifetime of ambition to work underwater as a marine biologist. In the late 1980s I had been struck by the devastation wreaked by Hurricane Hugo on Caribbean reefs, particularly those off St. John, in the U.S. Virgin Islands. It had taken nearly six years for those reefs to recover. My surveys suggested that many of the juvenile corals ("recruits") that managed to survive by attaching themselves to solid surfaces did so in cracks and on the undersides of ledges and pieces of rubble. I began to wonder whether this kind of settlement, in so-called cryptic locations, provided a springboard for growth onto the open reef. During our stay in *Aquarius,* my colleagues and I would begin trying to find out.

Our mission started with a dive like any of the others we had recently made; however, it differed in one critical way. On this dive, we stayed down so long that a sudden return to the surface would have meant a severe and possibly crippling or even fatal case of decompression sickness, better known as the bends. During this dive, the fact weighed heavily on our minds that we would have no choice but to take refuge in a 13-meter-long cylindrical chamber anchored to the seafloor. It was only when we were tired and cold, and the encrusted hull emerged from the blue as we swam toward it, that the habitat finally appeared as home.

People who have never been inside the *Aquarius* habitat invariably believe it to be damp and claustrophobic, which is untrue. The ocean

A Swim-by of the *Aquarius* Habitat

merges with the habitat through a "moon pool" in a wet porch. This porch is joined by a pressure door to a main living and working space and, beyond it, a bunk room, in which six beds crowd the walls. Other than the wet porch, the habitat is air-conditioned, with decor dominated by stainless steel, blue carpeting and stunning, watery blue light. Just off the wet porch, in the main section, the science area accommodates a submarine-style toilet and a bench with computers and digital displays for marine sensors. From this room, we could collect data from corals in their natural environment and talk with divers in the water as, for example, they positioned sensors on the reef.

The rest of the main room was where we relaxed, ate meals, discussed plans and, whenever possible, allowed ourselves to be distracted by whatever was happening outside the largest porthole in the habitat. Although strangely analogous to visiting an aquarium, our observations sometimes left us unsure whether we were watching or being watched. The main room was also where we decompressed at the end of our mission. During decompression, the room was sealed off from the wet porch and, over a period of 16 hours and 30 minutes, the pressure was slowly reduced to one atmosphere. We could then swim up without ill effects to the terrestrial world.

In the bunk room, which also has a large porthole, we awoke each day to an underwater vista of a shadowy, blue reef dappled by the gentle, watery, flickering rays of the rising sun. As if to remind us that important events were already taking place on the reef, our early-morning view was repeatedly interrupted by the passage of fish and the furious activity of a damselfish tending a clutch of eggs deposited in front of the porthole.

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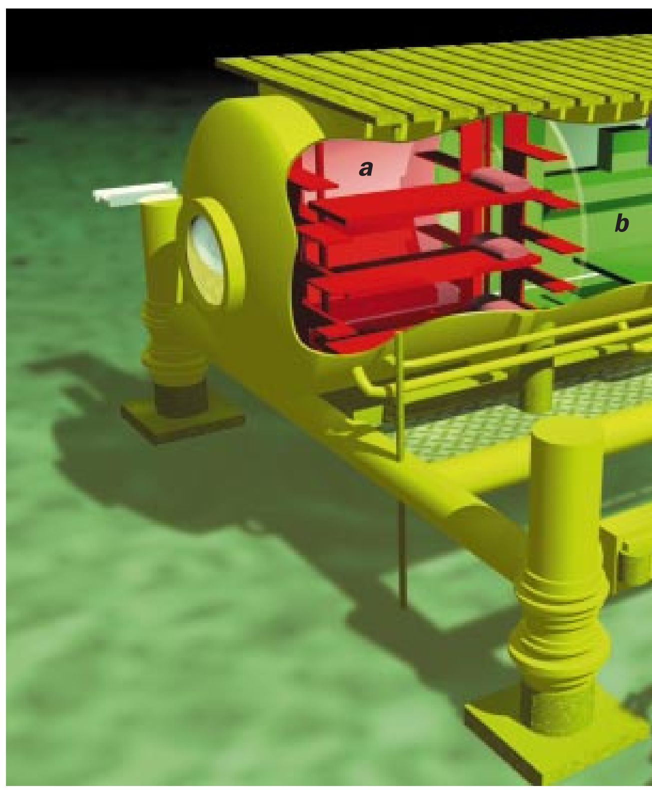
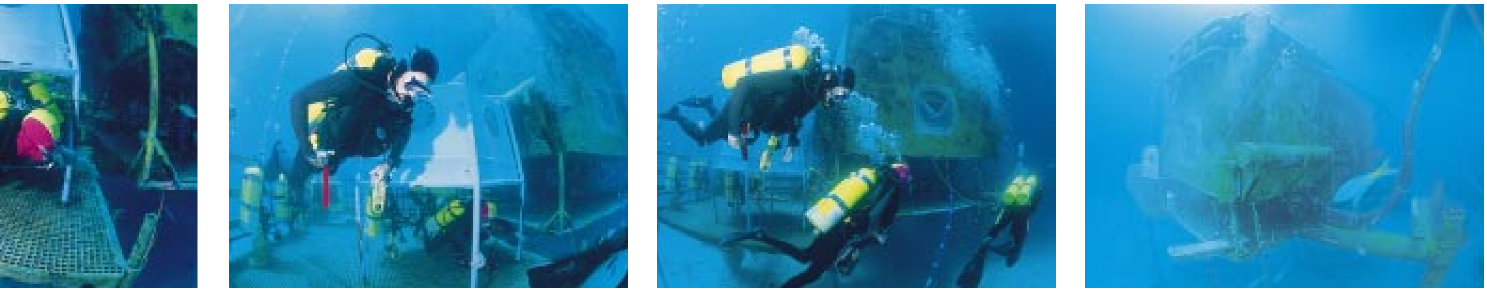


***AQUARIUS* HABITAT includes a wet porch (e *at far right in diagram*), which serves as a kind of vestibule between the main quarters and the sea. The main quarters consist of (*from left*) a bunk room (*a*), a kitchen area with a small table under a porthole (*b*), and a compact laboratory bench (*c*). In an air-filled "gazebo" (*d*) next to the wet porch, divers can speak with one another and with the support crew. *Clockwise, from above:* Aquanaut David B. Carlon spends a quiet moment in the bunk room; team leader Peter J. Edmunds and aquanauts Dione Swanson and Sean Grace relax after lunch; Carlon shows off instruments in the laboratory area; Carlon, Edmunds and Swanson pause in the gazebo to log the start of an excursion; Christopher Borne, of the support crew, arrives in the wet porch entrance, or "moon pool," with the day's lunch. Receiving it is Kenneth Johns, the habitat-support technician during the mission. (The only aquanaut on Edmunds's mission not seen in these photographs is John F. Bruno.)**



Living underwater was not all beauty and natural wonder. Throughout the mission, we were monitored—electronically in the habitat and visually, by support divers, on the reef. Although the monitoring was necessary for safety reasons, it added to the stress of living underwater, in a fundamentally hostile realm. Everywhere in the habitat, except for the toilet and the bunk room, video cameras relayed our movements to the surface, and microphones and speakers allowed our conversations to be listened to and comments to be interjected by members of the support staff above.

This supervision was most noticeable when it came to organizing our diving forays. Each of these sorties required planning to ensure that the support facilities were in place, necessitating a 6 A.M. start for the surface team when we wanted to leave the habitat at 8 A.M. Understandably, the surface crew were irritated if we were not ready as planned. On several occasions we were still huddled around the breakfast table when a voice from the speakers reminded us that we were scheduled to be in the water within five minutes. Such exchanges became part of the daily routine necessary to make the most of the lengthy bottom times allowed by so-called saturation diving.

Our days began with a three-hour dive, followed by lunch in the habitat and a second dive of similar duration in the afternoon. On most forays we swam about 500 meters along the reef. When the currents were strong, we hauled ourselves hand over hand along ropes affixed to the sea bottom. (These lines also enabled a lost diver to find his or her way back to the habitat.) At one end of each line we found spare scuba tanks and an air-filled dome; into this hemisphere we could stick our heads, eat fruit or candy and, of course, talk science with our buddy.

The lengthy periods in the water inevitably made us feel a greater affinity for the resident marine life than for our fellow humans visiting regularly from the surface with food and supplies. These feelings were accentuated at

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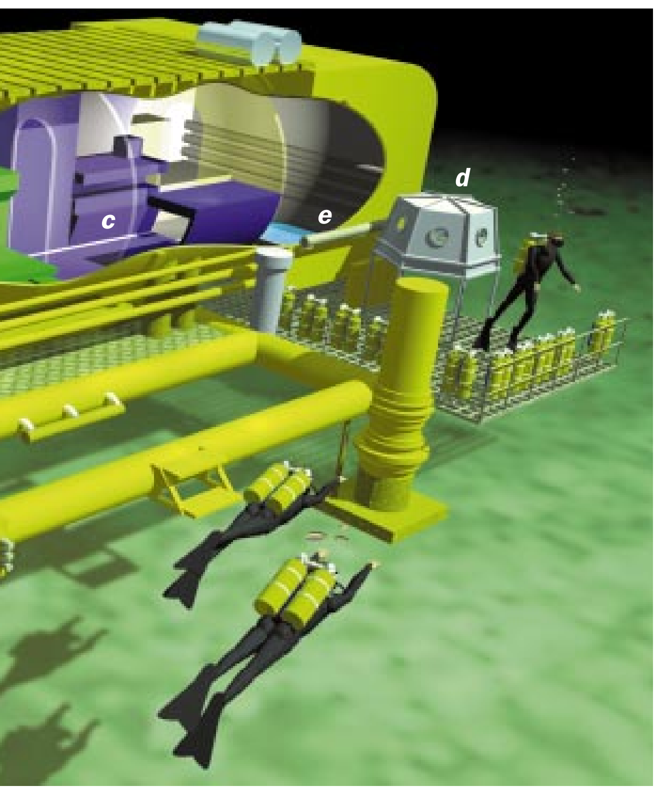

SLIM FILMS

e

night when we made short forays into inky darkness alive with the shadows of tarpon and big, inquisitive barracuda.

Although we worked in warm tropical water, our long dives left us bone-tired and so ravenous that even a dwindling chocolate supply could trigger quite an argument. Fortunately, however, hefty dinners were delivered daily, arriving late in the afternoon and ready for our return from the reef. To our taste buds, affected by the pressure, the meals seemed bland. Nevertheless, they were cheerfully consumed against the backdrop of a teeming ocean and along with conversation dwelling on marine creatures and our life underwater.

In the early evenings, as the effects of fatigue and nitrogen narcosis seemed to intensify, extraneous subjects occupied more of our discussions, and we found

How an Underwater Habitat Benefits Marine Science

by Steven Miller

Scuba divers joke that there are two ways to avoid decompression sickness, the rare but dreaded "bends": don't go down, or don't come up. In a sense, an underwater habitat is a way of making the latter option possible, at least for a few weeks.

To understand how such an option becomes possible requires a little knowledge of physiology. Breathing air in the relatively high ambient pressure of the underwater environment causes a diver's blood and tissue to accumulate excess inert gases—mostly nitrogen. The amount of excess gas absorbed by the diver's body depends on the depth and time spent underwater. Thus, simple physics dictates how long a diver can remain at specific depths without risking the bends, which occurs when the excess inert gas absorbed during a dive bubbles out of a diver's blood and tissues as he or she ascends and, consequently, the surrounding pressure declines [see "The Physiology of Decompression Illness," by Richard E. Moon, Richard D. Vann and Peter B. Bennett; SCIENTIFIC AMERICAN, August 1995].

This buildup of gases typically restricts diving scientists who work deeper than about 20 meters to approximately one hour a day at depth, which seriously limits their experimental and observational capabilities. To get around these limitations, marine scientists use an array of undersea technology, including manned submersibles, underwater robots and sampling and remote observational equipment lowered from ships. Still, many tasks—particularly those in support of scientific research—require a prolonged human presence to observe with eyes instead of cameras or to touch with hands instead of robotic arms. And nothing can substitute for the advantages of having a brain to observe, learn and improvise when the need arises.

The only technique that allows this kind of sustained human presence is saturation diving. Saturation diving allows marine researchers to live and work at pressure for days, weeks or even months at a time. The technique is based on the fact that after about 24 hours at any working depth, a diver's body becomes saturated with dissolved gas. Once the body is saturated, decompression—the period required to bring the diver gradually back to surface pressure without inflicting the bends—is the same regardless of how much time has been spent underwater. The advantage is essentially unlimited time to work underwater. The main risk to divers is accidental, rapid ascension or surfacing, which could cause a life-threatening case of the bends if the surfaced diver is not quickly returned to pressure.

Saturation diving was developed in the 1960s, when dozens of systems were built for commercial or scientific purposes. They were designed to keep divers under pressure between dives, either in seafloor habitats or in shipboard vessels called deck decompression chambers; the latter also included pressurized diving bells to transfer divers to and from underwater work sites.

In habitats, the pressure was matched to the pressure of the depth at which the habitat was placed, enabling divers to come and go as they pleased. Such advantages notwithstanding, habitats gradually fell out of favor. Accidents, including fatalities, shut programs down; inefficient operations and insufficient funding were common; and programs were never designed to meet national research objectives.

Currently the only underwater habitat devoted to science is *Aquarius.* Since 1993 it has operated off Key Largo, Fla., as the centerpiece of a research program focusing on the state's fragile and economically important coral reefs. The marine analogue of the terrestrial rain forest, coral reefs are home to between 20 and 40 percent of the 160,000 known marine species. (Knowledge of marine biodiversity is still relatively rudimentary, however, and these numbers are probably conservative.) Coral reefs are also among the earth's most threatened ecosystems.

But the reefs are significant for more than their biodiversity and their status as endangered ecosystems—there are economic reasons for their study as well. For example, they are often an important barrier against shoreline erosion; they support commercial and recreational fisheries; and they are one of the primary attractions for millions of recreational scuba divers. Reefs also help to maintain beaches through cycles of growth and erosion, and the development of sea-grass and mangrove ecosystems are linked to reefs as well.

Aquarius accommodates six-person teams (five scientists and one habitat-support technician) during 10-day missions. Amenities include a hot-water shower, unlimited freshwater, air-conditioning, various kitchen appliances and comfortable bunks—all of which help keep aquanauts rested, alert and productive. In contrast to its predecessors, *Aquarius* is really more a laboratory than a habitat. In addition to a comfortable living environment, *Aquarius* provides enough space to conduct experiments and includes computer and electronic capabilities to permit research that could not be accomplished any other way. Scientists spend six to nine hours a day in the water and often venture out at night as well.

With 21 missions off Key Largo, *Aquarius* has revolutionized the study of coral reefs. A few highlights attest to the habitat's emergence as a mainstay of reef research:

- Several years ago Daniel F. Gleason and Gerard M. Wellington of the University of Houston demonstrated that ultraviolet radiation from the sun can cause coral to "bleach." Bleaching is the term given to the occasional, massive and sometimes fatal coral maladies that have mystified and alarmed researchers for over a something to laugh about on almost any topic. On one occasion, the discovery that one of our team had developed an outbreak of "the funk," an unpleasant rash brought on by dampness and abrasion, caused our select scientific team to run around erratically, laughing

decade. Gleason and Wellington showed that solar ultraviolet radiation (which has become stronger because of losses of stratospheric ozone) can cause coral bleaching as far down as 25 meters. Researchers previously thought that ultraviolet radiation was filtered out in the top few meters of ocean water. Theories about bleaching must now consider ultraviolet light, as well as the higher ocean temperatures that have long been suspected, to play a role.

- Reefs near a densely populated region—such as the reefs that surround the *Aquarius* laboratory—face a more immediate threat: nutrient pollution from human sewage. Studies conducted from *Aquarius,* a mere 100 kilometers from Miami and just offshore from one of the more populated Florida Keys, have measured natural cycles related to nutrient chemistry and assessed the potential for sewage-contaminated water to affect reef organisms. Reefs typically thrive where nutrients are sparse, so they are sensitive even to low levels of chronic pollution. Recently Gene A. Shinn of the U.S. Geological Survey and Francis J. Sansone of the University of Hawaii installed special monitoring wells to search for evidence near the reef of contaminated groundwater.
- Virtually all substantive knowledge about the voracious feeding habits of corals is derived from work by *Aquarius* scientists, notably Kenneth P. Sebens of the University of Maryland. *Aquarius* scientists have also studied how corals reproduce and colonize reefs, which will have applications related to restoration of reefs damaged by ship groundings or other causes.
- Much of the three-dimensional structure of a reef comes from corals, but sponges are often found in greater numbers and diversity. Sponges filter and process vast quantities of plankton from water that passes around, over and through the reef. A recent *Aquarius* mission discovered that sponges are a net sink for some types of plankton, but, interestingly, they are also a net source for others (and for nutrients as well). These results have important ramifications for how reefs capture and cycle energy, especially in light of the fact that changes in water quality have been implicated in the demise of some reefs.

HAPPY AQUANAUTS are well rested, comfortable—and more productive. Swanson, Edmunds and Grace peer out of the porthole in the habitat's bunk room; habitat amenities include a hot-water shower and air-conditioning. The support barge is visible above.

Aquarius benefits science in several less direct ways. The marine laboratory has captured public attention and fired imaginations about the value and wonders of the undersea realm. Even scientists have had their consciousness raised. Stolid aquanauts report feeling a sense of belonging in the world beneath the waves and a kind of empathy with its creatures. Such experiences can make a difference later, when former aquanauts go on to positions in which they write, teach or help to shape private-sector and government policy regarding our waters.

In comparison to other scientific outposts, *Aquarius*'s operating costs of about $1.2 million a year are modest. The laboratory is less expensive on a daily basis than an oceanographic cruise; the cost of a single space shuttle mission would cover the habitat's expenses for the next 500 years. Nevertheless, federal budgets are being chopped, and the *Aquarius* program has been on the block every year since operations began. We hope this last underwater outpost will survive, allowing its users to continue expanding our knowledge of coral reefs, our oceans and our planet.

STEVEN MILLER is science director of the National Undersea Research Center at the University of North Carolina at Wilmington, which operates the Aquarius *habitat for the National Oceanic and Atmospheric Administration.*

SEAFLOOR SCIENTISTS spend about six hours a day in the water, attending to a variety of research tasks. Above, principal investigator Edmunds uses a contour gauge to measure the amount of topological texture on a small patch of reef, which may determine where juvenile corals are settling. The resulting gauge settings are then photographed for later analysis (*below*). In one of several experiments on the physiology of juvenile corals, aquanaut Swanson (*right*) samples water from a chamber containing a juvenile coral, to measure the animal's intake of nutrients.

SUPPORT BARGE is anchored above the habitat; it provides air, electricity and freshwater through cables and umbilicals. The barge also has a command center, in which staff members monitor the habitat and its immediate surroundings around the clock. The white boxlike shelter to the left on the barge houses a hyperbaric chamber (*right*), in which any divers afflicted by the bends would be treated.

so hard that for 10 minutes we were unable to answer the worried calls from the surface crew. Although we were warned that such behavior is common in divers whose tissues are saturated with nitrogen, we did not realize how much harder it would make the planning and execution of our research.

During many of our lengthy forays along the reef, we painstakingly quantified small coral recruits (less than four centimeters in diameter) in both conspicuous and cryptic locations as deep as 33 meters. When we were planning our project, the primary research tasks—requiring the recognition of khaki-brown, golf-ball-shaped objects nestling among tufts of algae—seemed simple. Yet as our mission wore on, our survey work became more challenging. Fatigue, shortening attention spans and fingers swollen from long immersion and repeated abrasions made it increasingly difficult to find and identify the small colonies.

Painful though it sometimes was to gather, our data have raised a number of interesting questions. Our working hypothesis—that hidden, confined locations provided a springboard for coral growth onto the open reef—initially seemed unsupported by the data. Instead of finding juveniles crammed disproportionately into such cryptic locations, we found that more than half were on open, horizontal surfaces, up to a third were on vertical surfaces and only the rest were hidden in caves and cracks. Most of the areas contained an average of six juveniles per square meter.

Cryptic locations may still be important; it is possible that the hidden juveniles have higher survival rates than those on open surfaces. To investigate this hypothesis, we permanently marked juveniles to determine their survivorship between 1995 and our second visit this past summer.

Another unexpected finding was the abundance of juveniles belonging to species that were rare as adults. One striking example was the large star coral, *Montastraea cavernosa,* which accounted for more than 15 percent of the juvenile corals in some locations and yet were rarely seen as adults. In other parts of the Caribbean we had found, conversely, that many of the most important reef-building corals are rare as juveniles. The observations seem to support a view of episodic coral recruitment, in which decades may pass between recruitment events of certain species. Once settled, however, a single age group, or cohort, might dominate the community for many years. Our results from Florida will shed light on this possibility if, years from now, adult large star corals are flourishing on the reef. Moreover, these results could help researchers understand how coral reefs will respond to the ever increasing impact of pollution, ship groundings and other disturbances plaguing the marine ecosystem.

Months after we returned from our *Aquarius* mission, I am left with a particularly vivid memory from one of our diving forays. After a hard, long swim against the current, we discovered that our video camera was not functioning. We had planned to record corals on tape so that we could compare colony sizes in 1995 with those we planned to measure on our second visit, a year later, in order to determine growth rates and the effects of mortality. With hand signals, we attracted the attention of the surface crew and watched a snorkeler swim down from the support vessel to recover the faulty camera. It was a bright July afternoon, and we could clearly see the limbs of the crew lolling over the side of their boat, framed in the rays of sunlight filtered through 15 meters of seawater. Never were the constraints of saturation diving more painfully apparent as we realized the impossibility of swimming to the surface and basking in the sun. Never did sunlight and dry skin seem like such incredible luxuries. SA

To obtain high-quality reprints of this article, please see page 127.

The Author

PETER J. EDMUNDS is associate professor of biology at California State University, Northridge. He was awarded a Ph.D. in marine physiological ecology by Glasgow University in 1986. In 1991 he was a postdoctoral research associate at the University of Southern California.

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Charles Darwin and Associates, Ghostbusters

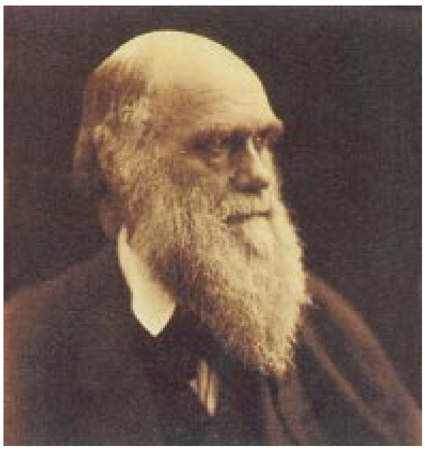
When the scientific establishment put a spiritualist on trial, the co-discoverers of natural selection took opposing sides

by Richard Milner

After lunch on September 16, 1876, Charles Darwin stretched out on his drawing-room sofa, as was his unvarying routine, smoked a Turkish cigarette and read the "bloody old *Times*." He often fumed at its politics (the editors supported the South in the American Civil War), and his wife, Emma, suggested that they give up the paper altogether. But he replied he would sooner "give up meat, drink and air."

In the "Letters" column, he noticed a report that a young zoologist named Edwin Ray Lankester was bent on jailing a celebrated spirit medium, "Dr." Henry Slade, who was bilking gullible Londoners. By hauling Slade into court as "a common rogue," Lankester would become the first scientist to prosecute a professional psychic for criminal fraud—an action Darwin thought long overdue. Although he was delighted at Lankester's attack on Slade, Darwin was distressed to learn that Alfred Russel Wallace, his friendly rival and co-discoverer of the theory of natural selection, was also a target.

The Slade trial was to become one of the strangest courtroom cases in Victorian England. Some saw it as a public arena where science could score a devastating triumph over superstition. For others, it was the declaration of war between professional purveyors of the "paranormal" and the fraternity of honest stage magicians. Arthur Conan Doyle, the zealous spiritualist whose fictional detective, Sherlock Holmes, was logic personified, characterized it as "the persecution [rather than prosecution] of Slade." But what made the trial unique was that the two greatest naturalists of the century ranged themselves



Charles Darwin, 1868

on opposite sides. The "arch-materialist" Darwin gave aid and comfort to the prosecution, and his old friend Wallace, a sincere spiritualist, was to be the defense's star witness—making it one of the more bizarre and dramatic episodes in the history of science.

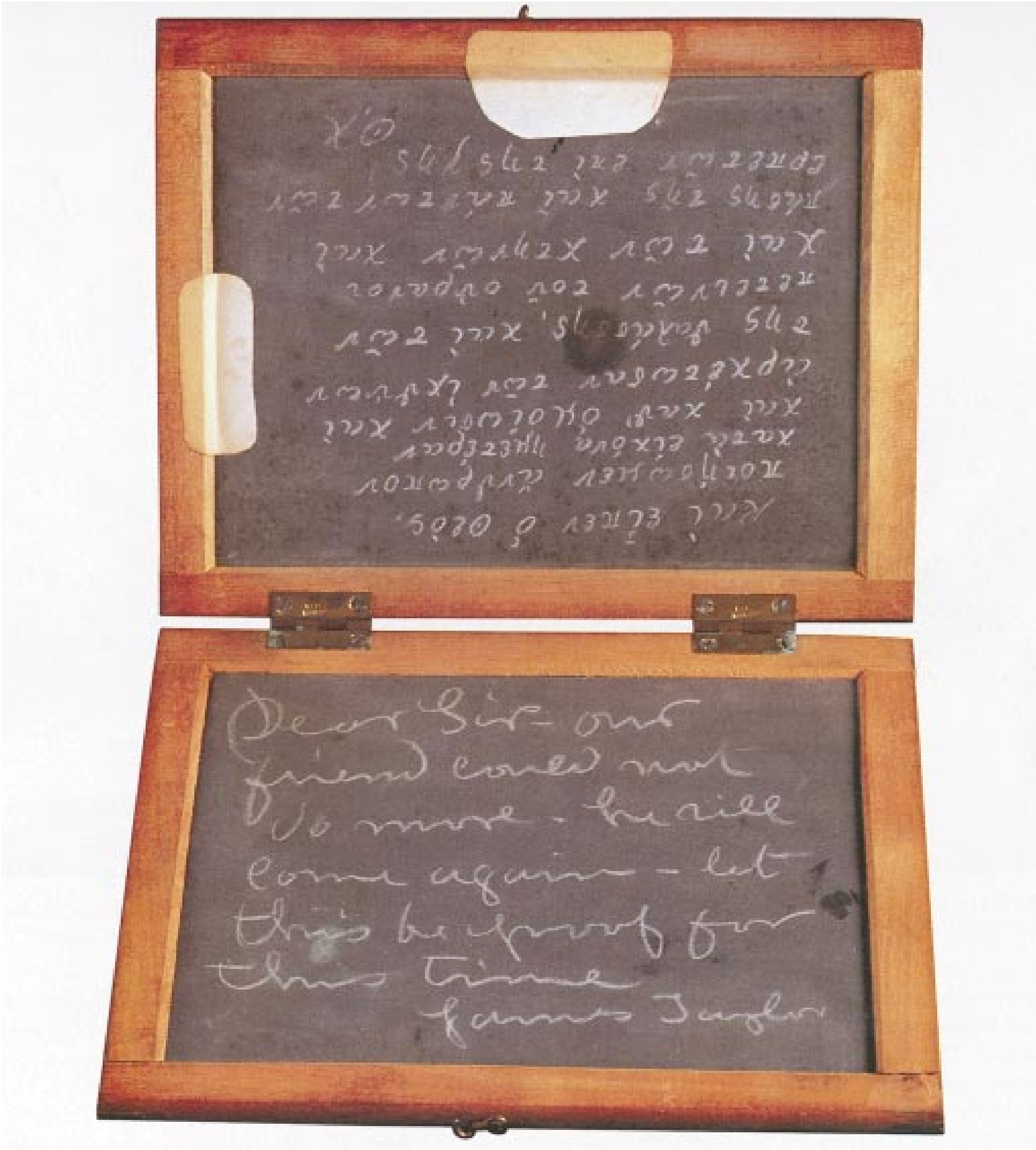
Wallace was respected as an author, zoologist, botanist, the discoverer of scores of new species, the first European to study apes in the wild and a pioneer in the study of the distribution of animals. But he constantly courted ruin by championing such radical causes as socialism, pacifism, land nationalization, wilderness conservation, women's rights and spiritualism. In addition to his classic volumes on zoogeography, natural selection, island life and the Malay Archipelago, he had written *Miracles and Modern Spiritualism,* which lauded spirit-mediums. And he had just allowed a controversial paper on "thought transference" to be read at a meeting of the British Association for the Advancement of Science—touching off an uproar that led him to avoid scientific meetings for the rest of his life.

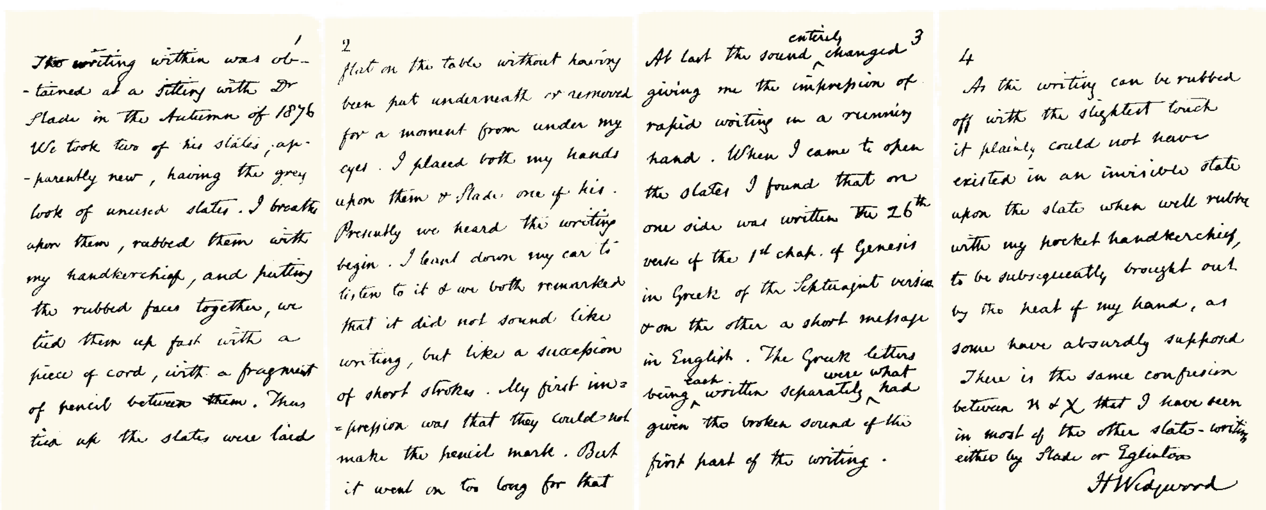
Wallace wanted the best of both worlds. With insects or birds, he was even more rigorous than Darwin in applying the principle of natural selection, but he questioned its efficacy for humans. If early hominids required only a gorilla's intelligence to survive, Wallace asked, why had they evolved brains capable of devising language, composing symphonies and doing mathematics? Although our bodies had evolved by natural selection, he concluded, *Homo sapiens* has "something which he has not derived from his animal progenitors—a spiritual essence or nature... [that] can only find an explanation in the unseen universe of Spirit."

Wallace's position did not stem from any conventional religious belief but from his long-standing interest in spiritualism: a melding of ancient Eastern beliefs with the Western desire to "secularize" the soul and prove its existence. When Wallace published this view in 1869, Darwin wrote him: "I differ grievously from you; I can see no necessity for calling in an additional and proximate cause [a supernatural force] in regard to Man.... I hope you have not murdered too completely your own and my child"—meaning their theory of natural selection.

Darwin the "Materialist"

Like Wallace (and his New Age intellectual descendants), many Victorians recoiled from the materialism axiomatic in physical science; they sought a "wireless telegraph" to an intangible world. Although Darwin and most oth-





1
The writing within was ob- -tained at a sitting with Dr Slade in the Autumn of 1876 We took two of his slates, ap- -parently new, having the grey look of unused slates. I breathed upon them, rubbed them with my handkerchief, and putting the rubbed faces together, we tied them up fast with a piece of cord, with a fragment of pencil between them. Thus tied up the slates were laid

2
flat on the table without having been put underneath or removed for a moment from under my eyes. I placed both my hands upon them & Slade one of his. Presently we heard the writing begin. I bent down my ear to listen to it & we both remarked that it did not sound like writing, but like a succession of short strokes. My first im- -pression was that they could not make the pencil mark. But it went on too long for that

3
At last the sound entirely changed giving me the impression of rapid writing in a running hand. When I came to open the slates I found that on one side was written the 26th verse of the 1st chap. of Genesis in Greek of the Septuagint version & on the other a short message in English. The Greek letters being each written separately were what had given the broken sound of the first part of the writing.

4
As the writing can be rubbed off with the slightest touch it plainly could not have existed in an invisible state upon the slate when well rubbed with my pocket handkerchief, to be subsequently brought out by the heat of my hand, as some have absurdly supposed. There is the same confusion between η & χ that I have seen in most of the other slate-writing either by Slade or Eglinton.
H Wedgwood

SOCIETY FOR PSYCHICAL RESEARCH ARCHIVE, CAMBRIDGE UNIVERSITY LIBRARY

SLATE containing alleged spirit writing has been preserved since a séance in the fall of 1876, along with an attached letter from Charles Darwin's cousin and brother-in-law, Hensleigh Wedgwood, attesting to its authenticity. The Greek text (*top slate*) is a passage from the biblical book of Genesis describing the creation of humans and animals—perhaps intended to be particularly galling to evolutionists. The author discovered the slate this past summer in the Cambridge University Library, where it had lain unnoticed as part of a collection of letters and photographs donated by the Society for Psychical Research Archive.

MARY EVANS PICTURE LIBRARY

COURTROOM DRAMA, seen here in a newspaper engraving, fascinated Victorian England as biologist Edwin Ray Lankester (*standing*) testified against "psychic" Henry Slade (*far left*). Lankester holds a slate used by Slade in his séances.

er scientists kept miracles out of their theories, a few shared Wallace's views. Among them were the physicist Oliver Lodge and the chemist William Crookes, discoverer of the element thallium.

Spiritualism attracted people with a wide spectrum of interests, but its major focus was on the possibility of communication with the dead. This part of the movement began in 1848, with the rise of Margaret and Kate Fox, sisters from Hydesville, N.Y. When the teenage girls conversed with "spirits," mysterious rapping sounds spelled out lengthy messages. (Thirty years later, after gaining fame and fortune, one of the sisters admitted that she had always produced the taps by snapping her big toe inside her shoe.) In England, the U.S. and Europe, over the next 80 years, spiritualism enjoyed tremendous popularity.

In the early 1870s Darwin's cousin and brother-in-law Hensleigh Wedgwood became a convert. Wedgwood yearned to become a respected savant like Darwin, their cousin Francis Galton and Darwin's grandfather Erasmus. But a pair of swindlers, Charles Williams and Frank Herne, recognized that he was the most gullible of the clan. At their urging, Wedgwood begged Darwin to come and see the self-playing accordions, levitating tables, automatic writing and glowing spirit hands at Williams's séances. Darwin always managed to be too tired, too busy or too ill to attend. "I am a wretched bigot on the subject," he once admitted.

In January 1874, however, Darwin sent two close members of his circle to attend a séance with Williams. His friend and lieutenant, the famous zoologist Thomas H. Huxley, was introduced as "Mr. Henry" (his middle name). Darwin's son George, then 29 years old, went as well. Although bottles moved around and a guitar played by itself, the two concluded they had observed nothing but crude trickery. George, a budding astronomer, wrote that he was shocked to find his uncle Hensleigh's account of Williams's séances "so worthless." Later that year Darwin wrote to a newspaperman, urging him to expose Williams as "a scoundrel who has imposed on the public for so many years."

The following year Huxley's young laboratory assistant, Edwin Ray Lankester, decided to catch Williams and Herne in fraud—an act he knew would impress his heroes Darwin and Huxley. But after Huxley and George's visit, the medium became wary, avoiding anyone connected to Darwin's circle. Then, in April 1876, a tempting new target moved into Lankester's sights: a celebrated American psychic, "Dr." Henry Slade, had come to London "to prove the truth of communication with the dead." Slade claimed that his wife's spirit wrote him messages on slates.

Lankester and his fellow medical student, Horatio Donkin, went to Slade's pretending to be believers. They paid the admission fee, asked questions of the spirits and received mysteriously written answers. Then, in the darkened room, Lankester suddenly snatched a slate out of Slade's hands, found the written answer to a question he had not yet asked, and proclaimed him "a scoundrel and an impostor."

The next day Slade and his partner, Geoffrey Simmonds, were in the hands of the police, charged with violating the Vagrancy Act, an old law intended to protect the public from traveling palm readers and sleight-of-hand artists. Throughout the fall of 1876, all London was abuzz over the Slade trial. The little courtroom was packed with Slade's supporters and detractors and 30 journalists, who spilled out into the street. The *Times* of London carried trial transcripts day after day.

Darwin, whose beloved 10-year-old daughter Annie had died in 1851, had nothing but contempt for the "clever rogues" who preyed on grieving relatives. Yet he avoided saying so publicly—*On the Origin of Species* had stirred up enough controversies for a lifetime. Privately, he wrote Lankester an effusive letter of congratulations. Jailing Slade was a public benefit, he said, and insisted on contributing £10 to the costs of prosecution. (Under English law, the complainant paid court costs; £10 was a substantial sum, comparable to a month's wages for a workingman.)

Packed Courtroom

As the trial got under way, the prosecutor announced that stage magician John Nevil Maskelyne was prepared to reproduce all the "alleged phenomena" that were observed at the séance. The judge, in turn, warned that performing magic slate tricks in court would prove nothing; the question was whether Lankester and Donkin had actually caught the defendants faking the alleged spirit writing.

Both scientists turned out to be terrible witnesses; their observational skills, developed in anatomy and physiology labs, were useless in detecting fraud by professional cheats. As Huxley later noted, "In these investigations, the qualities of the detective are far more useful than those of the philosopher.... A man may be an excellent naturalist or chemist; and yet make a very poor detective."

Indeed, Lankester and Donkin apparently could not agree on anything much beyond their charge that Slade was an impostor. Did the medium use a thimble device for writing, or did he hold a pencil stub while his thumb was visible on the tabletop? Did he switch the blank slate for one that was previously written on? Was the table of ordinary construction, or did it have sliding bars and trick panels? The two could not establish when or how the writing had been done.

Maskelyne's courtroom conjuring, in contrast, was perfect. In answer to a question about instant writing—and before the judge could stop him—he began scrubbing a blank slate with a wet sponge until writing appeared: "THE SPIRITS ARE HERE!" Then he wiped the slate clean and ran the sponge over it again. The message reappeared, and Slade's partner, Simmonds, was fascinated. "Marvelous!" he exclaimed. "May I examine the slate?" Maskelyne shot back, "Oh, you know all about it."

Whenever the prosecutor could, he had Maskelyne slip in another slate trick until the judge finally barred them. The prosecutor then offered Slade two small slates joined by hinges and a hasp lock. Why not make writing appear inside the locked slates and convince the world? Slade replied he had been so pestered by such tests that Allie, his wife's spirit, had vowed never to write on a locked slate.

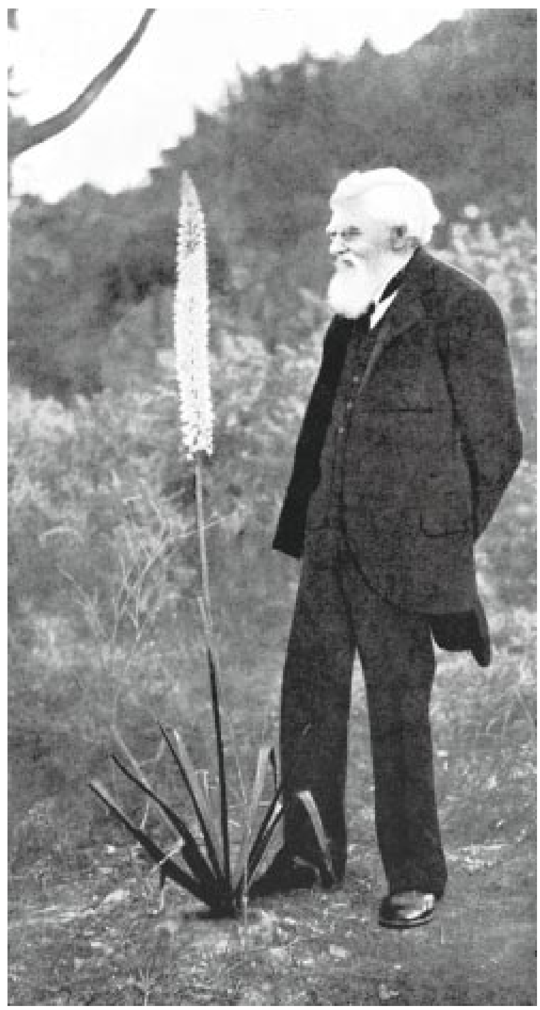
A chemist named Alexander Duffield was one of many witnesses for the prosecution. He said Slade had convinced him "that there could be established a sort of post office in connection with the 'other place.'" But now he had his doubts. Another witness testified that a few years earlier, in the U.S., someone had similarly snatched a slate from Slade in mid-séance and exposed him in fraud.

The high point of the trial was Wallace's appearance for the defense. His integrity and candor were known to all. When called, he said that he had witnessed the alleged phenomena but refused to speculate on whether the writings were caused by spirits. He considered Slade to be an honest gentleman, "as incapable of an imposture...as any earnest inquirer after truth in the department of Natural Science."

In his summation, Slade's lawyer argued that there was no real evidence against his client. No one had proved the table was rigged, and Maskelyne's demonstrations of how the trick *could* have been done were irrelevant. The writing's appearance before the corresponding question was asked proved nothing about its origin, and Lankester and Donkin could not agree on exactly what they had seen during the séance. Moreover, such an eminent scientist as Wallace should be considered at least as credible as young Lankester. The

COURTESY OF WEDGWOOD MUSEUM

BELIEVERS in spiritualism included Wedgwood (*above*) and Alfred Russel Wallace (*below, shown in his garden in 1905 with a king's-spear plant*). Wallace's scientific reputation suffered because he defended Slade; the episode left Wedgwood and Darwin permanently estranged.



COURTESY OF GARETH NELSON

barrister concluded by invoking Galileo, remarking that innovative scientists who challenge the beliefs of their time are always vilified. His irony was not lost on the evolutionists.

But nothing could save Slade. The judge said that he understood that spiritualism was "a kind of new religion" and did not wish to offend sincere believers. Still, the question before the court was whether Slade and Simmonds had fraudulently represented their own actions as paranormal phenomena. Concluding that he must decide "according to the well-known course of nature," the judge sentenced the defendant to three months' hard labor in the House of Corrections.

Slade never served his sentence. On appeal, another judge ruled that the Vagrancy Act, which prohibited palmistry, was not applicable to claims of spirit writing. Slade and his partner fled England for Germany. Within a short time, Slade had convinced his landlord, a local conjurer, the chief of police and several prominent German scientists (including the physicist Johann Zöllner of the University of Leipzig) that he was in contact with spirits and various paranormal forces. When his act wore thin, he took to the road again. Eventually he wound up an alcoholic in a run-down New York boardinghouse, easy prey for tabloid editors who sent cub reporters to expose him one more time.

After the Trial

The controversy took a toll on participants other than Slade. In 1879 Darwin tried to drum up support for a government pension in recognition of Wallace's brilliant contributions to natural history. Wallace, he knew, had to earn his meager living by grading examination papers. But when Darwin wrote to his friend Joseph Hooker, director of Kew Gardens, the botanist refused to help. "Wallace has lost caste terribly," he replied nastily, "not only for his adhesion to Spiritualism, but by the fact of his having deliberately and against the whole voice of the committee" allowed the paper on mental telepathy at the scientific meetings. In addition, he thought the government "should in fairness be informed that the candidate is a public and leading Spiritualist!"

Undaunted, Darwin replied that Wallace's beliefs were "not worse than the prevailing superstitions of the country"—meaning organized religion. Darwin and Huxley twisted a few more arms, then Darwin personally wrote to Prime Minister William Gladstone, who passed the petition on to Queen Victoria. In the end, Wallace got his modest pension and was able to continue writing his articles and books; he died in 1913, at the age of 90.

In the years after the trial, Wedgwood and Darwin did not see much of each other. In 1878 a reporter for the journal *Light* had finally managed to unmask Charles Williams, the medium who had attempted to use Wedgwood to win over Darwin's family. When the journalist suddenly turned on the lights at a séance, Williams was found to be wearing a

MARY EVANS PICTURE LIBRARY

LANKESTER eventually became director of the British Museum of Natural History and a well-known figure in British science. This 1905 *Vanity Fair* caricature pictures him eye to eye with a hornbill while observed by a horseshoe crab. Lankester's monograph on the arthropod is still considered a classic. In 1912, however, Lankester was himself taken in by a proevolutionary hoax, the Piltdown man.

false black beard, phosphorescent rags and, as Darwin later put it, "dirty ghost-clothes."

"A *splendid* exposure," crowed Darwin when he read of it. But even then, his brother-in-law's faith remained unshaken; a few faked performances indicated only that the medium was having difficulty getting through to the other side and was under pressure not to disappoint his sitters. For Darwin, this was the last straw: "Hensleigh Wedgwood admits Williams is proved a rogue," he fumed, "but insists he has seen real ghosts [at Williams's séances]. Is this not a psychological curiosity?"

In 1880 Wedgwood sent Darwin a long handwritten manuscript: a spiritualist synthesis of science and religion. Would Darwin read it and perhaps suggest where it might be published? In a melancholy mood, Darwin sat down to reply to his cousin. He may have remembered the times Wedgwood had gone to bat for him many years before: he had helped persuade Darwin's uncle and father to let him go on the HMS *Beagle* expedition, and it was to his cousin that Darwin had once entrusted publication of his theory of natural selection.

"My dear Cousin," Darwin wrote, "It is indeed a long time since we met, and I suppose if we now did so we should not know one another; but your former image is perfectly clear to me." He refused even to read Hensleigh's paper, writing that "there have been too many such attempts to reconcile Genesis and science." The two cousins, who had once been so close, were now hopelessly estranged over the question of science and the supernatural.

That same year Lankester, now a professor of zoology, declined requests to continue ghostbusting. "The Spirit Medium," he wrote in an 1880 letter to the *Pall Mall Gazette,* "is a curious and unsavoury specimen of natural history, and if you wish to study him, you must take him unawares.... I have done my share of the skunk-hunting; let others follow." He was later appointed director of the British Museum of Natural History.

Ironically, in 1912 Lankester, the nemesis of fakers, was completely fooled by the Piltdown man hoax, one of the most notorious frauds in the history of evolutionary biology. For the next 40 years, scientists accepted the "ape-man" fragments, dug up about 25 miles from Darwin's home, as remains of the "missing link." Fired with enthusiasm for the Darwin-Wallace theory, Lankester and the younger generation of evolutionists uncritically embraced this fossil forgery.

Huxley, who died in 1895, knew full well that more than a few scientists were prone to develop their own irrationally held beliefs. While young, he had battled churchmen to establish the scientific approach to unraveling human origins but later quipped to an educator that "we or our sons shall live to see all the stupidity *in favour* of science"—a fitting prophecy of Piltdown, the ersatz "Stone Age" Tasaday tribe of the Philippines, and cold fusion. In *The Descent of Man,* Darwin himself had urged a skeptical approach to unconfirmed observations; he believed that accepting flimsy evidence is much more dangerous than adopting incorrect theories. "False facts are highly injurious to the progress of science, for they often long endure," he wrote. "But false views, if supported by some evidence, do little harm, as everyone takes a salutary pleasure in proving their falseness." SA

Huxley the Medium


MICHAEL HUXLEY

Thomas H. Huxley, 1860s

In contrast to Charles Darwin, zoologist Thomas H. Huxley treated spiritualist claims with either disinterest or good humor. Once he was present when a clever, attractive American woman mystified a select company with a fraudulent display of psychic powers and thought reading. Although he saw through her game, Huxley later reported he was so charmed by the lady that he gallantly refrained from exposing her. "Fraud is often genius out of place," he mused, "and I confess that I have never been able to get over a certain sneaking admiration for Mrs. X."

When Alfred Russel Wallace sent him a copy of his book on spiritualism, Huxley responded: "It may all be true...but really I simply cannot get up any interest in the subject." Huxley had enough interest, however, to master the art of loudly snapping his toes inside his boots, so that he, too, could feign summoning the spirits. "By dint of patience, perseverance [and] practice," he explained, the toe snaps "may be repeated very rapidly, and rendered *forte* or *piano* at pleasure. To produce the best effect, it is advisable to have thin socks and a roomy, hard-soled boot; moreover, it is well to pick out a thin place in the carpet, so as to profit by the resonance of the floor." —*R.M.*

The Author

RICHARD MILNER is a historian of science who has focused on Charles Darwin for the past 20 years. He has uncovered several previously unknown episodes in Darwin's life. Milner received an M.A. in anthropology from the University of California, Los Angeles, and passed his doctoral exam in human evolution at the University of California, Berkeley, in 1968. He is now an editor at *Natural History* magazine at the American Museum of Natural History. This is his second article for *Scientific American.*

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Confronting Science's Logical Limits

The mathematical models now used in many scientific fields may be fundamentally unable to answer certain questions about the real world. Yet there may be ways around these problems

by John L. Casti

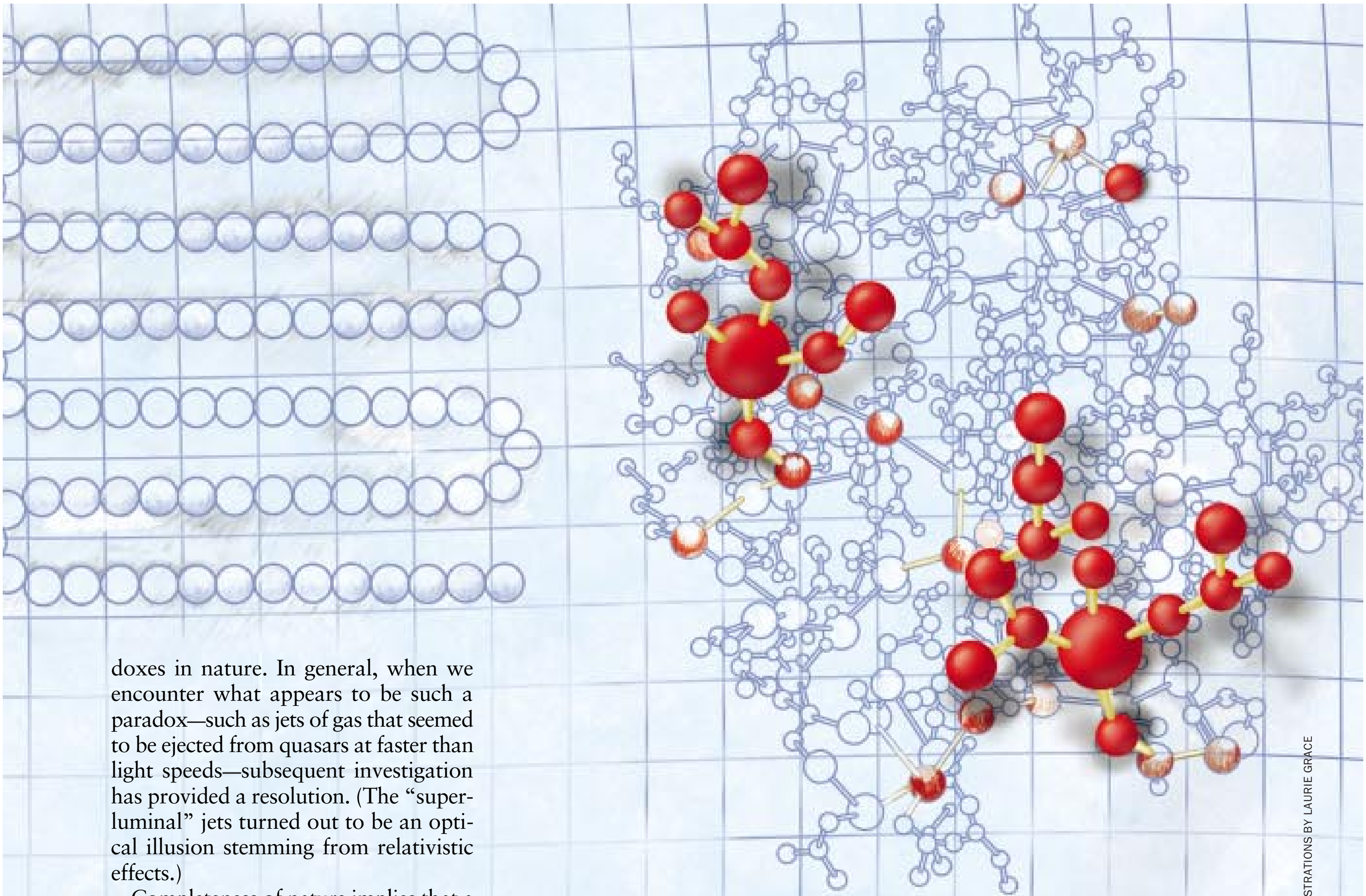
To anyone infected with the idea that the human mind is unlimited in its capacity to answer questions, a tour of 20th-century mathematics must be rather disturbing. In 1931 Kurt Gödel set forth his incompleteness theorem, which established that no system of deductive inference can answer all questions about numbers. A few years later Alan M. Turing proved an equivalent assertion about computer programs, which states that there is no systematic way to determine whether a given program will ever halt when processing a set of data. More recently, Gregory J. Chaitin of IBM has found arithmetic propositions whose truth can never be established by following any deductive rules.

These findings proscribe our ability to know in the world of mathematics and logic. Are there similar limits to our ability to answer questions about natural and human affairs? The first and perhaps most vexing task in confronting this issue is to settle what we mean by "scientific knowledge." To cut through this philosophical Gordian knot, let me adopt the perhaps moderately controversial position that a scientific way of answering a question takes the form of a set of rules, or program. We simply feed the question into the rules as input, turn the crank of logical deduction and wait for the answer to appear.

Thinking of scientific knowledge as being generated by what amounts to a computer program raises the issue of computational intractability. The difficulty of solving the celebrated traveling-salesman problem, which involves finding the shortest route connecting a large number of cities, is widely believed to increase exponentially as the number of destinations rises. For example, pinpointing the best itinerary for a salesman visiting 100 cities would require examining $100 \times 99 \times 98 \times 97 \times \ldots \times 1$ possibilities—a task that would take even the fastest computer billions of years to complete.

But such a computation is possible—at least in principle. Our focus is on questions for which there exists no program at all that can produce an answer. What would be needed for the world of physical phenomena to display the kind of logical unanswerability seen in mathematics? I contend that nature would have to be either inconsistent or incomplete, in the following senses. Consistency means that there are no true para-

TRAVELING SALESMAN would need the world's fastest computer running for billions of years to calculate the shortest route between 100 destinations. Scientists are now seeking ways to make such daunting problems more tractable.



ILLUSTRATIONS BY LAURIE GRACE

PROTEIN-FOLDING PROBLEM considers how a string of amino acids (*left*) folds up almost instantaneously into an extraordinarily complex, three-dimensional protein (*right*). Biologists are now trying to unravel the biochemical "rules" that proteins follow in accomplishing this feat.

doxes in nature. In general, when we encounter what appears to be such a paradox—such as jets of gas that seemed to be ejected from quasars at faster than light speeds—subsequent investigation has provided a resolution. (The "superluminal" jets turned out to be an optical illusion stemming from relativistic effects.)

Completeness of nature implies that a physical state cannot arise for no reason whatsoever; in short, there is a cause for every effect. Some analysts might object that quantum theory contradicts the claim that nature is consistent and complete. Actually, the equation governing the wave function of a quantum phenomenon provides a causal explanation for every observation (completeness) and is well defined at each instant in time (consistency). The notorious "paradoxes" of quantum mechanics arise because we insist on thinking of the quantum object as a classical one.

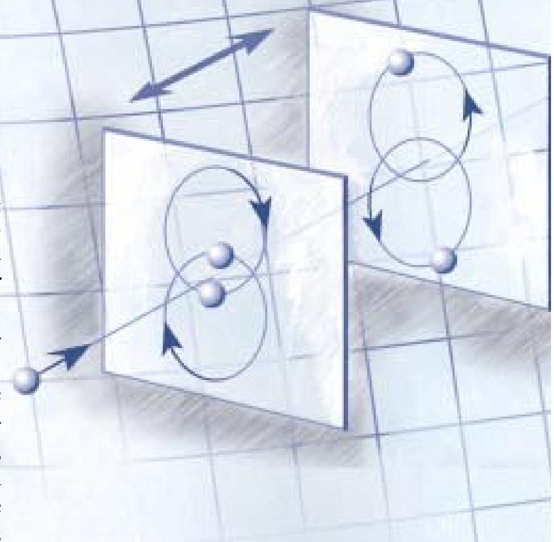
A Triad of Riddles

It is my belief that nature is both consistent and complete. On the other hand, science's dependence on mathematics and deduction hampers our ability to answer certain questions about the natural world. To bring this issue into sharper focus, let us look at three well-known problems from the areas of physics, biology and economics.

• Stability of the solar system. The most famous question of classical mechanics is the *N*-body problem. Broadly speaking, this problem looks at the behavior of a number, *N*, of point-size masses moving in accordance with Newton's law of gravitational attraction. One version of the problem addresses whether two or more of these bodies will collide or whether one will acquire an arbitrarily high velocity in a finite time. In his 1988 doctoral dissertation, Zhihong (Jeff) Xia of Northwestern University showed how a single body moving back and forth between two binary systems (for a total of five masses) could approach an arbitrarily high velocity and be expelled from the system. This result, which was based on a special geometric configuration of the bodies, says nothing about the specific case of our solar system. But it does suggest that perhaps the solar system might not be stable. More important, the finding offers new tools with which to investigate the matter.

• Protein folding. The proteins making up every living organism are all formed as sequences of a large number of amino acids, strung out like beads on a necklace. Once the beads are put in the right sequence, the protein folds up rapidly into a highly specific three-dimensional structure that determines its function in the organism. It has been estimated that a supercomputer applying plausible rules for protein folding would need 10^{127} years to find the final folded form for even a very short sequence consisting of just 100 amino acids. In fact, in 1993 Aviezri S. Fraenkel of the University of Pennsylvania showed that the mathematical formulation of the protein-folding problem is computationally "hard" in the same way that the traveling-salesman problem is hard. How does nature do it?

• Market efficiency. One of the pillars on which the classical academic theory of finance rests is the idea that financial markets are "efficient." That is, the market immediately processes all information affecting the price of a stock or commodity and incorporates it into the current price of the security. Consequently, prices should move in an unpredictable, essentially random fashion,



discounting the effect of inflation. This, in turn, means that trading schemes based on any publicly available information, such as price histories, should be useless; there can be no scheme that performs better than the market as a whole over a significant interval. But actual markets do not seem to pay much attention to academic theory. The finance literature is filled with such market "anomalies" as the low price–earnings ratio effect, which states that the stocks of firms whose prices are low relative to their earnings consistently outperform the market overall.

The Unreality of Mathematics

Our examination of the three questions posed above has yielded what appear to be three answers: the solar system may not be stable, protein folding is computationally hard, and financial markets are probably not completely efficient. But what each of these putative "answers" has in common is that it involves a mathematical *representation* of the real-world question, not the question itself. For instance, Xia's solution of the *N*-body problem does not explain how real planetary bodies move in accordance with real-world gravitational forces. Similarly, Fraenkel's conclusion that protein folding is computationally hard fails to address the issue of how real proteins manage to do their job in seconds rather than eons. And, of course, canny Wall Street operators have thumbed their noses at the efficient-market hypothesis for decades. So to draw any conclusions about the inability of science to deal with these questions, we must either justify the mathematical model as a faithful representation of the physical situation or abandon the mathematics altogether. We consider both possibilities in what follows.

What these examples show is that if we want to look for scientifically unanswerable questions in the real world, we must carefully distinguish between the world of natural and human phenomena and mathematical and computational models of those worlds. The objects of the real world consist of directly observable quantities, such as time and position, or quantities, such as energy, that are derived from them. Thus, we consider parameters such as the measured position of planets or the actual observed configuration of a protein. Such observables generally constitute a discrete set of measurements taking their values in some finite set of numbers. Moreover, such measurements are generally not exact.

In the world of mathematics, on the other hand, we have symbolic representations of such real-world observables, where the symbols are often assumed to belong to a continuum in both space and time. The mathematical symbols representing attributes such as position and speed usually have numerical values that are integers, real numbers or complex numbers, all systems containing an infinite number of elements. In mathematics the concept of choice for characterizing uncertainty is randomness.

Finally, there is the world of computation, which occupies the curious position of having one foot in the real world of physical devices and one foot in the world of abstract mathematical objects. If we think of computation as the execution of a set of rules, or algorithm, the process is a purely mathematical one belonging to the world of symbolic objects. But if we regard a computation as the process of turning switches on or off in the memory of an actual computing machine, then it is a process firmly rooted in the world of physical observables.

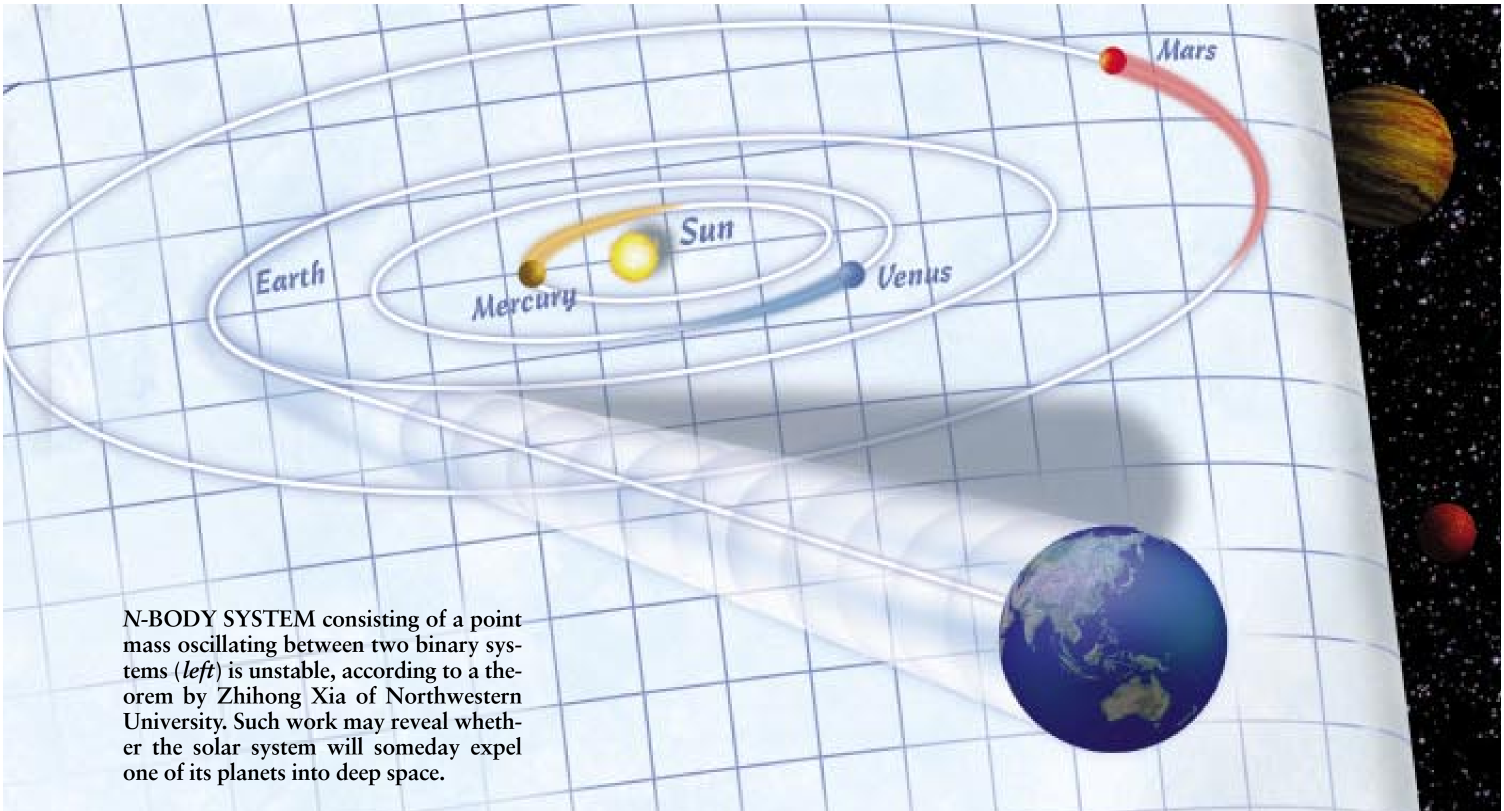
One way to demonstrate whether a given question is logically impossible to answer by scientific means is to restrict all discussion and arguments solely to the world of natural phenomena. If we follow this path, we are forbidden to translate a question such as "Is the solar system stable?" into a mathematical statement and thereby to generate an answer with the logical proof mechanism of mathematics. We then face the problem of finding a substitute in the physical world for the concept of mathematical proof.

A good candidate is the notion of causality. A question can be considered scientifically answerable, in principle, if it is possible to produce a chain of causal arguments whose final link is the answer to the question. A causal argument need not be expressed in mathematical terms. For example, the standard deductive argument "All men are mortal; Socrates is a man; therefore, Socrates is mortal" is a causal chain. There is no mathematics involved, just plain English. On the other hand, constructing a convincing causal argument without recourse to mathematics may be a daunting task. In the case of the stability of the solar system, for example, one must find compelling nonmathematical definitions of the planets and gravity.

Given these difficulties, it seems wise to consider approaches that mix the worlds of nature and mathematics. If we want to invoke the proof machinery of mathematics to settle a particular real-world question, it is first necessary to "encode" the question as a statement in some mathematical formalism, such as a differential equation, a graph or an *N*-person game. We settle the mathematical version of the question using the tools and techniques of this particular corner of the mathematical world, eventually "decoding" the answer (if there is one!) back into real-world terms. One challenge here is establishing that the mathematical version of the problem is a faithful representation of the question as it arises in the real world. How do we know that mathematical models of a natural system and the system itself bear any relation to each other? This is an old philosophical conundrum, entailing the development of a theory of models for its resolution. Moreover, mathematical arguments may be subject to the constraints revealed by Gödel, Turing and Chaitin; we do not know yet whether the real world is similarly constrained.

The Noncomputational Mind

There may be ways to sidestep these issues. The problems identified by Gödel and others apply to number systems with infinite elements, such as the set of all integers. But many real-world



***N*-BODY SYSTEM consisting of a point mass oscillating between two binary systems (*left*) is unstable, according to a theorem by Zhihong Xia of Northwestern University. Such work may reveal whether the solar system will someday expel one of its planets into deep space.**

problems, such as the traveling-salesman problem, involve a finite number of variables, each of which can take only a finite number of possible values.

Similarly, nondeductive modes of reasoning—induction, for instance, in which we jump to a general conclusion on the basis of a finite number of specific observations—can take us beyond the realm of logical undecidability. So if we restrict our mathematical formalisms to systems using finite sets of numbers or nondeductive logic, or both, every mathematical question should be answerable; hence, we can expect the decoded real-world counterpart of such questions to be answerable as well.

Studies of the human mind may reveal other ways to bypass logical limits. Some artificial-intelligence proponents have proposed that our brains are computers, albeit extremely sophisticated ones, that perform calculations in the same logical, step-by-step fashion that conventional computers (and even parallel processors and neural networks) do. But various theorists, notably the mathematical physicist Roger Penrose of the University of Oxford, have argued that human cognitive activity is not based on any known deductive rules and is thus not subject to Gödelian limits.

Recently this viewpoint has been bolstered by studies carried out under the aegis of the Institute for Future Studies in Stockholm by me, the psychologist Margaret A. Boden of the University of Sussex, the mathematician Donald G. Saari of Northwestern University, the economist Åke E. Andersson (the institute's director) and others. Our work strongly suggests that in the arts as well as in the natural sciences and mathematics, the human creative capacity is not subject to the rigid constraints of a computer's calculations. Penrose and other theorists have conjectured that human creativity stems from some still unknown mechanisms or rules, perhaps related to quantum mechanics. By uncovering these mechanisms and incorporating them into the scientific method, scientists may be able to solve some seemingly intractable problems.

Of course, science's ability to plumb nature's secrets is limited by many practical considerations—such as measurement error, length of computation, physical and economic resources, political will and cultural values. But none of these considerations bears on whether there is a logical barrier to our answering a certain question about the natural world. My contention is that there is not. So a tour of 20th-century mathematics need not be so disturbing after all!

The Author

JOHN L. CASTI is a professor at the Technical University of Vienna and at the Santa Fe Institute (casti@santafe.edu). He is grateful to Joseph F. Traub, Piet Hut, James B. Hartle and Åke E. Andersson for stimulating discussions on these matters and to the Institute for Future Studies in Stockholm for partial support of this research.

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Sounding Out Science

by Marguerite Holloway, *staff writer*

Photography by Stephen Ferry

Standing in front of his favorite boulder, Alan J. Mearns of the National Oceanic and Atmospheric Administration holds aloft a series of pictures, comparing this year's scene with those of the previous six. The rock is certainly a nice one—potato-shaped as it is and covered with a fuzz of light-brown *Fucus,* or rockweed—but that alone cannot explain the photographic frenzy it triggers. Mearns takes another shot of the rock, capturing in the frame his colleague Gary Shigenaka, who is taking a video of the same outcropping, as well as Dennis C. Lees, who is studying the beach adjacent to the rock. Meanwhile, as a fourth scientist quips about the Heisenberg uncertainty principle and clamors to get a picture of Mearns taking a picture of Shigenaka taking a picture of Lees and the rock, a photojournalist records the whole assemblage.

This concept of an image inside an image and so on to infinity, what the French call *mis-en-abîme,* provides one of the keys to understanding what has happened in Prince William Sound, Alaska, since the *Exxon Valdez* crashed into Bligh Reef in 1989. More important, it sheds light on how to interpret "recovery," a term that in the Sound means very different things to different people. The tanker spilled about 37,000 metric tons of North Slope oil, coating a total of 1,750 kilometers of shoreline and killing thousands of birds and animals. The accident was followed by massive infusions of money, lawyers and scientific studies into the same wilderness—and these inputs were about as clarifying as the coat of thick black crude itself.

For years, lawyers watched scientists watching other scientists watching an ecosystem that is little understood and infinitely variable; everyone used a different-size frame to peer through. The state of Alaska, the people who live on the Sound and the area's fishermen all wanted to document not only the extent of the devastation but the endurance of the spill's deleterious effects. Exxon wished to show the effectiveness of its intensive cleanup as well as the evanescent quality of the oil, which is, after all, a natural substance.

Exxon lost, both in court and out. In addition to $2.5 billion spent on cleanup, on claims and on reimbursing agencies for response expenses, the company is paying $900 million to the Trustees—a panel of state and federal agency representatives—for "restoration," another ill-defined term that has come to include buying land so as to protect it. This 1991 out-of-court settlement includes a reopener provision: if, between the years 2002 and 2006, other impacts

Prince William Sound is recovering, seven years after the Exxon Valdez *disaster. But the spill's scientific legacy remains a mess*

PHOTOGRAPHS BY STEPHEN FERRY *Gamma Liaison*

INTERTIDAL CREATURES on Rocky Islet in Northwest Bay are scrutinized and counted by researcher Dennis C. Lees.

of the oil spill come to light, the Trustees get $100 million more. Exxon, which is also due to pay $39.6 million to the region's fishermen and to Sound residents, plans to appeal a $5-billion punitive settlement.

The studies that Exxon and the state of Alaska—including the departments of Fish and Game and of Environmental Conservation—conducted to prove their respective points were kept largely secret until legal settlements were reached. This secrecy reduced most of the pillars of science to rubble: out went scientific dialogue, data sharing and, for some parties, peer review. Millions of dollars were shelled out in duplicate studies—that reached opposite conclusions. In a scathing review of post-spill research in this year's *Annual Review of Ecology and Systematics,* marine biologist Robert T. Paine and his colleagues at the University of Washington quote a juror grappling with these apparent paradoxes. Originally cited in the *American Lawyer,* the juror at the $5-billion punitive trial summed up many observers' feelings about the science: "You got a guy with four Ph.D.'s saying no fish were hurt, then you got a guy with four Ph.D.'s saying, yeah, a lot of fish were hurt.... They just kind of delete each other out."

Viewfinders

Now, seven years after the disaster, one can see the *mis-en-abîme* effect—or perhaps instead, the Sound uncertainty principle—at work. Scientists are still sparring, lawyers are still lurking around the edges of disputes, and both claim to be searching for the truth. Nevertheless, it is becoming obvious that, with a few exceptions, most of the frames people have been looking through as they study the Sound are too small to permit clear conclusions about the effects of the oil—suggesting that the next big spill may be a scientific fiasco as well. Further, it appears oil may not be the whole story: there may be much larger factors at play in the Sound.

Some of this perspective has become possible because Exxon recently published its studies in a thick blue volume, and the Trustees' tome came out this summer. Not surprisingly, almost every abstract in the Exxon book has the same refrain: by 1991 the Sound was well. To the oil company, recovery was defined as the reestablishment of a "healthy" biological community characteristic of the area. By this standard, even a biological community that was quite different from the one before the spill could, obviously, qualify as healthy.

If one scrutinizes Exxon's research, one can see how the company reached its conclusions. For example—and this will relate later to Mearns's favorite rock, still sitting at the beginning of this article but not forgotten there—the intertidal zone can appear very healthy, two years after the spill. This zone is usually one of the most biologically active and important in marine ecosystems. *Fucus* and other algae anchor to tidally flooded rocks there; barnacles, drills, periwinkles, mussels, sea anemones, starfish, sea urchins, baby herring, pink salmon eggs, tiny sculpins, hermit crabs and other creatures that are part of the immense food web thrive in this rich, diverse place. Ravenous sea otters rake the intertidal, as do oyster-catchers and Harlequin ducks, searching for mussels and other invertebrates.

Looking through tiny frames called quadrats, Exxon contractor Edward S. Gilfillan of Bowdoin College and his team saw something quite different from what other intertidal researchers saw. Biologists lay down a quadrat on the spot they want to investigate and count every organism inside the boundaries. They then repeat this procedure many times, comparing species composition and diversity between beaches—in this case, oiled beaches versus unoiled ones. Frames can also be placed at different elevations—the lower, the middle and the upper intertidal—or along "transects" perpendicular to the water. In places such as Prince William Sound, the intertidal is normally patchy and uneven, so that within a foot of a *Fucus*-matted rock, there may be a naked boulder; six inches to the right, there may be more *Fucus* and a bevy of barnacles.

At each of his sites, Gilfillan put down one baby quadrat, 12.5 by 25 centimeters, at four places along three transects. If he got, say, *Fucus* in one, none in the next and partial covering in the third, the beach looked extremely variable. And what he concluded, in essence, was that there was so much variability on any beach, it was almost impossible to distinguish oiled from unoiled sites: every beach resembled every other. Therefore, recovery had occurred.

The Importance of Being Random

Further, because his many sites had been chosen randomly—the cornerstone of all good field biology—Gilfillan's results could be extrapolated to the entire region. "By 1990 between 73 and 91 percent of the area had recovered," Gilfillan notes, adding that people mistakenly describe the Sound as a fragile ecosystem. "As anyone who has been through an Alaskan winter knows, it is not fragile. The animals and plants there are very good at making good their losses."

Needless to say, Gilfillan's findings bemuse some observers—among them, Charles H. Peterson, a marine scientist at the University of North Carolina at Chapel Hill. Peterson, who was an expert witness in various Sound-related trials, points out that the Exxon approach not only exploits the Sound's patchiness, it mixes species together, wreaking havoc with biodiversity. For example, Gilfillan lumps different kinds of barnacles together in measuring total barnacle cover. And to him, the barnacle cover in 1990 looked much the same at oiled and unoiled beaches. In truth, Peterson explains, the lumping was misleading: the oiled sites principally contained one kind of barnacle—a little opportunistic gray species called *Chthamalus dalli*—whereas the unoiled beaches had larger, more diverse barnacles.

In another grouping, Exxon counted worms in the lower intertidal and mixed these figures into totals for the number of organisms. Yet, Peterson cautions, those worms congregate at oily sites. It is akin to saying you have 100 creatures at place A and 100 at place B; therefore, place A and B are equivalent. In fact, 99 of the animals in place A could be worms that love to eat the microorganisms that love to eat oil. "I have never seen a data set in my life that combines these communities," Peterson exclaims. "Some have argued that what Exxon did was create a study that was inconclusive by design."

PICTURES INSIDE PICTURES reveal an obsession with frames and views in Prince William Sound.

Whatever the study was designed to do, its results gave Exxon evidence that all was well in 1991, so the company stopped monitoring the intertidal in quantitative ways. (Exxon researchers continue to conduct counts of sea otters and birds.) The Trustees, for their part—with Exxon's fiscal contribution—are still watching, waiting for the long-term negative effects they are sure will manifest themselves.

Ernie Piper of the Alaska Department of Environmental Conservation, normally loquacious, hesitates for a long time before answering a question about recovery. "In terms of the ecology, that, in many ways, it appears to me, is a lot more resilient than we deserved," he says slowly. "At the same time, there are lots of effects from the spill and the cleanup that are not going to go away."

"I think it is an improved picture," adds Robert B. Spies of Applied Marine Sciences in Livermore, Calif., and the chief scientist for the Trustees panel. "But it is still variable, depending on what resource you are talking about. Pink salmon have improved, yet we are worried about the herring." The Trustees also remain concerned about sea otter populations and the intertidal.

The state's principal study of the intertidal, directed by Raymond C. Highsmith of the University of Alaska–Fairbanks, resembled Exxon's in that it used randomly selected sites. It differed in that it incorporated more transects at each site and more spacious quadrats (40 by 50 centimeters). Highsmith and his colleagues—among them, Michael

S. Stekoll of the University of Alaska–Fairbanks—found a counterpoint to Gilfillan. By 1991 they saw only incomplete recovery.

And there the study stopped. Despite all the money available, the Trustees deemed the work too costly at its original price: $10 million for three additional years. Even when the biologists proposed doing half the sites one year, half the next, it was still not cheap enough: "There is a lot of politics," Stekoll says, explaining that the Trustees are under great pressure to use the $900 million to acquire land for the state, thereby protecting it from deforestation. Two hundred million dollars have already been spent to do so, and there are plans to spend about $180 million more.

As unfinished business, nonetheless, the study permits the Trustees to defer conclusions about recovery. "I would like to bring closure to this intertidal thing. It is a question of priorities," Spies notes.

The Way We Were

For the Trustees, "recovery" will occur when the Sound looks as it would have if the spill had not occurred. The biggest problem with this criterion is that no one really knows exactly what the Sound was like before the blanket of oil and scientists descended on it or how it would have evolved. The scientists have had to grapple with the absence of baseline data, except for a few specific species, including murres on the Barren Islands, killer whales, sea lions and, of course, the commercially crucial salmon.

To a lay traveler visiting Prince William Sound this summer for the first time since 1991, it appears beautiful and healthy. Although oil still lies under the boulders and cobbles on some beaches, it takes longer to find, and the oil is largely weathered—that is, nontoxic. Humpback whales can be seen in open water before they dive, flashing their *Fucus*- or barnacle-encrusted tails. Also visible are orcas, porpoises, seals, sea lions, puffins, kittiwakes, pigeon guillemots and river otters in coves or channels. In one unoiled eastern bay, sea otters float everywhere, bobbing like buoys, some with young on their chests, while myriad bald eagles make their high-pitched, halting cries. And the intertidal, even in places that were heavily damaged, seems more luxuriant than it did five years ago—with purple and orange sea stars and tousled green, brown and red seaweed.

This big picture, however, can be just as misleading as a little quadrat. And that is why Mearns's rock is so interesting. Mearns belongs to yet another intertidal team, funded by NOAA. The NOAA study was designed differently from those of Exxon and the state, because it was never intended to be part of damage assessment—that is, it was not driven by litigation. Instead its agenda was to describe differences in recovery between oiled beaches that were left alone and those that were cleaned with high-pressure jets of very hot water.

INTERTIDAL VARIABILITY can range from a quadrat full of *Fucus* (*top*) to barren rock (*bottom*) a few feet away.

Given that they spend most of their time on the beach staring into fairly big quadrats—50 by 50 centimeters—it is perhaps not surprising that Mearns and the rest of the NOAA team constantly joke about views and frames. Through these windows, this group—led by Jonathan P. Houghton of Pentec Environmental in Edmonds, Wash., and Lees of Ogden Environmental and Energy Services in San Diego—has watched recovery at many sites for the past seven years. Generally, they say, the intertidal looks good, although wide swings in species diversity and density persist.

The NOAA results suggest that hot-water cleaning sterilized the beaches; whatever survived the oiling did not survive the cure. The scientists report that a few years after the spill, the uncleaned beaches showed more health than did stark, cleaned sites. The finding—something oil spill experts warned about to no avail during the invasion of the cleanup crews—is not popular. Both Exxon and the state were, and are, under considerable public pressure to rid the Sound of every last inch of black veneer.

"Yeah, cleanup is disruptive, and if you clean up it is going to look like a very different shoreline," comments Piper of the Department of Environmental Conservation. But, he argues, as do some members of the NOAA team, hot-water washing just needs to be done more judiciously. One possible solution, Mearns suggests, is washing in strips, which would leave patches of beach oiled but alive so they can recolonize the bald spots.

The NOAA intertidal work has also

been criticized on statistical grounds. Gilfillan of Exxon argues that because the sites were not randomly chosen, they have little statistical power and therefore are not generalizable. (According to a recent paper by Gilfillan, in which he and three colleagues compare the three intertidal studies, the Exxon study was statistically the most powerful.) Stekoll concurs: "From a pure statistical viewpoint, you would have to say that it was not a design to extrapolate to the Sound."

Houghton and Lees retort that they have fully characterized the biology of recovery—even if their sites were selected by different criteria, such as accessibility and the availability of baseline information (sometimes frantically gathered just before the oil came ashore). Thus, they are permitted to describe what is happening throughout the area. Statistics aside, it is true that by virtue of having monitored consistently for seven years, the NOAA crew has tracked some fascinating shifts in the ecosystem. And this is where the shaggy rock enters the picture again.

OIL SHEEN can still be found in the mud or under boulders in parts of the Sound.

Mearns's subject sits in Snug Harbor, one of the loveliest places in the Sound. High mountains rise directly up from the shore, and a waterfall flows right onto the beach. Snug was heavily oiled and a large part of it left uncleaned, as "set-aside." Such places serve as important controls, allowing scientists to study how long it takes for oil to disappear naturally from various types of beaches. Nevertheless, set-asides are controversial: because most Alaskans wanted all oil removed, NOAA officials had to fight to get the few they have.

As a protected area, not scoured by winter waves, Snug is a particularly important reference. The harbor looks oil free these days, except for a small patch of asphalt, and the intertidal seems lush. But Mearns's photographs reveal that his Snug rock is going through a dramatic cycle. In 1990 its top was covered with young *Fucus;* in 1991 the rest of the rock sported a similar ensemble. Rockweed—a keystone of the intertidal ecosystem—was rebounding.

Or was it? If the NOAA workers had stopped there, they could have shared the stand with Gilfillan: the Sound looked recovered. But they went back, and in 1992 the rock had lost a lot of cover. The next year some scattered germlings covered the crown again; in 1994 it was naked; the cycle began anew in 1995. And this past summer Mearns found a fuller shag and a few small mussels in the crevices.

Mystery of the Vanishing *Fucus*

The NOAA scientists have seen this pattern in cleaned places as well. The hypothesis they present is that most intertidal zones contain *Fucus* plants of different ages, whereas in the oiled and the cleaned sites, most, if not all, of the *Fucus* was killed in 1989. The slate wiped clean, every subsequent plant that recolonized the site was the same age, with the same life span. So when the *Fucus* dies, taking most of the creatures it protects with it, the system returns to ground zero. This suggestion is bolstered by recent research on the coast of Britain, where the *Torrey Canyon* tanker spilled 119,000 tons of oil in 1967. *Fucus* there, it seems, still goes through similar cycles. "Ten years after *Torrey Canyon* they said it was fine," Lees states. "Now they are going back and seeing flux still." In particular, *Fucus* and limpets seem to be in a race for space.

There are anecdotal reports, however, that such die-offs are being seen in other, unoiled environments. And despite observations in the Sound, biologists admit that they do not really know all that much about the omnipresent algae. As Jennifer L. Ruesink of the University of Washington remarks, scientists are not even sure how to measure the age of *Fucus*. Is it necessarily older when it is darker? Does the number of dichotomies, or branches off a stem, reflect its age in years, like tree rings? How do adults help or hinder the establishment of young plants?

Ruesink tried to answer some of these questions as she accompanied the NOAA crew through the Sound over the summer; she sat on top of the Snug rock as well as many others, meticulously counting strands of *Fucus,* plying them apart. Her preliminary findings are "equivocal." It looks as though *Fucus* may have slip-slided away, even at sites never touched by oil. So the mystery remains.

The *Fucus* provides yet another frame through which to view the *Exxon Valdez* disaster. The basic questions asked about this seaweed give the real story away: nobody actually knows much about anything in the Sound—or in any such complicated ecosystem, for that matter. Most of the studies conducted in the early years after the spill centered on one zone, or one species, at a time.

But, as David Duffy of the University of Alaska–Anchorage puts it, you have a problem if your species—say, the otter—starts eating your colleague's, the mussel. It is more appropriate instead to try to examine from the outset how the frames fit within one another—like zooplankton inside herring inside salmon inside bear. Indeed, the relation between links in the food chain is proving to be perhaps the most important information that could be gleaned from science in the Sound.

A Bird's-Eye View

The opportunity for real insight may, however, have been squandered. "The tragedy is that people are trying to look at oil spill relations seven years after the fact," Duffy explains. "There should have been greater thinking about an ecosystem approach." Spies of the Trustees agrees: "We are very aware that looking on a species-by-species basis has limitations. We thought that that was very appropriate at the time of the spill to learn what was killed." Still, he notes, "we have got some very exciting projects right now that go beyond 'When did this resource recover?' to the basic processes going on in the ecosystem." The panel is funding several studies that take this wider perspective, looking at oceanographic trends in the Gulf of Alaska and at the food web. The frame is hundreds of kilometers a side.

For his part, Duffy is looking at birds, evaluating declines reported among kittiwakes and pigeon guillemots. "We don't know whether it is the spill, or the spill and environmental change, or just environmental change," Duffy says. "We have victims, we have the weapon, we have the [birds] at the scene of the crime, but we don't know whether something happened before that affected the population and that this spill was only the trigger. And we will never know."

What Duffy and others are piecing together is that the Gulf of Alaska, and Prince William Sound with it, seems to be going through a shift that predates the spill. Researchers have already had trouble teasing apart the pre-spill effects of an extremely cold winter in 1989; those of a 9.2-magnitude earthquake in 1964 that upturned the Sound, devastating the ecosystem and wiping out communities of people; and those of the 1982–1983 El Niño (a periodic oceanic disturbance that affects weather and ocean currents).

According to the only long-term study of bait fish in the region, the population of fatty pelagic fish on which sea lions, seals and many seabirds feed plummeted in the early 1980s. Today there are only 17 percent as many sea lions as there were 20 years ago. The shrimp fishery, which peaked at about 119 million pounds in 1976, was down to 10 million in 1982. "At that time, there was a lot of arrow slinging about overfishing," remarks Robert Otto of the National Marine Fisheries Service. "But the fact of the matter was that [shrimp] were declining both where they were fishing and where they were not."

Shrimp was the center of attention because it supports a large industry. But the problem did not stop there. Paul J. Anderson, also at the National Marine Fisheries Service, started sampling in the 1970s with a small mesh net and caught bait fish, such as capelin and candlefish. These so-called by-catch are routinely netted along with shrimp but are not typically counted, because they are not important to fish markets. They are, however, the meals for commercial fish and as such are as worthy of care as their flashier predators.

The by-catch turned out to be the big catch after all. What Anderson saw was that capelin fell off when shrimp did, whereas cod and pollack increased. At the same time, the crab fishery crashed, and salmon numbers rose (while prices, consequently, sank). "There was something that happened in the North Pacific that changed the whole ecological structure," Otto says.

"We may be right in the middle of a shift back; people just don't know," Duffy remarks. He speculates that salmon may be plentiful because it is simply a salmon period. "When the fishery was under the feds, it was downtime for salmon, and the government workers were criticized as idiots for not managing it well. Maybe the state is not good or bad. Maybe salmon are just doing what they do."

The changes in bait fish numbers could be the result of the growth of hatcheries. These outfits release young fish each spring to feed in the Sound and the Gulf

PRESSING ALGAE for careful identification is still done, here by a member of the NOAA team, even after seven years of studies, because the intertidal seaweeds can be difficult to tell apart.

SOUND-WIDE STUDIES that attempt to look at the bigger—albeit more confusing—picture have just recently started to receive financial support.

of Alaska before they return home to spawn. These fish are, however, additions to the ecosystem—"extras" in a way—and they may be devouring bait fish that would have been available to wild fish and animals. Or the bait fish fluxes may be related to even bigger trends, such as those observed by Thomas C. Royer, an oceanographer at the University of Alaska–Fairbanks. Royer began taking water samples in 1970 and has concluded that the temperature fluctuates by two degrees Celsius every 15 to 25 years—shifts that could dramatically alter fish distribution.

In addition, he has gathered evidence that salinity shifts in 10- to 11-year cycles. Salinity differences could alter the way water flows through the Sound, changing the amount of nutrients available in the upper layers of the water column and disrupting the food chain. "I keep preaching that we need long-term studies," Royer comments, adding that many natural cycles are so long, however, that funders lose interest in them. "The funding for science is declining dramatically. There is just a great deal of frustration."

When there is suddenly a large influx of money into a poorly studied ecosystem—and finally the opportunity to do in-depth work—there is bound to be similar frustration. More money flooded into Prince William Sound after the *Exxon Valdez* spill than has flowed after any other. But, clearly, wherever litigation and science intersect, there is little hope for a frame with an expansive view. The federal rules governing damage assessment were recently modified to protect against another scientific fiasco after the next big spill; the new provisions try to ensure data sharing and to eliminate duplicative effort. Yet many observers doubt whether these changes will make any difference if billions of dollars are at stake. "I am not convinced at all that once we had the next big one everyone wouldn't go to their respective battle stations—'I have my science, and you have yours,'" comments David Kennedy of NOAA.

A Delicate Balance

Beyond the quality of science lies the public interpretation of science. Even though NOAA has shown that cleaning up can do more harm than good, demands to clean up persist. The Alaskan native village of Chenega has paid close attention to the spill-related research. Many of the residents of this community on Evans Island in the Sound are concerned about the oil's persistence.

Chenega residents thought the oil was having a biological effect, Piper says. "But there is nothing to show that it did. So are we going to spend a lot of money to clean up when there is no problem?" he asks. But science was not the point; ridding the beaches of unsightly oil was. "It was more an issue of trashing the neighborhood. It was a very legitimate complaint," Piper explains. And so the Trustees, who go through a public review process before they allocate their funds, will spend $1.9 million next summer to apply de-oiling compounds, at least one of which is known to be toxic to intertidal organisms.

Chenega is not alone. Ultimately, it is the frame of the television set and the mind-set of the media that dictate people's responses to images of oiled animals. The public wants the animals saved—at $80,000 per otter and $10,000 per eagle—even if the stress of their salvation kills them. "Scientists waste a lot of time saying, 'Do nothing,'" Duffy notes. "You have to balance the show and the science."

by Shawn Carlson

Working in a Vacuum

There's no way around it. Sooner or later, every serious amateur needs a vacuum system. Vacuums are crucial if you ever want to experiment with particle beams or make your own optical filters or radiometers, to name a few projects. The systems, however, have a reputation for being complex and costly, discouraging many amateurs from bringing vacuum techniques into their laboratories. But this need not be the case. Vacuum systems adequate for many scientific needs can be easily built and inexpensively maintained. Here's how to construct a system capable of achieving pressures as low as one ten-millionth of an atmosphere.

When it comes to vacuum vessels, think small. Low volumes are easier to seal and pump down. A smooth glass canning jar (having no designs, artwork or scratches, which can weaken the glass) makes an adequate chamber for the vacuum. From a scrap-metal yard, purchase a one-inch-thick aluminum plate to serve as a base. It should be larger than the jar's lid. Secure the lid to the base plate with a generous helping of aluminized epoxy. (If your local hardware stores don't carry it, call Devcon in Danvers, Mass., at 508-777-1100, for the nearest distributor.) The epoxy should ooze out evenly from around the lid when the lid is pressed into place under the weight of a few old books. Wipe away the excess and let the epoxy set.

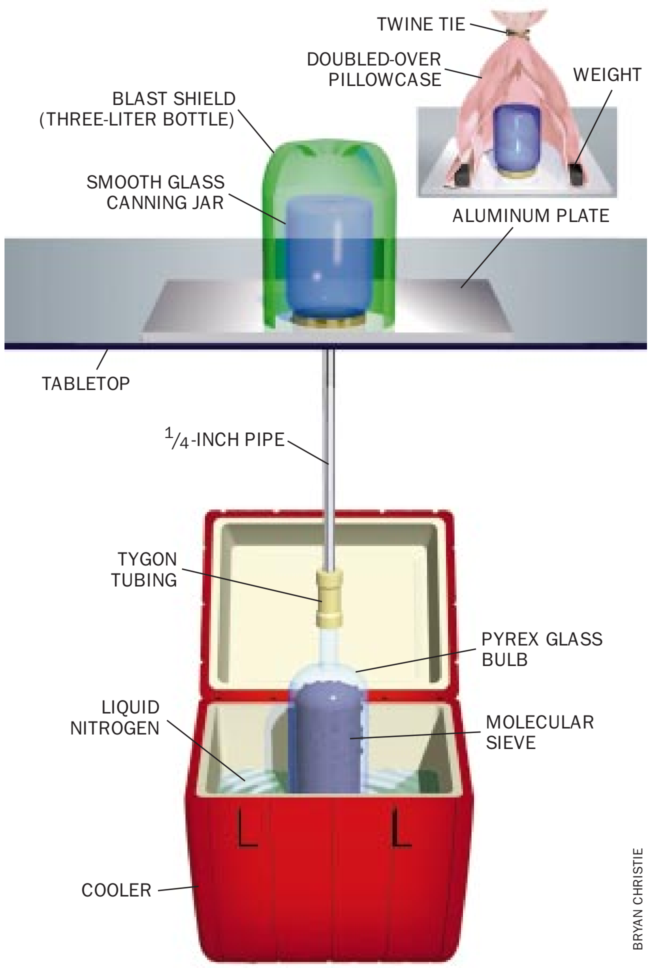
Next, drill a hole one quarter inch in diameter through the center of the lid and the base plate. If possible, tap the hole to give it threads. Obtain a one-quarter-inch-wide threaded pipe from a hardware store. Coat its threads with epoxy, then screw it through the bottom of the base plate. If you can't tap the hole, just glue in an unthreaded pipe. Draw a bead of epoxy around the pipe as it is inserted to make sure the gap is completely filled with epoxy.

Cut a half-inch-wide hole in an old card table and rest the base plate on the table so that the pipe hangs down through the hole. The pipe's end should be about 10 inches from the floor. If the pipe's end has threads, cut them off and file the edge smooth.

Canning jars are designed to hold a vacuum, so you will most likely be able to screw the jar right into its lid. If you need pressures approaching 10 millionths of an atmosphere, you may want to take special precautions against tiny leaks. You can place a layer of Teflon tape (check your local hardware store) over the threads on the jar's lip before screwing it in. It may be necessary first to put a bead of vacuum grease along the rim of the jar's mouth to ensure an airtight seal. The grease is available from Duniway Stockroom Corporation in Mountain View, Calif. (800-446-8811 or 415-969-8811).

Precautions are needed in case the jar implodes. (It eventually will if you conduct enough vacuum experiments or if the jar has some structural weakness.) On implosion, small glass fragments could hurtle out at nearly the speed of sound! It is therefore absolutely vital that you always keep your vessel under a protective shield whenever you pump it down. If you don't need to see inside, a doubled pillowcase affords the necessary protection. Otherwise, cover the jar with a clear, thick-walled plastic container, such as a three-liter plastic soft-drink bottle with its neck cut off. Additionally, Ace Glass in Vineland, N.J. (800-223-4524 or 609-692-3333; catalogue no. 13100-10), sells a protective plastic coating that will hold the glass together in case of a catastrophe. Half a liter will run you about $28 and is well worth the cost for the protection. Use it in addition to, not in lieu of, a shield.

For many applications, sorption pumps are the vehicles of choice for creating a good vacuum. They have no moving parts; instead they work by chilling a type of substance, called a sorbent, to a temperature at which it absorbs gases. Activated charcoal works, but a molecular sieve is better. Molecular



BRYAN CHRISTIE

EVACUATING A GLASS CANNING JAR is achieved with molecular sieve pellets. A plastic shield or a doubled-over pillowcase protects in case of implosion.

BRYAN CHRISTIE

HEATING THE MOLECULAR SIEVE *drives off any moisture in the pellets.*

sieves are little pellets with so many microscopic nooks and crannies that they have fantastically large surface areas; a one-gram pellet may have more than 1,000 square meters of surface.

When chilled, air molecules get caught in these microchasms. A 50-gram supply can pump a one-liter volume down to 10 millitorr in 20 minutes. (Atmospheric pressure is about 760 torr.) Half a gallon of molecular sieve from Duniway Stockroom sells for about $35.

To hold the sorbent, you need to obtain a Pyrex bulb approximately one inch in diameter and three and a half inches long, with a one-quarter-inch glass tube neck. A local glassblowing shop will probably make you one for less than $30. Fill it with the sorbent, then stuff in a little glass wool on top to keep the molecular sieve in place. Over the neck of the glass tube, slip a short length of flexible tubing, called Tygon tubing (check your local hardware store).

Before it can be used, the molecular sieve must first be activated—that is, it must be baked. Wrap the bulb with heating tape, available from Omega Engineering in Stamford, Conn. (800-826-6342 or 203-359-1660; model no. FGS0031-010). The 12-inch-long piece sells for $20. Or cannibalize an old toaster for its heating element. In either case, be sure that the heater does not cross over itself and that all of it touches the bulb. Wire in a dimmer switch to control the temperature of the heater.

To monitor the temperature, use a thermocouple probe (Omega, model no. 5TC-GG-J-30-36, $33) wired to a digital voltmeter. Place the probe against the bulb between windings of the heating tape and then wrap the bulb with aluminum foil. Safely secure the bulb so that the neck points downward and turn on the current. Adjust the current so that the voltage from the thermocouple increases by 18 millivolts, the signal that the sieve has reached the correct baking temperature of 350 degrees Celsius. The heat drives off the trapped molecules, including water vapor, which will condense on the bulb's neck and drip out. Leave the heater on until the neck is completely dry. Turn off the heater and pinch off the Tygon tubing to prevent the sieve from absorbing moisture from the air while the bulb cools. And you're ready to connect it to your vessel.

You will need to chill the sorbent with liquid nitrogen. Don't worry—liquid nitrogen is inexpensive (less than $1 per liter) and easy to obtain (try the Yellow Pages under "Welder's Supplies"). It can be safely handled if you exercise some common sense. Store it in a large plastic drink cooler—10 liters will last a weekend. Make sure the container does not have a spigot at the bottom. Do not put the lid on tight, or else pressure from the boiling nitrogen will build up inside and burst the container.

To pump the air out of the canning jar, immerse the Pyrex bulb in the liquid nitrogen. The molecular sieve will suck the air out of the glass chamber, producing a vacuum as low as 10 millitorr.

A few hints. Thoroughly wash and dry the vacuum-vessel assembly before using it, making certain not to touch the inside with your fingers. I'm told that a fingerprint can outgas (evaporate under low pressure) for years if not removed. To drive off moisture, bake the vessel above 100 degrees C for an hour. The epoxy will also outgas, as will any plastic seals in the lid of the canning jar and any coating on the inside of the lid. Minimize the surface area of these materials exposed to the vacuum. If more than about one square centimeter of any of the materials is exposed, consider coating it with vacuum grease, which outgases at a much lower rate.

You can insert a vacuum gauge between the sorption pump and vessel. To measure pressure in the tens of millitorr range, you'll want a thermocouple gauge or a Pirani gauge. These devices exploit the fact that the thermal conductivity of a gas drops sharply from a constant at about one torr to essentially zero at one millitorr. You can purchase a complete thermocouple gauge from Kurt J. Lesker Company in Clairton, Pa. (call 800-245-1656 or 412-233-4200) for about $200. The electronically inclined can save about $150 by buying a type 531 thermocouple vacuum tube for $45 (part no. KJL5311) and then building a simple power supply and amplifier circuit. Pirani gauges, however, are much more versatile and are quite easy and inexpensive to build. I'll describe how to do that next month.

As a service to Scientific American *readers, the Society for Amateur Scientists is offering a complete sorption pump kit, including a Pyrex flask packed with a molecular sieve, heating tape, a small liquid-nitrogen holder and Tygon tubing. A vacuum vessel is not included. The cost is $60 for domestic orders, $70 for international ones (shipping included). This offer expires September 30, 1997.*

For more about vacuum systems, visit the SAS World Wide Web site at http://www.thesphere.com/SAS/ and the Bell Jar*'s site at http://www.tiac.net/users/shansen/belljar/ I gratefully acknowledge insightful conversations with George Schmermund, an amateur scientist from Vista, Calif., and with Steve Hansen, editor of the* Bell Jar, *a newsletter of vacuum experiments and the best amateur science quarterly I've seen.*

Editors' note: *In the power-supply circuit schematic in "Detecting Micron-Size Movements" [August], the lower integrated-circuit chip is incorrectly identified as a type 7805. It should be a type 7905. The upper chip is correct.* SA

Further Reading

PROCEDURES IN EXPERIMENTAL PHYSICS. John Strong. Lindsay Publications, Bradley, Ill., 1986 (originally published in 1938).

BUILDING SCIENTIFIC APPARATUS. J. H. Moore, C. C. Davis and M. A. Coplan. Addison-Wesley, 1989.

AN EXPERIMENTER'S INTRODUCTION TO VACUUM TECHNOLOGY. Steve Hansen. Lindsay Publications, 1995.

The Bell Jar. Quarterly journal. Edited by Steve Hansen (35 Windsor Drive, Amherst, NH 03031). $20 per year in U.S., $23 in Mexico and Canada, $29 elsewhere.

MATHEMATICAL RECREATIONS

by Ian Stewart

Monopoly Revisited

In the April column I described a mathematical model of the board game Monopoly. At the start of the game, when everyone emerges from the GO position by throwing dice, the probability of the first few squares being occupied is high, and the distant squares are unoccupied. Using the concept of Markov chains, I showed that this initial bunching of probabilities ultimately evens out so that the game is fair: everyone has an equal chance to occupy any square and to buy that property. This outcome is true, however, only when certain simplifying assumptions are made. Monopoly enthusiasts were quick to point out that in the real game, the long-term distribution of probabilities is not even.

So what are the true probabilities? The Markov chain method can also be applied to the real game; I have to warn you, however, that the analysis is complex and requires substantial computer assistance. Let me first remind you how Markov chains are used for Monopoly. A player can be in any one of 40 squares on the board, which, for convenience, we number clockwise from zero to 39, starting with GO (which is zero).

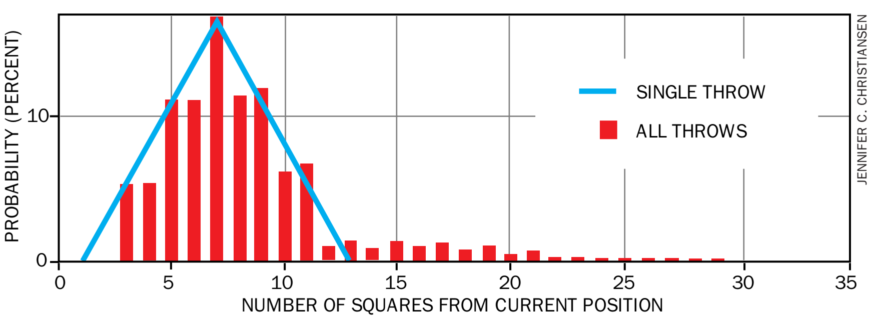
Given any two squares A and B, there is a quantity called the transition probability—the probability that a player who starts from A will reach B at the conclusion of his or her turn at throwing the dice. If this move is impossible, then the transition probability is zero.

There are 40 × 40 = 1,600 transition probabilities in all, and they can conveniently be encoded in a square matrix M with 40 horizontal rows and 40 vertical columns. For example, the entry in the sixth row and 10th column describes the probability of moving from Reading Railroad to Connecticut Avenue in one turn. The initial probabilities for a player are 1 for position 0 and 0 for all the rest; they can be encoded as a vector v = (1,0,...,0).

The theory of Markov chains tells us that the evolution of this probability distribution is given by the sequence of vectors v, Mv, M^2v, M^3v and so on: each throw of the dice corresponds to the matrix M operating on the vector v. The resulting vectors can be calculated by standard matrix methods, available on any good computer algebra package. Such packages can also calculate the so-called eigenvectors and eigenvalues of M. A vector u is an eigenvector with eigenvalue c if Mu = c × u, where c can be a real or complex number. Markov's key theorem is that the long-term probability distribution is given by the eigenvector whose eigenvalue has the largest absolute value.

So in order to analyze the fairness of Monopoly, all we need to do is compute M and apply matrix algebra. For my simplified model this was easy, but for the real game we must also take into account multiple rolls of the dice, special squares such as GO TO JAIL and instructions on cards that players draw when they land on CHANCE and COMMUNITY CHEST.

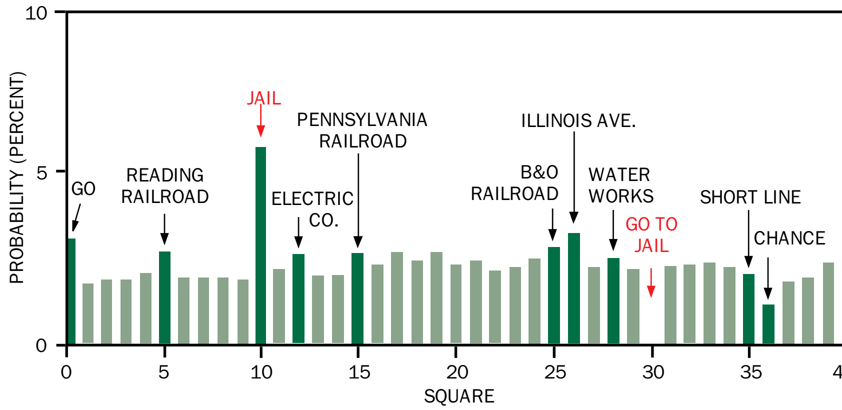
JAIL, and the many ways to land in it, makes Monopoly complex.



***PROBABILITIES OF MOVING** a given number of squares in one turn, after accounting for rules for throwing dice, peak at the number seven. If a player throws a double, he or she gets to throw again, but three consecutive doubles mean Jail.*

Many readers sent me their analyses of the game. The most extensive were from William J. Butler of Portsmouth, R.I., Thomas H. Friddell, a Boeing engineer from Maple Valley, Wash., and Stephen Abbott of the mathematics department at St. Olaf College in Northfield, Minn., who collaborated with his colleague Matt Richey. Butler wrote a Pascal program, Friddell used Mathcad and Abbott used Maple. The discussion that follows is a synthesis of their results. (All models of Monopoly make assumptions about the degree of detail to be incorporated; there were insignificant differences in the assumptions made by various correspondents.)

The first modification of my original model is to take full account of the rules for the dice. A pair of dice is thrown, and if the result is a double, the player throws again, but three consecutive doubles lands him or her in Jail. The throw of the dice is a tiny Markov chain in its own right and can be solved by the usual method. The result is a graph of the probability of moving any given distance from the current position [*see illustration at left*]. Notice that the most likely distance is 7, but that it is possible to move up to 35 squares (by throwing 6,6; 6,6; 6,5). Yet the probabilities of



JENNIFER C. CHRISTIANSEN

LONG-TERM PROBABILITY DISTRIBUTION *shows that the Jail square is most likely to be occupied.*

moving more than 29 squares are so small that they fail to show up on the graph. These results are incorporated into M by appropriately changing each individual entry.

Next the effect of the GO TO JAIL square must be included. The Jail rules pose a problem, because players can elect to buy their way out or stay in and try to throw doubles to get out. (Or at later stages, when Jail becomes a refuge from high rents, they can stay in and hope *not* to throw doubles!) The probabilities associated with this choice depend on the player's psychology, so the process is non-Markovian. Most correspondents got around this poser by assuming that the player did not buy his or her way out. Then Jail becomes not so much a single square as a Markov subprocess—a series of three (virtual) squares where players move from Just in Jail to In Jail One Turn Already to Must Come Out of Jail Next Turn. The GO TO JAIL square itself has probability zero because nobody actually occupies it.

The next step is to modify M to account for the CHANCE and COMMUNITY CHEST cards, which may send a player to Jail or to some other position on the board. This refinement can be made quite straightforwardly (if laboriously) by counting the proportion of cards that send the player to any given square. The extra probability is then added to the corresponding position in M.

Having set up an accurate transition matrix, one can work out the steady state probabilities either by numerically computing its eigenvalues and eigenvectors or by calculating the effect of a large number of moves from the powers M^2, M^3 and so on. Thanks to Markov's general theorem, these two methods are mathematically equivalent.

The long-term probabilities of occupying different squares are shown in the table [*see illustration at left*]. The most dramatic feature is that players are almost twice as likely to occupy the Jail square (5.89 percent) as any other. The next most frequented square is Illinois Avenue (3.18 percent). Of the railroads, B&O is occupied most often (3.06 percent) with Reading (2.99 percent) and Pennsylvania (2.91 percent) just behind; however, the probability of occupying Short Line is much less (2.44 percent). The reason for this is that unlike the others, Short Line does not feature a CHANCE card. Among the utilities, Water Works (2.81 percent) wins out, with Electric Company (2.62 percent) being marginally less probable. GO (3.11 percent) is the third most likely square, and the third CHANCE square (0.87 percent) is the least likely—except for GO TO JAIL (0 percent occupation by logical necessity).

Friddell went further and analyzed Monopoly's property market, which is what really makes the game interesting. His aim was to find the break-even point for buying houses—the stage at which income starts to exceed costs—and to determine the best strategies for buying houses and hotels. The exigencies of the property market depend on the number of players and which version of the rules is being adhered to. Assuming that houses can be bought from the start, a number of general principles emerge:

- Although it costs more to buy houses early, the break-even point will be reached more quickly if you do.
- With two houses or fewer, it typically takes around 20 moves or more to break even. Three houses produces a definite improvement.
- Between GO and Indiana Avenue the property square that offers the quickest break-even point for three houses is New York Avenue, which breaks even in about 10 turns.

Properties beyond Indiana Avenue were not evaluated: Friddell says he

FEEDBACK

Alan St. George's sculptures in the May column stimulated a discussion of how to make three-dimensional objects based on regular polyhedra. William J. Sheppard of Columbus, Ohio, sent details of his cunning method for cutting a regular tetrahedron or octahedron from solid wood, pointing out that "sturdy, solid models are more convenient than hollow models made by taping together equilateral triangles." His methods can be found in the *Journal of Chemical Education,* Vol. 44, page 683; November 1967.

Norman Gallatin of Garrison, Iowa, has been working on Platonic solids for a quarter of a century and has developed remarkable sculptures, some made from mirror glass. The picture at the right represents a three-dimensional projection of a four-dimensional hypercube and makes clever use of reflections to create a complex effect from simple components.

Any more mathematical sculptors or modelers out there? —*I.S.*


NORMAN GALLATIN

"Tesseract View of HyperCube III"

stopped there because he never expected to publish his results.

Many other readers contributed interesting observations, and I can mention a few. Simulations by Earl A. Paddon of Maryland Heights, Mo., and calculations by David Weiblen of Reston, Va., confirmed the pattern of probabilities. Weiblen points out that these probabilities do not really affect how "fair" the game is, because all players face the same situation. Developing this point, he notes that "if the rewards for landing on low-probability squares were out of proportion to that lowered probability, then there would be a problem. When out of sheer luck, a player in a game gets a big advantage, the game is unfair." He concludes that Monopoly is not unfair in that manner.

Bruce Moskowitz of East Setauket, N.Y., remarked, "In my youth I played Monopoly many times with my brothers and friends, and it was common knowledge that the tan-colored properties, St. James Place, Tennessee Avenue and New York Avenue, are especially valuable since there is a relatively high probability of landing on one of them when leaving Jail." This suggestion receives confirmation from the calculations, given that all three of these properties figure among the top 12 in the chart of probabilities.

Jonathan D. Simon of Cambridge, Mass., chided me for suggesting that cheap properties were put near the start to help even out the game. "Monopoly was...created during the Great Depression by a *single designer,* Charles Darrow, with lots of presumably unwelcome time on his hands. Under the trappings of wealth, the illustrated fat and rich men, it is (slyly) a poor man's game. In virtually all Monopoly contests...the 'cheap' properties turn out to be the most vital to Monopolize....The 'lucrative' properties...are expensive to own and prohibitively expensive to build without a source of income provided by ownership of a cheap group with houses." Point taken, though I would still argue that putting a lucrative property on the first half of the board would definitely be unfair, by Weiblen's criterion that no player should gain a big advantage purely by chance. And I'm not convinced that buying up lots of cheap properties and renting them out is a poor man's strategy! SA

REUTERS/CORBIS-BETTMANN

MISTAKES WERE MADE

Review by John Adams

The Logic of Failure: Why Things Go Wrong and What We Can Do to Make Them Right
BY DIETRICH DÖRNER
Henry Holt and Company, 1996 (originally published in German in 1989) ($25)

Why Things Bite Back: Technology and the Revenge of Unintended Consequences
BY EDWARD TENNER
Alfred A. Knopf, 1996 ($26)

Perhaps the human race carries a gene for hubris. The history of technology, since the time of Icarus's ill-fated aviation project, is littered with accounts of Man (it usually is the males) overreaching himself. Accidents happen, and after nearly every major one there is an inquest. With the benefit of hindsight, it is usually possible to identify the human error, or chain of errors, that caused things to go wrong. Most of the voluminous literature on risk management—with a few exceptions, such as that aimed at venture capitalists—is devoted to picking over the bones of past accidents and drawing lessons to ensure that those particular mistakes can never happen again. It is a frustrated literature. Things continue to go wrong, and there is little evidence that we are learning from this catalogue of mishap and disaster. Dietrich Dörner's book demonstrates why.

The Logic of Failure is a prescriptive book, and not a modest one: Dörner sets out a five-step "schema for the entire problem-solving process." Address the tasks laid out in each step, and whatever problem is at hand will be solved in the most effective possible way. Or so one might wish.

First, Dörner states, "We need to have clear goals in mind." Here is the initial problem; rarely can individuals, let alone societies, define clearly what they want. We are ambivalent. No one wants an accident, but everyone appears to want to be free to take risks. And risks, by definition, carry the possibility of adverse outcomes.

Second, according to Dörner's schema, we must have a model. "Can we as citizens," he asks, "ever have a complete understanding of the issues?" The answer is, clearly, "No," but he presses on: "Once we have acquired enough information about a situation and have formed a model that fits this information together, we should be in a position to assess not only the status quo but also developments likely to follow from the current situation." Perhaps we "should be," but we never are; prediction routinely founders on inadequate information.

Fourth comes planning, decision and action—activities that Dörner acknowledges to be challenging: "Decision making," he observes, "is rarely an easy task," and "action is a difficult enterprise." The final step is review and revision: "We must be prepared to acknowledge that a solution is not working." Who could disagree with such an obvious conclusion?

Dörner illustrates his prescriptions mostly by showing what happens when people apparently fail to follow them. In one study, he and his colleagues gave participants dictatorial powers to run "Tanaland," an imaginary nation somewhere in the Sahel. They controlled key variables such as infrastructure provision, medical care and birth control, water and irrigation and agricultural methods. Most participants produced simulated catastrophic famine, because their initial successes generated increases in the human and cattle populations that soon overran resources. Dörner's analysis of these failures smugly presumes that the developers of the computer simulation knew the "right answer" and that their model was sufficiently realistic to constitute a fair test of the participants' risk-management abilities. In fact, the study used a simplistic Malthusian model certain to trip up players who did not share the pessimism that was built into the game.

When a Grand Prix driver has an accident, is it because he made a mistake or simply because he was unlucky? Dörner would almost certainly answer that someone—a member of the pit crew, a competitor, the car or track designer, the driver himself—made an error. As a result of that attitude, he litters his book with impossible platitudes guaranteed to bring a wry smile to the face of a racer entering a chicane or to anyone else who must make a decision without adequate information—which is all of us most of the time: "We must learn to cope with side effects"; "Taking the middle path between clinging stubbornly to a doomed plan and giving up a fundamentally good one is not easy. Finding this path, though, will give us greater chances for success."

How can anyone manage these tricks in a nonlinear world characterized by conflicting values and populated by billions of people acting on one another and on their environment—and in the process constantly changing one another and the world? Dörner's ultimate answer is a bit lame: "What matters is not, I think, development of exotic mental capabilities.... There is only one thing that does in fact matter, and that is the development of our common sense."

Why Things Bite Back is a refreshing antidote to such earnest risk-management orthodoxy. Edward Tenner has a keen nose for paradox and irony and a very different idea of common sense. Given the catalogue of errors that serves as his subject matter, he is remarkably cheerful—partly, I suspect, because he is one of nature's optimists and partly because like most of us he enjoys what happens when pomposity steps on a banana skin.

Although he presumably has not read *The Logic of Failure* (it was published in German in 1989, but the English translation has just been released), Tenner provides an excellent implicit critique of it. He shows that our inability to articulate clear goals for the management of risk is found even in sport, where arguments rage over the use of new equipment and techniques that could improve safety and performance. It is possible, for example, to devise

NOW ON VIEW

Art and Science: Investigating Matter
PHOTOGRAPHY BY CATHERINE WAGNER
At the Gallery of Art at Washington University in St. Louis (through November 3); at the International Center for Photography in New York City (March 28–June 15, 1997)
Exhibit catalogue. Nazraeli Press, 1996 ($45)

Catherine Wagner, a photographer and art professor at Mills College in Oakland, Calif., uses the camera to pick apart everyday parts of our culture. Earlier exhibits have focused on the knickknacks in people's homes and on the construction of a convention center. While serving as artist-in-residence at Washington University, she turned her lens on the laboratory to "demystify the technical language of science by creating visual questions." Her new exhibit contains 65 works from that project. One might quibble that photographs such as *Sequential Molecules* (*left*) are more about the form of science than about its method. But therein lies Wagner's strength: the utilitarian apparatus and rigorous organizational schemes of scientific research make for stark and oddly beautiful compositions, affirming the artist's parallel fascination with the nature of the material world.

—*Corey S. Powell*

CATHERINE WAGNER

BRIEFLY NOTED

"POLAR EXPLORATION" CIGARETTE CARD, 1915–1916

I MAY BE SOME TIME: ICE AND THE ENGLISH IMAGINATION, *by Francis Spufford. Faber and Faber, 1996 ($24.95).*
Captain Oates's famous last words before perishing in the Antarctic ("I'm just going outside, and I may be some time") have set Francis Spufford off on a lyrical rumination on the meaning and mythology of the icy unknown—in science and in literature, in high society and in the attitudes of the masses. The result is a wholly original concoction. British fantasies of Eskimo life, the denouement of *Frankenstein* and the bizarre hollow-earth theory of John Cleves Symmes blend together naturally into a kind of neo-Victorian poetry.

EMPIRE OF LIGHT, *by Sidney Perkowitz. Henry Holt and Company, 1996 ($25).*
Using light as a unifying theme, Sidney Perkowitz roams widely through classical and modern physics, the nature of vision, optics, cosmology and fine art. The author displays an obvious love of breaking down the boundaries between disciplines; artists and scientists alike may discover some intriguing new personalities in the course of reading this book. The trade-off is a superficiality that erodes the subtlety behind some of the scientific anecdotes and reduces a few sections to little more than name-dropping.

A FIELD GUIDE TO GERMS, *by Wayne Biddle. Anchor Books, 1996 ($12.95).*
Some are deadly, others crucial to sustaining modern life. Wayne Biddle leads the reader from adenoviruses to Zika fever, with more than five dozen stops along the way, including *Clostridium botulinum* (from the Latin *botulus,* "small sausage," the food once most likely to harbor the microbe's highly lethal neurotoxin). Given the high price of even this paperback version, however, far too few people will enjoy this lively book.
Continued on page 123

procedures that permit mountaineers to achieve the summit of a particular peak with less risk than before, but many climbers resist "improvements" that diminish demands on their skill.

Things tend to "bite back" whenever we interfere with them in ignorance—the state, Tenner amply demonstrates, in which the real world usually compels us to operate. The same is true, only more so, of our attempts to anticipate the future. Tenner devotes three chapters to describing the way that insect pests bite back, often literally, when nature's rules turn out to be much more complex than those understood by the pests' would-be controllers.

Tenner has enjoyable sport with the hubris implicit in calls for perfect planning. Where Dörner endorses a goal of gathering information that will lead to an accurate model of future events, Tenner invokes Paul Valéry to telling effect: "Unpredictability in every field is the result of the conquest of the whole world by scientific power. This invasion by active knowledge tends to transform man's environment and man himself—to what extent, with what risks, what deviations from the basic conditions of existence and of the preservation of life we simply do not know. Life has become, in short, the object of an experiment of which we can say only one thing—that it tends to estrange us more and more from what we were, or what we think we are, and that it is leading us...we do not know and can by no means imagine where."

Tenner covers an impressive range of "revenge effects" and shows convincingly that unintended and undesired consequences are the norm whenever new technologies are introduced: the revolution that now permits information to be stored and transported electronically has produced a proliferation of paper. Flood-control work by the U.S. Army Corps of Engineers has actually increased the damage caused by floods. Helmets and other protective gear help to make football more dangerous than rugby. Roads designed to relieve congestion are themselves clogged with traffic. Clear, straight roads often have the highest fatality rates.

The more that we introduce conspicuous safety measures, Tenner argues, the greater becomes the likelihood of a *Titanic*-style disaster in which "belief in the safety of the ship [becomes] the greatest single hazard to the survival of its passengers."

Why can't we use reason to stamp out failure? Why do things bite back? The brief answer appears to be that "things" are densely interconnected. Whenever we intervene to change one specific item, we set in motion innumerable other changes. Risk and uncertainty are therefore inescapable.

Perhaps the single most effective thing that we can do to improve our luck is to devise ways of ensuring that the people responsible for sweeping changes in the world (or any small part of it) are in the front line when it comes to suffering the unintended consequences of their actions. The irony at the heart of both books, vainly resisted by Dörner but thoroughly embraced by Tenner, is one appreciated more than 100 years ago by Herbert Spencer: "The ultimate result of shielding men from the effects of folly is to fill the world with fools."

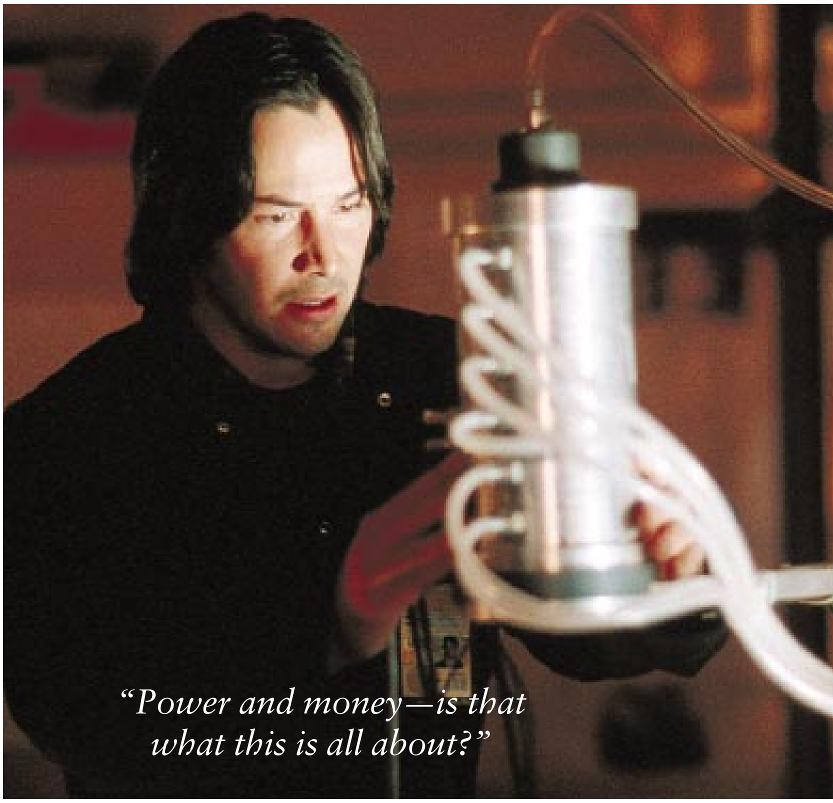
JOHN ADAMS is a reader in geography at University College London. He is the author of Risk *(UCL Press, 1995).*

ON THE SCREEN

Chain Reaction
DIRECTED BY ANDREW DAVIS
20th Century Fox, 1996

The specter of the notorious 1989 "discovery" of cold fusion—not to mention the mythical 100-mile-per-gallon carburetor—looms large over this scientific thriller. An enterprising college dropout, adequately portrayed by Keanu Reeves (*shown at right*), chances on a technique for extracting a nearly limitless supply of energy from ordinary water. The scientists leading the project want to release the news to the world via the Internet; sinister forces, however, do not want the secret revealed, and the chase is on.

Chain Reaction displays some welcome signs of scientific literacy. The film intriguingly invokes sonoluminescence as the key to the energy breakthrough, albeit vaguely (it is never really clear if we are watching fusion or simple hydrogen combustion). And it is nice to see a mainstream movie in which a lab technician is depicted as heroic and socially functional. On the other hand, the conspiracy-minded plot suggests a basic frustration with big science. In Hollywood mythology, collaboration and peer review are just obstacles to the triumph of the inquisitive spirit. *—Corey S. Powell*


"Power and money—is that what this is all about?"

MICHAEL P. WEINSTEIN

BEING MEDICAL

Review by Sherwin B. Nuland

Life after Medical School
BY LEONARD LASTER
W. W. Norton, 1996 ($27.50)

A few months ago I received a telephone call typical of many that I and other doctors have grown used to. A medical school junior had become infatuated—that is the only word to describe the intensity of her enchantment—with the idea of entering a training program in my specialty. As I listened to this intelligent young woman describe the aesthetic intensity of touch and sight that are the core of a surgeon's working life, I remembered the magnetizing influence those very qualities had held for me at a similar stage of my own professional education. I also knew well—as she anticipated—the personal satisfaction of witnessing the direct, curative outcome of one's handiwork.

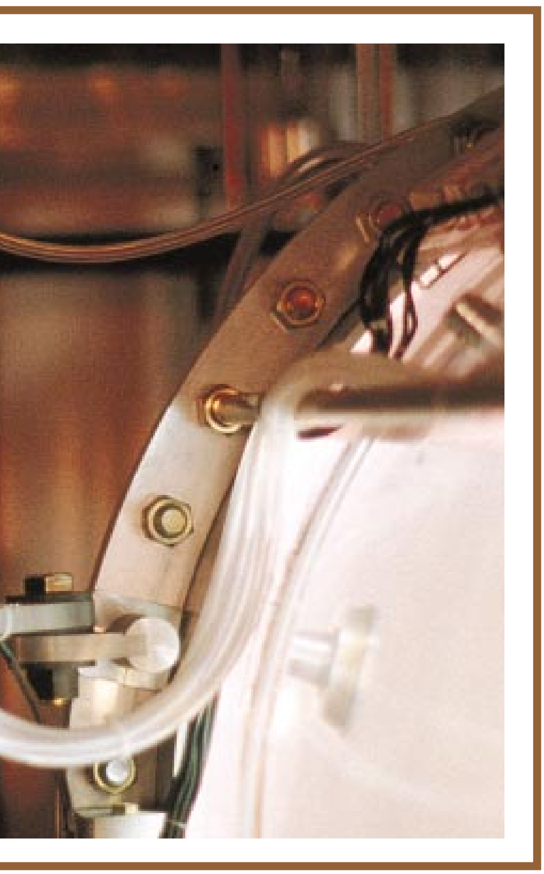
But after more than 30 years of a busy career, I recognized that I would have to temper the student's newfound fascination and tell her of the sometimes harsh realities of a surgeon's daily portion. Joseph Campbell's pop philosophy notwithstanding, I have seen more than one young person follow an ill-considered bliss right up the garden path, whether in matters of work or of the heart.

I interrupted the cavalcade of enthusiastic adjectives rolling through the receiver to speak of the rigors of training, the constant urgencies of the surgeon's life and their effect on a family. I made the point that precisely the solo responsibility that brings such satisfaction when things go well becomes the source of much gnashing of teeth when it does not. Adding to this tension is the fact that in many cases a surgeon must make crucial decisions about diagnosis and treatment before all necessary evidence is available—the internist's leisure to contemplate is too often absent.

I told my caller to speak to other surgeons, to visit training programs at several different schools and to look carefully at other specialties. Throughout our long conversation, I found myself wishing for a single published volume I might recommend, one in which the experiences of many specialties were condensed, compared and contrasted. I know my own field of medicine well but cannot speak authoritatively about alternatives.

Those of us who have received more than a few of these calls (and those who crave the insights of practitioners in the medical field) can now relax, at least a little. *Life after Medical School,* compiled by Leonard Laster, an internist and chancellor emeritus of the University of Massachusetts Medical Center, is a collection of 32 interviews of experienced physicians who have spent their careers in a particular specialty or in some offshoot of a medical career. It should help guide the aspiring student, and it may also provide useful understanding of the variety of medical experience for nonphysicians.

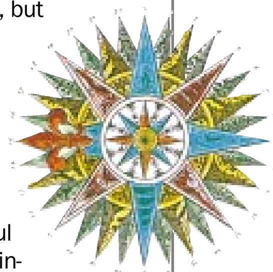
Laster's subjects tell us about the background that made them choose their fields, their experiences in training and practice, and their reflections on the decades of work. He has assembled a remarkably mixed group: some of them are academics, some in private practice, some are superspecialists and others are in primary care. They are



BRIEFLY NOTED

Continued from page 121

WEATHER: DRAMA OF THE HEAVENS, *by René Chaboud. Translated by I. Mark Paris. Harry N. Abrams, 1996 ($12.95).*
This unpretentious book packs a lot of glossy illustrations and basics of weather research into a pocket-size format. The translation from French has left behind an odd mix of English and metric units, but the text itself could hardly be clearer. The extensive marginalia (captions, quotes, anecdotes) encourage random browsing; a further reading section provides useful grist for those whose interest grows past the book's intentionally limited depth.



JEAN-LOUP CHARMET

UNRAVELING PILTDOWN, *by John Evangelist Walsh. Random House, 1996 ($25).*
The famous Piltdown man fossils excited and confounded paleontologists until they were exposed as fakes in 1953. The question ever since has been, Who perpetrated this elaborate fraud? John Walsh frames the story as a very entertaining whodunit. Disputing several recent theories, he points the finger back at the most obvious culprit: Charles Dawson, the amateur fossil hunter who allegedly discovered the bones. The wrap-up is unsurprising and unsatisfying, however, as Walsh supplies no persuasive motive and uncovers no smoking gun.

CHARLES DARWIN'S LETTERS: A SELECTION, *edited by Frederick Burkhardt. Cambridge University Press, 1996 ($21.95).*
These letters, culled from the seven-volume *Correspondence of Charles Darwin*, span the years from Darwin's student days to the publication of *On the Origin of Species* in 1859. There are some revealing personal insights, such as his battle with seasickness on board the H.M.S. *Beagle,* but high drama is not much in evidence. The real draw is the meticulous way the letters tell the inside story of Darwin's energetic, 22-year quest for evidence in support of his theory of evolution through natural selection.

black, white, male, female, married and single, born to wealth or raised in poverty. Laster chose his interlocutors—friends, professional acquaintances or simply interesting physicians—not so much for prominence as for the wide range of the tales they tell. We read comments from the former editor of the *New England Journal of Medicine* and from a former U.S. surgeon general. We also learn about the careers of a general practitioner in a small town in Massachusetts, an internist caring for homeless patients in Baltimore and a salaried ophthalmologist working for an HMO in Oregon. Several physicians' interests led them far afield: one now runs a major corporation, and another oversees a charitable foundation. A third is governor of the state of Vermont.

BOSTON MEDICAL LIBRARY, FRANCIS A. COUNTWAY LIBRARY OF MEDICINE

FIRST OPERATION under ether is performed by John Warren in 1846. William Morton (left) *administers the anesthetic.*

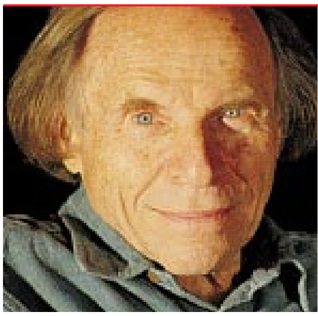
In addition to explaining the reasons that they chose one specialty over others, Laster's contributors have described why they ruled out certain career choices. This information is almost equally important. One urologist, for example, abandoned the idea of neurosurgery after doing duty with a potential mentor who embodied the opposite of almost everything the younger man wanted to be as a doctor. A radiologist and an anesthesiologist both abandoned other specialties after realizing that their healing talents did not include direct interaction with patients.

Within this diversity, all these doctors have a few things in common—most clearly, their love of the art of healing. Without exception, they agree that the medical life is both useful to society and the source of great personal rewards. Although such attitudes are not surprising in a group that has been found worthy of interviewing for posterity, it does provide a good counterpoint to the widespread media coverage of doctors' dissatisfaction with their profession.

Although a book like this calls out to be read in its entirety, I must attach a caveat to that recommendation. Laster has constructed each chapter by transferring a long interview from speech to print; the result is a set of monologues all delivered—despite the differences among the speakers—in a single voice. The reader may soon grow tired of "listening" to one contributor after another "speaking" at the same pace and with the same inflections in the transcribed and Laster-edited sentences. Although the effort is more than repaid by the broad view of the medical landscape a reader attains, the book is very difficult to read in long sittings.

This volume is no medical *Arabian Nights;* still, Laster introduces such a sympathetic group of personalities doing work of such a high degree of intrinsic interest that the end of each chapter only stimulates the reader to brave the stylistic tedium and go on. *Life after Medical School* will be of immense help to my young caller and to countless others in and out of medicine. I have already phoned her with the advice to buy her own copy, because I will be needing mine when the next student calls.

SHERWIN B. NULAND teaches surgery and the history of medicine at Yale University. He is the author of How We Die, *which won the National Book Award for nonfiction in 1994.*



COMMENTARY

WONDERS

by Philip Morrison

New World and Old: A Matter of Magnitude

Scientists and engineers map their world in numbers, a form of expression that is as colorless as it is information-rich. Common speech (apart from age, time and the arresting topic of money) hardly uses numbers. Speech does draw its distinctions of quantity—few or many, cheap or dear—but oddly enough, words rarely part any range into more than three categories.

One instructive exception is the list of six nouns that are used for natural rock fragments: silt, sand, gravel, pebbles, cobbles, boulders. Although most of these are everyday terms, they have been given standardized meaning among geologists. Still, you don't have to be a sediment scientist to grasp how much fine silt differs from big boulders in a mountain stream. The words offer understanding over a scale of size that extends a millionfold.

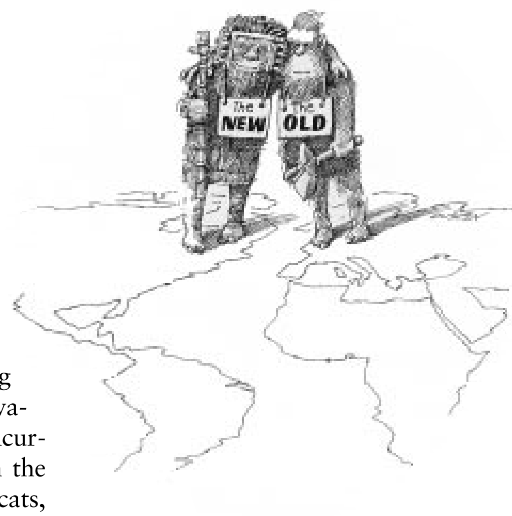
Two terms that scale not space but time are quite widely used, the New World and the Old World. They record the European surprise when 500 years ago the newly emboldened voyagers found an inhabited continent that barred the seaway westward to the distant shores of the wealthy Emperor of Cathay. In truth, each side then found that the other was new enough. Novelty was fully reciprocal: the ruins that dot Eternal Rome are not a bit older than those that awaited the Aztec entry to the Valley of Mexico. The long-term consequences of conquest did not divide an American New World from a Eurasian Old World, as we sometimes imagine, but instead linked them tightly, for good and for ill.

What endures is the fascinating fact that for human beings our Americas are really new; the wider landmasses of Africa, Europe and Asia are factually very much older, not in their rocks, but in human experience. The true distinction between Old and New has nothing much to do with the modern story of Admiral Columbus or even of lucky Leif a mere thousand years before him, but rather with the chronology of our prehistory. The protohuman evolutionary timescale can be set roughly but firmly at some few million years, 100 times as old as Niagara Falls or Great Salt Lake. We fix that long time not only by dating a few excavations but by a diverse range of concurrent, datable fossil markers, from the bones of extinct saber-toothed cats, cave bears and odd little mice to multiple layers of volcanic ash and pollen, in valley walls as deeply eroded as Olduvai in East Africa.

The evidence of protohumanity lies within four corners of the Old World: the shores of the North Sea, the Cape of Good Hope, the southeastern tip of Java's island chain and north beyond the Great Wall of China. Scores of excavations over that entire wide hemisphere have shown us worked stones, old hearths and skeletal remains, all left by our ancient forebears. They were not yet members of our own species, but they are ancestral kinfolk of our own genus, the hominids, in all those places.

Across the Americas we can point out scrupulous excavations in plenty to show who came here to the New World. A score of sites are found from the Bering Sea south to the region of the Straits of Magellan. None bears any witness to protohumans at all. All those bison hunters, spearhead shapers and cunning basket weavers whose handiwork and physical remains have been found in these Americas are of our very own kind, that single species we self-servingly dub *Homo sapiens*. Our living species is proved by long experience to be a single species, fully interfertile. By no means anything like a million years old, *H. sapiens* might go back a tenth of that time, possibly even as much as a third of it. Contrast those protohominid fossils of the African Rift: famous little Lucy, our apelike ancestor there, is about 10 times the age of any *sapiens* find anywhere.

All over the globe, Old World and New, there are no living hominids save sapiens.



DUSAN PETRICIC

That order of magnitude carries my point. All over the globe, Old World and New, there are no living hominids save *sapiens*. All of us today are united by one visible anatomy and by a whole catalogue of common blood proteins. The languages that in some way part us nonetheless share so much that we can conclude as a first-rate working hypothesis that language is in general, like art, a common heritage of our species. We are unsure how much of either language or art the earlier species had. It is sure that some of them prepared effective tools of stone according to very slow-changing patterns and that they sometimes occupied cave shelters. Above all some were the Prometheans who first

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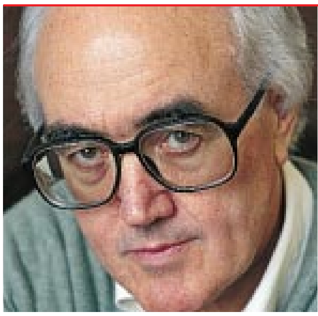


COMMENTARY

CONNECTIONS

by James Burke

Making Your Mark

DUSAN PETRICIC

I was watching the news the other night when I saw a story about somebody being identified by the so-called DNA-fingerprinting technique. On the screen were the now familiar black-and-white bands you're starting to see in all the cops and robbers movies. Back in the 1930s, it was the Swedish Nobel laureate Arne Tiselius who made all this fun possible. He worked out how to make protein molecules line up according to size, by putting them in a gel that he then zapped with various charges. Electrophoresis.

The hardly visible differences in the gel (caused by the migrating proteins) were more easily seen with Schlieren photography. With it, the slightest variations in density show up (because of changes in the refractive index) in a transparent medium such as a protein-loaded gel. Or turbulent air. Which is why, right from the start, the Schlieren method was also a great success with airflow freaks such as Theodor von Kármán, whose vortices you'll sometimes see curling away, like streaks of fog, from the wings of an airplane taking off on a damp day.

Both von K. and his streaks were well known to a pal of his, A.H.G. Fokker, of the planes of the same name. But Fokker did something else besides build great flying machines that would first cross the U.S. nonstop in 1926 and in the same year take Byrd first over the North Pole.

During World War I, Fokker worked out a clever way to synchronize a propeller with a machine gun, so fighter aces wouldn't shoot their own props off. All you had to do with this new system was point the plane and fire. The arrangement was so successful (particularly in the hands of such hotshots as Manfred von Richthofen, the Red Baron, in his red Fokker) that it became known as "the Fokker scourge." At the time, machine guns were doing well on the ground, too. Especially against thousands of infantry snagged on barbed wire during advances. Sitting ducks, really.

The amazing new invention called the tank was supposed to prevent this, by crawling over (and knocking down) the barbed wire, thus clearing a path for the troops. Irony was, that the tanks got taken over by cavalry regiments. The majority of the horses had been requisitioned from rural America for transport regiments in Europe, to haul supplies (to the men who were now *also* missing from the farms). Which caused the invention in the first place.

Back in California, the shortage of horsepower and man power had inspired a farmer named Ben Holt to invent an entirely new kind of agricultural implement. Holt lived in the San Joaquin Valley, where a lot of the land was so wet it wouldn't support anything on wheels (or in some cases, hooves). He came up with a crawler tractor that ran on tracks as it spread the load. A friend remarked that it looked like a caterpillar, and the rest is farm-equipment history.

What would you expect from a guy who once said: "As pants the deer for cooling streams, so do I for regulation"?

Most of the early Holt tractors got sold to the Allies during the war, which is how the military saw them and—bingo—came up with tanks. The tractors ran on gasoline, but later Holt switched to the diesel (after Rudolf Diesel) engine, which itself was so successful because it was cheaper to run than gasoline engines and could start cold. Also, people thought it would burn almost any junk for fuel; there was even one that ran on peanut oil. It may have been this last selling point that won Diesel his financial backing from the outset. Because right from the start, when talking to anybody about his engine, he used the magic word "coal."

It was how the engine worked that made such talk possible. With a diesel, all you do is compress air in a cylinder so its temperature goes up to near 800 degrees Celsius. At the top of the piston stroke, when the air is hottest, you inject a suitable liquid, gas or particulate. Just the heat of the air causes it to combust, which pushes the piston down and starts the cycle all over again. So the diesel looked as if it'd burn anything that—well—burned. Like coal dust. In 1897 this sounded like sweet music to a man who had a great deal of the stuff. And so it would to you, if you ran the biggest steel plant in Europe and the railways and, to top it off, owned all the coal mines that went with this way of making money. In Friedrich Krupp's case, a lot of money.

Not surprisingly, Friedrich's father, Alfred, who'd brought the firm to greatness earlier in the century, was less than keen on the new wind of Socialism sweeping through the industrial world just then. For him it meant social anarchy. So he devised ways to keep his workers happy enough not to want such inconveniences as trade unions.

He gave them canteens, pensions, housing, company discount stores and even uniforms to wear at home (what would you expect from a guy who once said: "As pants the deer for cooling streams, so do I for regulation"?).

Such a "welfare" scheme (as well as his love of trees and dislike of company) bonded him with the chap running Prussia at the time. This person was, I suppose, regulation personified. Otto von Bismarck (also an antisocial tree lover) and Krupp were meant for each other. After all, Otto made war and Alfred made guns. Bismarck was also keen on welfare (he started the first universal old-age pension) and statistics and such, because the more numbers you had on all the average joes out there in the streets, the better you could regulate people so as to increase national output (or fight wars). Bismarck had developed this passion for the average joe because Ernst Engel, the head of the Prussian Statistical Bureau, greatly admired the Belgian astronomer who had *invented* the average joe.

Here's how. In 1835 Brussels, Lambert Adolphe Quételet modified the kind of math that astronomers used to calculate the probable path of rarely sighted heavenly bodies to do the same thing for population statistics. He believed if you applied this math to large numbers of people you could develop what he called "social physics." This way, you could work out what the average joe was up to and do statistically meaningful sampling. Well, this was better than previous methods (like multiplying the number of chimneys by an assumed average family size to get the population), so it attracted the interest of such mathematical biggies as Charles Babbage.

Babbage's involvement with Quételet led to the formation of statistical societies in Britain and eventually motivated a young man called Francis Galton to go looking for ways in which any individual could be singled out from the masses. The result of his work was the discovery of a surefire way to differentiate one person from another, known as the fingerprint. Which was, until the advent of the DNA version I saw on TV the other night, the ultimate ID.

P.S. Ironically, given how valuable electrophoresis was to prove in the original discovery of DNA, guess who Galton's cousin was? Charles Darwin. SA

Wonders, continued from page 125

came bravely to know the use of fire.

But the Americas are a New World, a new place for humans. No sign of humanity is found here anything near a million years back. The true dates remain to be fixed firmly, but no finds here are the work of another species. Distant Australia as well belongs to our New World of humanity. Its oldest human remains are also those left by clever *sapiens,* our siblings. Most oceanic islands, like the three seagirt continents, have also never felt the tread of any ancestral species. Big Madagascar and New Zealand were first settled by seafarers from the Pacific only a couple of millennia past, a timescale that overlaps familiar written history.

Firmer, more precise dates indeed are important—just when did the first people come to America?—but the inference from our wealth of loosely dated clues is fully adequate to distinguish the Old from the New. The difference between our own species and those who came before us has as sharp a meaning in ordinary speech as the simple terms "silt," "sand" and "gravel." The terms "Old World" and "New World" therefore broadly transcend any uncertainties in the precision of dating.

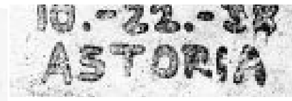
We can offer a plausible explanation. Primates are land animals. Even now, at any moment, not as many as one human out of 1,000 is to be found afloat or aloft. Those ancestral folk could not cross the seas during their million years of foraging afoot. The New World was reached overseas only after the eventual appearance of a dynamic younger species, our very own. It was only the sapient men and women who journeyed a couple of hundred centuries ago along icy coasts and inland valleys. So much water was locked ashore as glacial ice that the level of the high seas dropped by hundreds of feet, and many islands were for a while part of the main. A few daring sea passages probably demanded the mastery of sailing canoe or raft.

The remoter islands and the coasts of distant Antarctica were left unvisited until explorers could arrive under big sails. Both ends of the earth's axis remained for the 20th century itself as icy adventures by foot and by sledge. At last our own kind has spread over all the habitable lands, in both the Old and New Worlds. SA

WORKING KNOWLEDGE

PHOTOCOPIERS

INVENTOR CHESTER F. CARLSON re-creates the experiment that marked the advent of xerography. The original machine never worked well, but it provided the technological prototype for today's photocopiers.



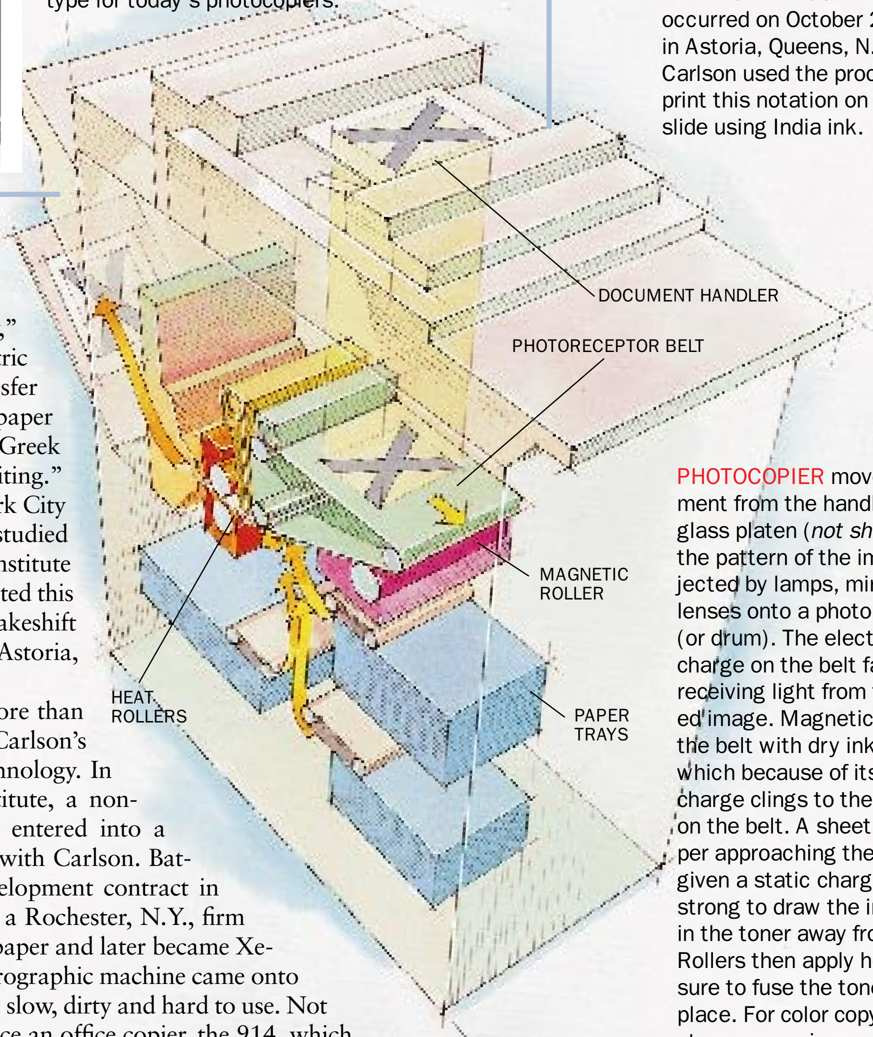
BIRTH OF XEROGRAPHY occurred on October 22, 1938, in Astoria, Queens, N.Y., when Carlson used the process to print this notation on a glass slide using India ink.

by Chip Holt

The term "xerography," the use of photoelectric phenomena to transfer an image from one sheet of paper to another, comes from the Greek words for "dry" and "writing." Chester F. Carlson, a New York City patent attorney who had studied chemistry at the California Institute of Technology, first demonstrated this technique 58 years ago in a makeshift laboratory above a bar in Astoria, Queens, N.Y.

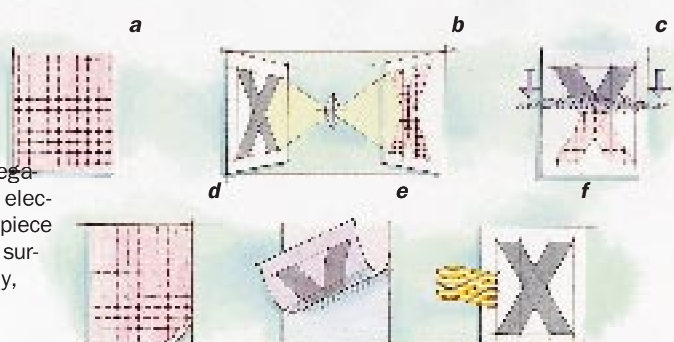
Over the next six years, more than 20 companies turned down Carlson's proposals to develop the technology. In 1944 Battelle Memorial Institute, a nonprofit research organization, entered into a royalty-sharing arrangement with Carlson. Battelle eventually signed a development contract in 1947 with Haloid Company, a Rochester, N.Y., firm that produced photographic paper and later became Xerox Corporation. The first xerographic machine came onto the market in 1949, but it was slow, dirty and hard to use. Not until 1959 did Xerox introduce an office copier, the 914, which became the basis for the current multibillion-dollar industry.

CHIP HOLT is vice president of the Joseph C. Wilson Center for Research and Technology at Xerox Corporation.



PHOTOCOPIER moves a document from the handler to the glass platen (*not shown*), where the pattern of the image is projected by lamps, mirrors and lenses onto a photoreceptor belt (or drum). The electrostatic charge on the belt fades in areas receiving light from the projected image. Magnetic rollers brush the belt with dry ink (toner), which because of its static charge clings to the image area on the belt. A sheet of copy paper approaching the belt is also given a static charge sufficiently strong to draw the image pattern in the toner away from the belt. Rollers then apply heat and pressure to fuse the toner image into place. For color copying, a multistep process is used, which scans the image through color filters and then applies separate toners for magenta, cyan, yellow and black.

DRY COPYING exploits the principles that materials with opposite electrical charges attract one another and that some materials conduct electricity better after exposure to light. In the basic xerography process, a photoconductive surface receives a positive electrical charge (*a*). An image is then exposed on the surface; because the illuminated sections (the nonimage areas) become more conductive, their charge dissipates (*b*). Negatively charged powder spread over the surface adheres through electrostatic attraction to the positively charged image area (*c*). A piece of paper is then given a positive charge (*d*) and placed over the surface, where it attracts the negatively charged powder (*e*). Finally, heat fuses the image as etched in powder to the paper (*f*).



XEROX CORPORATION; BARRY ROSS (*drawings*)