SCIENTIFIC AMERICAN

NOVEMBER 1995
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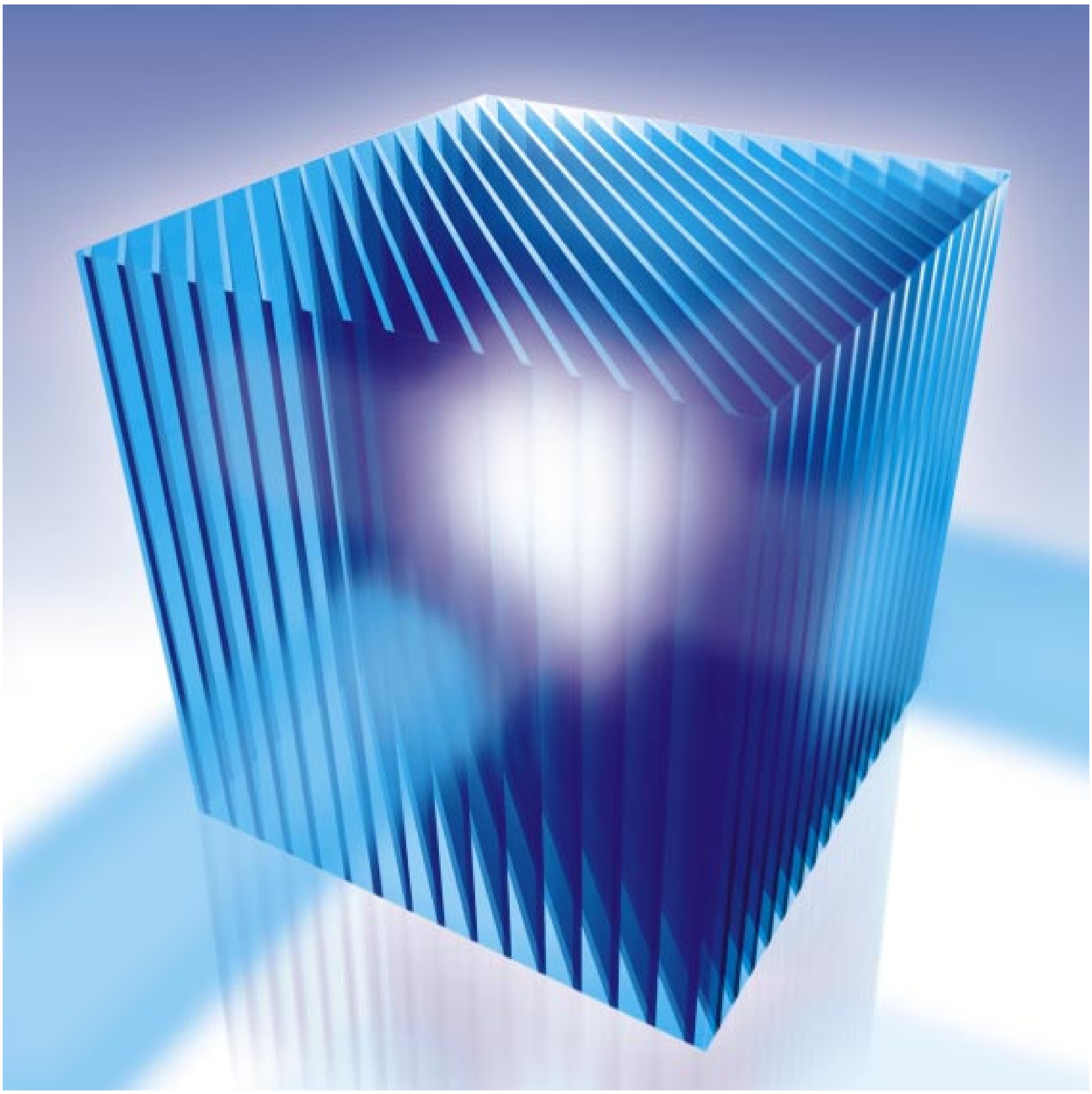
Guardian cells in the brain.

Saving the world's fisheries.

Juggling's tricks exposed.



Memory crystal *could trap a trillion bytes of data in 3-D.*

SCIENTIFIC AMERICAN

November 1995 Volume 273 Number 5

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DEPARTMENTS

Letter from the Editor

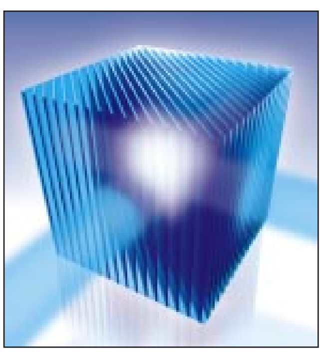
All living things are the products of evolution, a point that renowned biologist Richard Dawkins of the University of Oxford makes forcefully in this issue. Magazines evolve over time, too, which makes this a fitting moment to introduce some additions and refinements that readers will find in *Scientific American*'s pages this month.

First, we are glad to mark the debut of two new features, both of which appear in our expanded "Reviews and Commentaries" section. One is in fact a contribution from an old friend: physicist Philip Morrison, professor emeritus of the Massachusetts Institute of Technology. For almost 30 years, Professor Morrison has served as *Scientific American*'s faithful book reviewer, a role in which he produced a steady outpouring of lyrical, literary essays that revealed as much about his own far-ranging enthusiasms and knowledge as about the books under discussion. In his new column, "Wonders," he carries on that tradition, taking as his credo the words of Michael Faraday, "Nothing is too wonderful to be true." (Incidentally, on a more personal note, this month Professor Morrison celebrates his 80th birthday. Happy birthday, Phil, from all of us you've amazed, informed and inspired.)

We are also delighted to welcome historian of science James Burke, best known to millions as the creator of the television series *Connections*. In his column of the same name, Burke wittily traces the threads—slender, frayed and oddly tangled—that tie together diverse technological developments through the centuries. Check page 109 to learn, for example, how innovations in 17th-century textile making revolutionized 20th-century automation.

Fans of "Mathematical Recreations" and "The Amateur Scientist" may be pleased to see that those features, which formerly alternated from month to month, will now be appearing in every issue. "Mathematical Recreations" continues under the reliable authorship of Ian Stewart of the University of Warwick. Shawn Carlson joins us as the new writer of "The Amateur Scientist." The subject of the column is one close to his heart: he is director of the international Society for Amateur Scientists. We hope readers will be able to use the projects he describes as a springboard to further explorations of the natural world and technological innovation.

JOHN RENNIE, *Editor in Chief*



THE COVER shows the pattern of varying refractivity that represents a bit of data, stored three-dimensionally in a crystal. Such holograms are created when two laser beams, one imprinted with the data, meet and interfere with each other in the crystal. The resulting interference pattern is not actually visible. But when the crystal is reilluminated at the correct angle, the pattern diffracts the light so that the beam with the data is reconstructed (see "Holographic Memories," by Demetri Psaltis and Fai Mok, page 70). Image by Slim Films.

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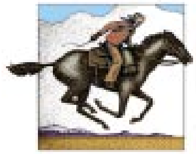


LETTERS TO THE EDITORS

Foreign Exchange

In their article “Protecting the Greenback” [SCIENTIFIC AMERICAN, July], Robert E. Schafrik and Sara E. Church stress that photocopiers and computers are the main threats to U.S. currency. The article did not go into how some foreign countries make high-quality counterfeit bills. For example, Iran allegedly uses the same intaglio press as the U.S. and is said to have obtained counterfeit $100 plates. The bills created are so well made that some banks will not take U.S. currency in large amounts from Iran for fear that these “superbills” will be mixed in. Some estimates put the number of superbills now in circulation at around $5 billion.

GREGORY MORROW
Portland, Me.

Schafrik and Church reply:
The National Research Council report, “Counterfeit Deterrent Features for the Next-Generation Currency Design,” which is referenced in our article, gives a full discussion of counterfeiting threats from opportunistic individuals, well-financed criminal organizations and state-sponsored counterfeiters. Although the features we discussed will pose significant obstacles to professional counterfeiters, the long-term strategy to combat counterfeiting should rely on the use of a well-chosen suite of visible and machine-detectable features that are changed at intervals frequent enough to make counterfeiting an expensive and difficult job.

According to the Secret Service, which works closely with law enforcement and banks all over the world, the face value of counterfeit bills in circulation at one time is on the order of one hundredth of 1 percent of the $380 billion of circulating currency—much smaller than the figure of $5 billion quoted by Morrow. Ideally, the number of counterfeit notes should be zero; from a practical standpoint, the average citizen will only rarely, if ever, run across a counterfeit note.

Distorted Images

The most striking demonstration of the phenomenon described in John Horgan’s “The Waterfall Illusion” [“Science and the Citizen,” SCIENTIFIC AMERICAN, July] can be seen in a rotating spiral disk. When one gazes at it for a while with the disk rotating in one direction, then looks at a person’s face, the face seems to expand. When the spiral is rotated the other way, the face seems to contract. Jerry Andrus, a magician and inventor of optical illusions, had the happy idea of putting several spirals on one disk, alternating their directions. After one observes this disk rotate for a minute or so, then looks away, the scene bubbles with curious distortions.

MARTIN GARDNER
Hendersonville, N.C.

The Origin of the Hybrid

In their article “The Problematic Red Wolf” [SCIENTIFIC AMERICAN, July], Robert K. Wayne and John L. Gittleman present evidence that strongly supports the idea that the red wolf is not a species of long standing. Their evidence does not argue nearly so well, though, that the red wolf is merely a hybrid of the coyote and the gray wolf, the main contention of the article. Perhaps the genetic similarities of the red wolf to both the gray wolf and the coyote reflect the possibility that the red wolf has become a distinct species only in the past few thousands or even hundreds of years. The red wolf has suffered a more recent decline, so that now only hybrids exist. By adopting a very restrictive definition of species, the authors may have been led to a conclusion that the evidence does not exclusively support.

KEITH W. SPOENEMAN
Des Peres, Mo.

Wayne and Gittleman reply:
We do not mean to apply a restrictive definition of species to the red wolf. A population may have no observable unique genetic markers and yet be morphologically distinct from other populations and so considered by some to be a species. If the red wolf originated within the past few thousand years, as Spoeneman suggests, we agree that there may not have been time for unique genetic markers of the kind we analyzed to evolve in the red wolf. But the group may have had time to become physically distinct. Rapid morphologic changes, however, such as those seen in the many varieties of domestic plants and animals that have arisen in the past few hundred years, generally involve a limited number of genes and require intense artificial selection. In particular, the purity of these new groups is carefully maintained by breeders.

Even if some of these restrictive conditions applied to the origin and evolution of the red wolf, the species would have had to persist in genetic isolation, despite the overwhelming possibility of crossbreeding with the plentiful gray wolf and coyote that lived in the same range. In eastern Canada, crossbreeding between gray wolves and coyotes occurs because of habitat changes that are analogous to past events in the historic range of the red wolf. Thus, in our opinion, a simpler and more likely scenario for the origin of the red wolf is that it results from hybridization between the gray wolf and coyote.

Women at Harvard

Ruth Hubbard was not “the first woman to receive tenure in the sciences at Harvard” in 1973, as described in the profile by Marguerite Holloway [“Science and the Citizen,” SCIENTIFIC AMERICAN, June]. The astronomer Cecilia Payne-Gaposchkin had been promoted to tenure in 1956. When I came to Harvard as a freshman in 1959, she was not only Phillips Professor of Astronomy but also what we then called chairman of the astronomy department. It was years before I realized that it was not typical to have women as professors or as chairmen! Jane S. Knowles, archivist of Radcliffe College, informs me that Payne-Gaposchkin was preceded as tenured professor at Harvard by the physician and toxicologist Alice Hamilton (in the medical school) and by the historian Helen Maud Cam and the anthropologist Cora DuBois in the faculty of arts and science.

JAY M. PASACHOFF
Williams College

Letters selected for publication may be edited for length and clarity. Unsolicited manuscripts and correspondence will not be returned or acknowledged unless accompanied by a stamped, self-addressed envelope.

50, 100 AND 150 YEARS AGO

NOVEMBER 1945

Miniature oxygen tents for babies born prematurely are now being fabricated from Ethocel sheeting. Still in the experimental stage, the clear plastic tents permit a full view of the tiny patient."

"Release of DDT to civilians for general use recently led to a flood of preparations presumably containing this highly effective insecticide but actually too dilute to be useful. Fear is expressed by legitimate insecticide producers that unfortunate experiences with early improper DDT preparations made by unscrupulous persons may prevent its legitimate later use for valuable purposes."

"War trends as foreseen by General H. H. Arnold include: One, airplanes traveling at supersonic speeds; at such speeds, aerial combat as it is known today would be impossible. Two, development of guided missiles; refinement of their controls could enable exact hits on targets of a mile square or less, at any part of the world from any part of the world. Three, great developments in defense against aircraft and guided missiles; every new weapon of offense brings forth a weapon of defense, and this should remain true even in the case of the atomic bomb."

NOVEMBER 1895

Common earthworms, despised by man and heedlessly trodden under foot, 'have played a more important part in the history of the world than most persons would at first suppose,' says Charles Darwin. Vast quantities of earth are continually being passed through the bodies of earthworms and voided on the surface as castings. A layer of dirt one-fifth of an inch thick, or ten tons by weight, has been calculated in many places to be brought annually to the surface per acre."

"The buffalo of the West has rapidly disappeared before the huntsman's rifle. The hunters received on an average from $2.50 to $3.50 per hide, to be shipped out of the country and sold for leather making, belting, harness, and kindred purposes. The most successful hunting parties consisted of a hunter and six men known as strippers, and many thousands of men were engaged in the enterprise. At one station alone on the Topeka and Santa Fe Railroad as many as 750,000 hides were shipped in one year. The same territory which a quarter of a century ago was supporting vast herds of wild game is now sustaining millions of domestic animals."

"The federal government has been experimenting at its military posts with condensed rations, so called. At Fort Logan, the rations issued consisted of coffee and soup, condensed into small tablets; the bread was crushed into a flat cake of the weight and hardness of a stone. The bacon was solidly packed in a tin can. The soldiers marched and ate as ordered, but their marching and eating were brought to an abrupt end by more than half falling sick before one-half the allotted time expired. The report to the War Department at Washington is wholly against the experiment."

"E. W. Scripture of Yale University writes: 'I have found a method of a stereoscopic projection of lantern views showing relief effects on a screen. Spectacles of colored glass can be arranged with a particular red for the left eye and a particular green for the right eye, made from the standard red and green glass used by railways. The relief appears just as real as a real object. When the pictures are life size, the observer finds it hard to believe that, for example, he cannot actually advance along the shaded roadway before him or step into the boat waiting on the shore.' "

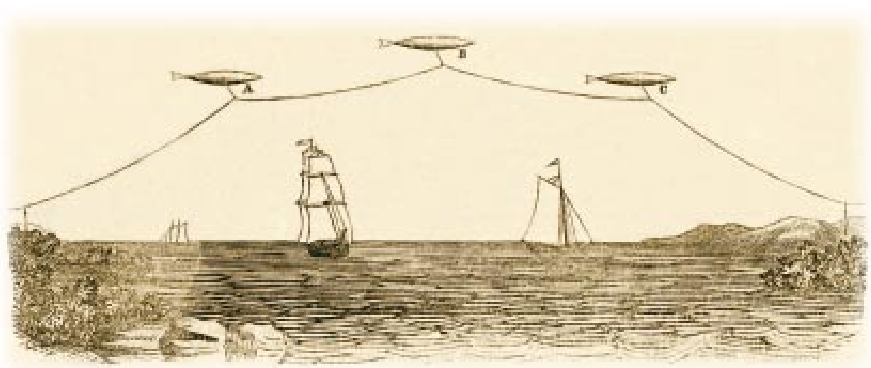
NOVEMBER 1845

The steamship Britannia arrived at Boston on Thursday last, having made the passage from Europe in fifteen days. The accounts of the general failure of the potato crops by the rot, especially in Ireland, are of a very serious and alarming character."

"The editors and publishers of several newspapers have promptly refused to advertise for grocers or innkeepers who deal in ardent liquors. That is as it should be; and it is to be hoped that all editors, especially those who advocate the temperance cause, will refrain from aiding the rum trade by advertising any thing in the line."

"The western papers complain of the depredations of burglars from New York. This must be a mistake, as there appears to be none missing here."

"A new method has been proposed for extending the lines of the Magnetic Telegraph across rivers and bays. It is proposed to support the wires in an elevated position, by means of elliptic balloons. These balloons, being each sixty feet in length, will support about 40 pounds each besides its own weight. The cost will not exceed $200 each, being made of thin varnished cloth and inflated with hydrogen gas. A small pipe 1.4 inch in diameter will be extended to each balloon, by means of which the gas in the balloon may be occasionally replenished."



The Magnetic Telegraph crossing a river

SCIENCE AND THE CITIZEN

Get Smart, Take a Test

A long-term rise in IQ scores baffles intelligence experts

Is the average high schooler of today brilliant compared with his or her grandparents? Or, conversely, are those grandparents dull-witted relative to their children's children? One must conclude as much—if one believes intelligence is a fixed trait that can be accurately measured by IQ tests. The reason is that scores on intelligence tests have risen steadily and dramatically ever since such tests were introduced early in this century.

This phenomenon, called the Flynn effect, was first described more than a decade ago. But it has received widespread attention only recently as a result of the tintinnabulation emanating from *The Bell Curve: Intelligence and Class Structure in American Life.* In that book, published last year, political scien-

Archives of the History of American Psychology, University of Akron

tist Charles Murray and the late Richard J. Herrnstein, a psychologist, argued that the economic stratification of American society reflects ineradicable differences in intellectual ability. The authors mentioned the Flynn effect only to dismiss it as a curiosity with little relevance for their overall argument.

Actually, the Flynn effect demonstrates that intelligence is much more mysterious than Murray and Herrnstein imply, says Ulric Neisser, a psychologist at Emory University. Neisser is the lead author of a new study by the American Psychological Association (APA) entitled *Intelligence: Knowns and Unknowns.* The report considers various possible explanations of the "striking" effect but acknowledges that none are satisfactory. "The fact that there could be such a large effect, and that we don't know what causes it, shows the state of our field," Neisser says. "It shows that we should be quieter than we are."

The phenomenon is named after James R. Flynn, a political scientist at the University of Otago in New Zealand. In the early 1980s, while studying intelligence testing in the U.S. military, Flynn found that recruits who were merely average when compared with their contemporaries were above average when compared with recruits in a previous generation who had taken exactly the same test. The trend had escaped notice because testers calculate IQ scores by comparing an individual's performance

UPI/Bettmann

RAY STOTT *The Image Works*

SMART, SMARTER, SMARTEST? These photographs show children taking IQ tests in 1927, 1951 and 1989.

with those of others in the same age group. (A score of 100 is average by definition.)

Investigating the implications of this trend, Flynn found that scores on virtually every type of IQ test—administered to military recruits and to students of all ages—had risen roughly three points per decade since they were first instituted in the U.S. Flynn learned that 20 other countries for which sufficient data are available—including Canada, Israel and a number of European nations—showed similar increases.

The gains ranged from 10 points per generation, or 30 years, in Sweden and Denmark to 20 points per generation in Israel and Belgium. The upward surges tended to be greatest for tests that minimize cultural or educational advantages by probing the ability to recognize abstract patterns or solve other nonverbal problems. Flynn has recently analyzed scores from Raven's Progressive Matrices, which is considered to be one of the least "culturally loaded" IQ tests. The birth dates of those examined span a century, ranging from 1877 to 1977. Flynn concluded that someone scoring in the 90th percentile 100 years ago would be in the fifth percentile today.

The effect can mislead intelligence researchers, according to Flynn. Many investigators have asserted, for example, that the elderly suffer a progressive decline in intelligence, because when they take modern IQ tests they do not score well compared with modern 20-year-olds. But if the average 70-year-old takes a test that was used 50 years ago, Flynn says, he or she will usually score as well as the average 20-year-old of that era did on the same test.

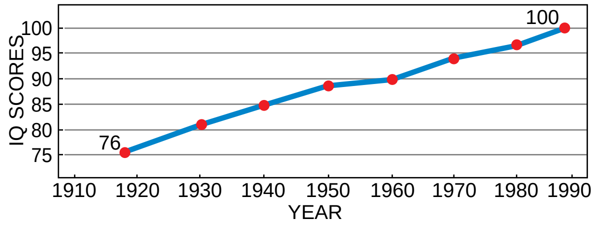
Similarly, some experts have claimed that the academic success of Chinese-Americans, relative to their white contemporaries, is correlated with higher intelligence as measured by higher IQ scores. But the IQ disparity reported in some studies resulted in part from the administration of old tests to the Chinese-Americans, Flynn says.

All researchers, including Murray and Herrnstein, agree that the IQ gains must stem not from genetic factors but from environmental ones. Nevertheless, Flynn himself has shot down every hypothesis put forward so far—for instance, the proposal that children in successive generations attain higher scores because they take more tests and thus learn how to perform more efficiently. IQ tests have actually become less common in recent years, Flynn remarks, while the rise in scores has persisted. Moreover, studies have shown that "practice" in taking tests generally confers only a small advantage at best.

Nor can the effect be attributed solely to improvements in education, Flynn says. To be sure, the rise in IQ in Denmark has been matched by increases in the time that students spend in school. But IQs of American children have risen even during periods when the time spent in school has not. Flynn also looks askance at the idea that the growing pervasiveness of the media, and television in particular, has made children smarter. Television was usually considered a "dumbing down" influence, Flynn comments wryly, "until this effect came along." Moreover, scores began rising in the U.S. decades before the advent of television in the early 1950s.

The Flynn effect should become even more widely discussed over the next year or two. Neisser hopes to convene a conference on it at Emory next spring. The noted intelligence researcher Arthur R. Jensen of the University of California at Berkeley also dedicates a chapter to the Flynn effect in a forthcoming book.

Jensen, whose proposals on intelligence in the 1970s anticipated those aired in *The Bell Curve,* was an early critic of Flynn's research. But he has become convinced that the Flynn effect is genuine and important. Jensen contends that the gains must be at least partially biological—related to improvements in nutrition and medicine—as well as cultural. He points out that height, a human attribute that is largely heritable, has increased steadily for more than a century; nutrition might have spurred comparable boosts in intelligence.



DIMITRY SCHIDLOVSKY

SCORES from both Wechsler and Stanford-Binet tests rose 24 points in the U.S. between 1918 and 1989. The scores have been calibrated according to 1989 levels.

But the recent APA report finds little support for a correlation between nutrition and intelligence (as long as minimal needs are met). Flynn also counters Jensen's hypothesis with a question: In 1864 did the Dutch, who were on average shorter than 99 percent of their modern descendants, really have an intelligence stunted to the same degree? Did they have the same intelligence as people who today score 65 on IQ tests?

Flynn thinks not. In fact, he even finds the notion that his generation is significantly more intelligent than that of his parents ludicrous—and yet that is the implication of his own research. "You can see why I'm baffled," he says with a sigh. —*John Horgan*

FIELD NOTES

Attracted to the Pole

Although the magnetic pole lies more than 1,000 kilometers to the south, the earth's geographic North Pole emits its own invisible force, enticing scientists to cross vast stretches of the frozen Arctic to reach it. In 1991 a pair of European icebreakers were the first research vessels to make the trip. Last year U.S. and Canadian ships mounted a joint expedition, and their journey produced some unexpected, young heroes.

The two vessels, the American Coast Guard's *Polar Sea* and the Canadian Coast Guard's *Louis S. St. Laurent,* left Alaska in July 1994 and headed to the earth's northern limit the hard way—through some 1,700 kilometers of icebound ocean. They planned to make a circuit of the western basin, where sea ice is typically older (and thus harder to break) than in the eastern route taken by the Europeans. The vessels struggled past heavy ice and came within 50 miles of the North Pole, when, according to E. Peter Jones of the Bedford Institute of Oceanography in Halifax, "the *Polar Sea* suffered major propeller damage." Lt. Commander Steven G. Sawhill reports that a cracked retaining ring caused a blade to fly off one of the three main shafts: "Once we knew we had lost that propeller, it was pretty obvious what the implications were." As James A. Elliot of the Bedford Institute explains, the problems were not severe enough to threaten the ship, but they did cut the mission short: "We wanted to get out. When you're up there, you don't want to get frozen in for a year—or two, or three."

Tension must have run high as the scientists pondered their options from the middle of this daunting wilderness. Then, like an Arctic mirage, there appeared a curious, completely unanticipated sight: a huge ship with a strange, toothy smile painted on the bow. It was the Russian icebreaker *Yamal.* Employed during winter months to keep sea lanes open, Murmansk Shipping's newest nuclear-powered icebreaker was spending some of its off-season time ferrying about 50 Russian children to the North Pole. The youngsters were on the jaunt to celebrate a national festival for children with music, singing and dancing.


STEFAN NITOSLAWSKI

Along with the many exuberant boys and girls was a Russian television crew producing a live broadcast.

Kent Berger-North, a Canadian oceanographer who acted as translator, explains that the Russians "very graciously left the Pole" long enough for the American and Canadian scientists to complete their struggle to reach it, then came back: "They didn't want to steal anybody's thunder." Russian generosity did not end there. After the appropriate number of toasts, barbecues and baseball games on the ice, the *Yamal* spearheaded the procession home. Whereas the research vessels might have picked their way at three to four knots, the *Yamal* charged ahead at 12 to 15 knots through giant walls of frozen sea. "It just threw blocks away," Elliot recounts with awe.

So the children's ship led, and the scientists followed in what James H. Swift of the Scripps Institute of Oceanography in San Diego describes as "the giant Slurpee the *Yamal* leaves behind." The researchers were fortunate. Had fate been less kind, they might easily have missed the *Yamal*—or met up with it during one of its American-chartered excursions to the Pole that summer. Such an encounter would have made the polar research expedition seem awfully mundane. After all, how exotic would it have been to bump into an alumni tour group from California or Indiana? At least the kids spoke another language. —*David Schneider*

Fiber That May Not Be Good for You

Researchers investigate whether fiberglass causes cancer

For the past several years, the fear that fiberglass insulation might be carcinogenic has permeated scientific and public health circles. Although the typical homeowner encounters levels far too low for concern, the risk for people who routinely install the material—about 30,000 in the U.S.—remains controversial. The insulation industry points to studies indicating that airborne fiberglass has not raised the rate of cancer among workers. Some government scientists, however, perceive shortcomings in those studies and cite analyses showing a link. Because of these uncertainties, no U.S. regulatory body has completed a formal risk assessment. But an experiment begun this past August may finally permit regulators to decide once and for all.

Fiberglass, manufactured since the 1930s, belongs to a class of materials known as man-made vitreous fibers (MMVFs). Others include wools cast from rock or slag—sometimes called mineral wools—and refractory ceramics, made from clay. But fiberglass dominates the insulation market, constituting 80 percent of the U.S. production of MMVFs and garnering more than $2 billion annually in sales.

Concern that this widely used material might be "asbestos lite" came to the fore in 1988, when the International Agency for Research on Cancer (IARC), a division of the World Health Organization, classified MMVFs as a possible carcinogen. The U.S. Department of Health and Human Services followed suit last year, describing fibrous glass as "reasonably anticipated to be a carcinogen" and placing it on the list with saccharin and automobile exhaust.

The industry cried foul. The North American Insulation Manufacturers Association in Alexandria, Va., claimed that the designation derives from obsolete scientific protocols. The IARC had drawn its conclusions from studies in which rats and hamsters were injected or implanted with massive numbers of fibers. Some rodents developed mesotheliomas, tumors on the interior linings of body cavities.

"These injection studies by definition overload the target organ," says Thomas W. Hesterberg, a researcher for Schuller International, an insulation manufacturer based in Denver. "They're inappropriate: humans are not exposed that way." All the fibers are placed in the animal at once, but in humans exposure is gradual. Moreover, body cavities lack the mucosal and cilia linings of the lungs that can clear fibers from the system.

A more suitable test, Hesterberg says, is inhalation of fiberglass, whereby rats are forced to breathe air with various concentrations of MMVFs—in some studies up to 300 fibers per cubic centimeter. (A weekend project of laying insulation in the attic typically kicks up only 0.1 fiber per cubic centimeter, according to Thomas Calzavara, Schuller's manager of product safety and health.) None of these studies concluded that breathing glass fibers would cause tumors. One class of MMVF, the refractory ceramic fibers, did appear to be almost as carcinogenic as asbestos is; this type of insulation, however, appears only in specialized applications, such as linings for coke ovens.

Some scientists discount the inhalation work. Rodents have to breathe through their noses; humans do not. Thus, rats may be inappropriate models because they take in fibers that are narrower than the fibers humans inhale, notes Loretta D. Schuman, a toxicologist at the Occupational Safety and Health

Administration. So, she argues, just because inhalation studies turn up negative results does not prove glass wool poses no risk. “An analogy is asbestos. They finally got rats to get cancer by breathing, but it took ages. Long before that, they did injection studies,” Schuman recounts.

That rats are nose breathers, however, does not invalidate them in Hesterberg’s opinion. “A lot of the proposed differences between rodent and human size exposures are pretty theoretical,” he states, pointing out that no one knows exactly how the fibers actually trigger cancer. In any case, he says, the rodents would be inhaling narrower fibers, which are thought to be more toxic because they can reach deep into the lungs.

Perhaps more disconcerting are possible technical problems in the inhalation studies. Schuman and her OSHA colleague Peter F. Infante have sharply criticized them, finding flaws in the methodology and incomplete presentation of results. In a review published last year, they concluded that a slight association exists between fiberglass inhalation and cancer in test animals. Hesterberg counters, saying that the recrunching of the numbers—in part, pooling control animals from different studies—was inappropriate. “In rats, there is enormous variability. You want to use concurrent controls: same lot, same litter,” he argues.

SCHULLER INTERNATIONAL

BLOWING IN FIBERGLASS, done when the installation of blankets is infeasible, kicks up enough potentially carcinogenic fibers to require full protective gear.

The industry also maintains that MMVFs differ chemically from asbestos. An inorganic fiber mined from rocks, asbestos takes up residence in the lungs to cause cancer, mesotheliomas and fibrosis (scarring). In contrast, fiberglass is a synthetic substance that breaks up easily and is quickly removed from the lungs by macrophages. But the solubility argument does not assure all: Vanessa T. Vu, a scientist at the Environmental Protection Agency, points out that the most commonly used kind of asbestos, called chrysotile, is also relatively soluble, yet it still causes cancer.

More important, the body's clearance mechanisms may not help a professional installer. "Workers are going to be exposed for 45 years," Schuman notes, "and anything that goes away is going to be replaced." Currently OSHA has no occupational guidelines for MMVFs (it regards them as nuisance dust); an attempt to push through some standards in 1992 fell through because of legal technicalities. The insulation manufacturers association recommends precautions, including a mask and an exposure limit of one fiber per cubic centimeter. But there are some instances where that level is easily exceeded. "OSHA is worried particularly about the blowing in of insulation," Schuman remarks.

Epidemiology studies have not helped settle the controversy. Most find no rise in cancer risk, although some subgroups demonstrate slightly elevated levels. Some investigators believe the studies are flawed, because the analyses drew mostly on workers who came from production facilities, where airborne fiber levels are kept low. Hence, the sample may have consisted of individuals not exposed to levels experienced by those who blow in insulation. Others take the opposite tack and state that confounding factors, such as smoking, may have caused the correlations.

To evaluate the risk completely, the EPA suggested industry conduct a new inhalation study. Begun this past summer, it is designed to address some of the criticisms of past inhalation trials, one of the most important being whether the animals were dosed sufficiently. (In an unpublished analysis, Hesterberg concludes they were: the maximum tolerated dose, he recently found, is a concentration of 30 milligrams of fibers per cubic meter.) The study, using hamsters, should be finished by mid-1997.

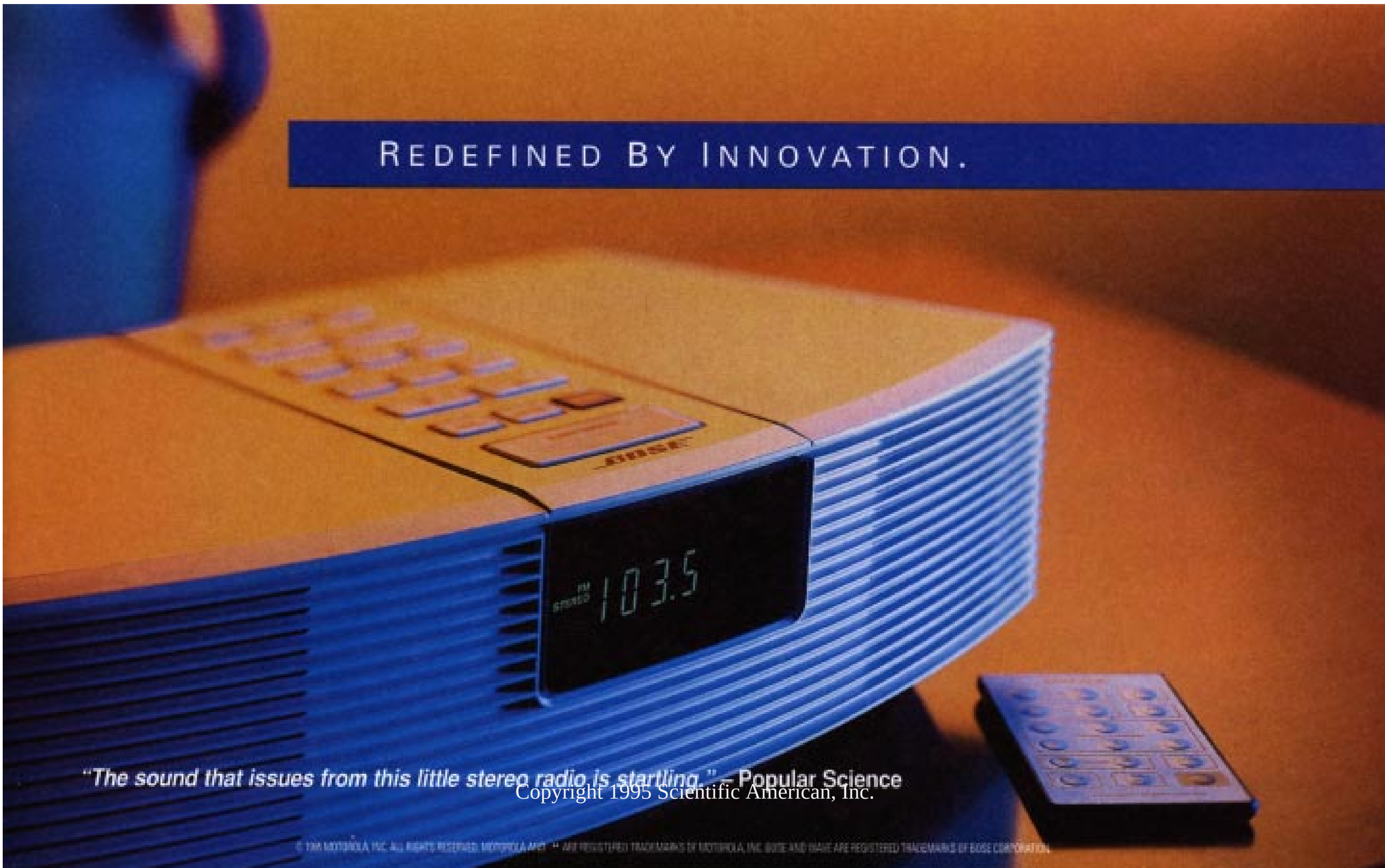
Although scientists on both sides of the issue feel that this experiment will lead to a more complete risk assessment of MMVFs, it probably will not end the debate. Lacking funds, government agencies rarely test for safety themselves; instead they rely on industry-sponsored work. Even though such studies take advice from government scientists, are open to auditing and must pass peer review, a feeling of bias can still exist. "It is a reality we have to live with," Hesterberg says, conceding that "our company has made some mistakes" but that it has learned its lessons from asbestos. "I feel we've adequately tested fiberglass," he adds. "I feel it won't cause cancer or fibrosis." —*Philip Yam*

The Big Thaw

Stability of the Antarctic ice remains unclear

The vast shield of ice capping the Antarctic is the largest body of freshwater on the planet. If it melted, sea levels would surge by 60 meters, submerging coastal areas around the world. Some scientists have therefore become increasingly alarmed in recent years as David M. Harwood of the University of Nebraska and others have presented evidence that a mere three million years ago, during the Pliocene epoch, the Antarctic ice sheet melted, transforming the frozen continent into a collection of tree-covered islands. The disturbing implication is that global warming, which may push temperatures to Pliocene levels by the middle of the next century, might trigger a catastrophic meltdown of the ice sheet.

Now a group led by David E. Sugden of the University of Edinburgh has challenged this scenario. Sugden and his six co-workers report in *Nature* that they have discovered ice at least eight million years old in a region that, in Harwood's view, should have been clear of ice as recently as three million years ago. The



NOEL POTTER, JR. *Dickinson College*

BEACON VALLEY, in the Transantarctic Mountains, contains ice at least eight million years old, says David E. Sugden and his team, whose camp is shown here.

new finding has intensified what was already a fierce debate between "stabilists" and "dynamists" over the ice cap's past and, more important, its future.

The Harwood group based its claim of a big thaw on fossilized beech trees and marine diatoms found high in the Transantarctic Mountains, a rocky spine that cuts the Antarctic roughly in half. The beech fossils were undatable, but the diatoms were of a type known to have existed in the southern oceans three million years ago.

According to Harwood, the beech trees grew on the ice-free shores of Antarctic islands during the warm Pliocene, and the diatoms thrived in the marine basins surrounding the landmasses. When the balmy weather of the Pliocene gave way to a more frigid climate, the beech trees all died off; the expanding sea ice pushed sediments laden with diatoms up over the islands, where the diatoms mingled with the beech fossils. Those Pliocene islands became the peaks of the Transantarctic Mountains.

But George H. Denton of the University of Maine, a member of Sugden's group, questions Harwood's analysis. Denton says that even today diatoms can be blown from the open sea surrounding the Antarctic far inland. The three-million-year-old diatoms found by Harwood might also have been transported from open sea into the Transantarctic Mountains, mingling with the much older fossilized beech trees, Denton explains.

The recent findings of Sugden, Denton and others cast still more doubt on the big-melt scenario. The workers found glacial ice covered with a layer of volcanic ash in a region of the Transantarctic Mountains near where Harwood's group had taken samples. By analyzing the levels of argon isotopes in the ash, Sugden's crew concluded that it was eight million years old; the underlying ice, therefore, had to be at least that old.

David R. Marchant of the University of Maine, another member of Sugden's team, believes conditions during the Pliocene were probably much the same as they are today. The Antarctic ice, he maintains, is among "the most stable geologic features on the planet."

Harwood replies that both his findings and those of Sugden's group might be correct. The climate might have warmed enough during the Pliocene for most of the ice cap to melt, Harwood elaborates, while still allowing some ice to persist high in the mountains.

Moreover, just as Harwood's findings have been challenged, so have those of Sugden and his colleagues. In a commentary in *Nature,* Dick van der Wateren of the Free University in Amsterdam and Richard Hindmarsh of the British Antarctic Survey suggest that the volcanic ash dated by Sugden might have been pushed onto much younger ice long after the ash was originally deposited. At the moment, however, the stabilists may be prevailing. John A. Barron of the U.S. Geological Survey in Menlo Park, Calif., a previously neutral observer, says the recent report by Sugden and his co-workers has left him "75 to 80 percent" convinced that the stabilists are right. *—John Horgan*

Transforming Hyde into Jekyll

Researchers redesign thalidomide

For many people, the horrifying side effects associated with thalidomide should eliminate the drug from consideration as a treatment for anything. Yet scientists have returned to the controversial medication, seeking therapies for a variety of illnesses, including AIDS and cancer. Despite the drug's dark past, recent experiments indicate that a family of related compounds might safely and effectively treat diseases of the immune system.

In the 1950s thalidomide was given to thousands of pregnant women for morning sickness. Those who took the drug early in the first trimester gave birth to severely deformed babies—the compound somehow stunts the growth of arms and legs. In the 1960s, however, thalidomide given to leprosy patients eased their condition, and the drug was reexamined as a possible medication. Thalidomide is now used routinely to treat leprosy patients around the world. (In certain developing countries, where the drug is not carefully regulated, some patients, unaware of the side effects, still give birth to deformed infants.)

Several years ago Gilla Kaplan of the Rockefeller University determined that thalidomide combats immune disorders—such as the inflammation associated with leprosy—by regulating the amount of tumor necrosis factor alpha (TNF-alpha) circulating in the bloodstream. This hormonelike protein initiates immune response, but high levels of it have been linked to cachexia (the wasting syndrome seen in some AIDS or cancer patients), rheumatoid arthritis, lupus, bacterial meningitis and septic shock, among other maladies. Because of its ability to control TNF-alpha activity, thalidomide is now being studied as a treatment for AIDS, cancer and graft versus host disease, which can occur after bone marrow transplants. Preliminary results show the drug can relieve many of these conditions.

The Noses Have It

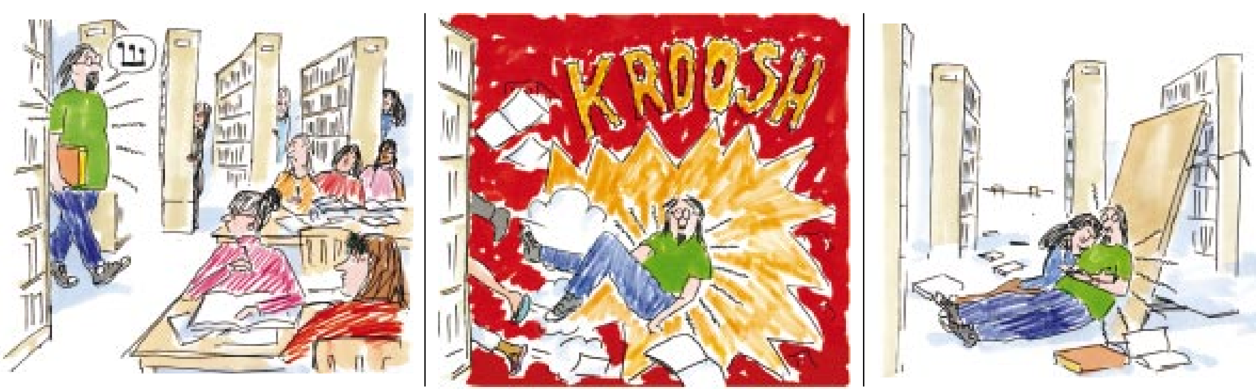
"Tell me where is fancy bred, Or in the heart or in the head?" William Shakespeare wonders in *The Merchant of Venice*. "How begot, how nourished?" He then answers his own question: "It is engender'd in the eyes, With gazing fed." Yeah, well, Shakespeare, writing in the days before daily showers, must have been keeping the pungent truth to himself. The eyes may be the windows to the soul, but smell might be the doorway.

Swiss researchers recently published a report in the *Proceedings of the Royal Society of London* that tested the role male body odor has in female mate choice. Perhaps just as important, the researchers finally found a place in science for the T-shirt—as something other than the standard uniform of the graduate student.

In a smelly nutshell, male volunteers slept in T-shirts for two nights. Female volunteers then sniffed the repositories of chemical emissions, after which they rated the odoriferous shirts for pleasantness and sexiness. All this might be the modus operandi for some low-tech dating service had not the researchers bothered to tissue-type their subjects to determine their major histocompatibility complexes, or MHCs, a crucial part of the immune system.

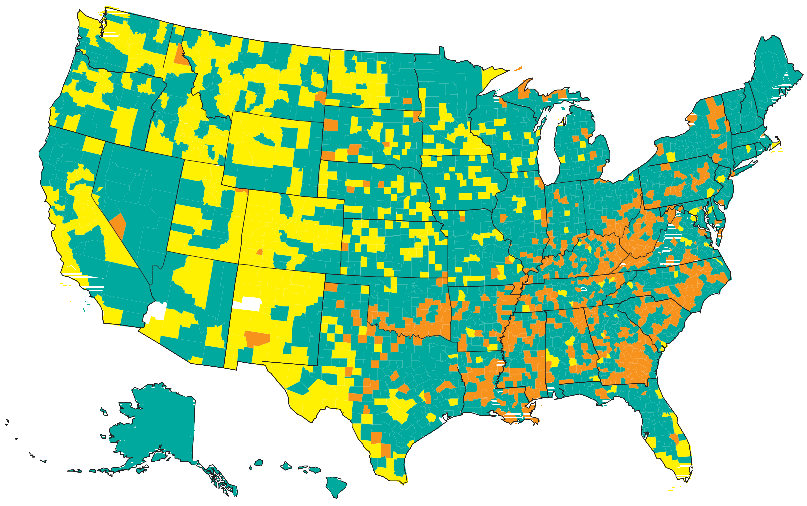
Studies with mice have revealed a preference for mates that have differing MHCs—presumably because offspring will have a wider array of immune options to draw on if their parents' MHCs are not alike. The T-shirt study showed the same: females rated as more alluring the smells from those T-shirts that had been worn by men whose MHCs differed most from their own. Such smells reminded females of their own mates or ex-mates twice as often as did smells of men whose MHCs were similar to their own.

The Swiss study also indicated a potentially disturbing side effect of the contraceptive pill. Females on the pill preferred males of similar MHCs. (This phenomenon may be a result of the pill's physiological mimicry of pregnancy: pregnant mice prefer to nest with MHC-similar individuals, most likely supportive relatives, not the unrelated scoundrels who got them into the situation.) A woman who chooses her husband while on the pill, stays on the pill through the first few years of marriage, then goes off the pill may suddenly wonder who the stinker in bed with her is. *—Steve Mirsky*



MICHAEL CRAWFORD

Male Deaths Caused by Heart Disease, by County



SOURCE: National Center for Health Statistics, 1979–1992

In 1994 heart disease killed 735,000 Americans. More than two thirds died from coronary heart disease (CHD), which occurs when the coronary arteries, suppliers of oxygen-rich blood to the heart, become blocked by atherosclerosis (fatty deposits on the arterial wall) or thrombosis (blood clotting). These changes may result in a heart attack—erratic heartbeats and the sudden destruction of part of the heart muscle.

Far more men than women die of CHD, because women are protected against the disease by hormones, particularly those present before menopause. In the early 1920s, when CHD mortality started to increase, the numbers of men and women 65 and older were roughly equal, but by 1970 men this age were outnumbered by women almost 10 to seven, largely because of CHD. Why CHD rates rose in the 1920s is not clear, but it is likely that the popularity of cigarettes among men was partly responsible. Smoking, which is a prime risk factor for CHD and other types of heart disease, started to decline in the 1960s, after a 1964 report by the U.S. surgeon general. In the 1960s, CHD rates also began to fall—a trend that continues today.

Cigarette smoking most likely contributes to the pattern on the map, which shows age-adjusted mortality rates for all forms of heart disease for white men age 45 to 74. (Total heart disease mortality, rather than recorded CHD mortality, is depicted because an unknown but probably substantial number of CHD deaths are misclassified.) State-by-state information on smoking, available since 1984, reveals that there are more smokers in the eastern than the western U.S. Several of the eastern regions with the highest mortality for heart disease are also areas where lung cancer death rates are highest. Because 80 percent or more of lung cancer is attributable to cigarette smoking, this fact suggests that high heart disease mortality in these places is the result, in part, of smoking. There are, however, important exceptions to this congruence—such as northern Virginia—where lung cancer mortality is high, but heart disease mortality is low.

Other CHD risk factors—elevated blood pressure, augmented serum cholesterol and minimal physical activity—also contribute to the pattern of heart disease, but their impact is impossible to gauge because little geographic information is available. Another risk factor for CHD—diabetes—does not help explain the map. Diabetes mortality is high in parts of the east but also in Utah and New Mexico, where heart disease mortality is low.

The pattern of heart disease mortality among women and blacks in the same age group is roughly the same as that of white men, although blacks have lower rates in the north. —*Rodger Doyle*

Such uses for thalidomide could become even safer. Researchers at Celgene Corporation in New Jersey and at Rockefeller announced at the fall meeting of the American Chemical Society that they have altered the structure of the agent to create a family of several hundred thalidomide derivatives that may be more effective and less dangerous.

"Thalidomide was developed as a sedative, and so we felt the structure hadn't been optimized" to treat immune conditions, comments George W. Muller of Celgene. Muller and David I. Stirling, also at Celgene, and their colleagues created the novel compounds by determining how the body metabolizes thalidomide. Such analysis can pinpoint which parts of the molecule make it into the bloodstream and thus might inhibit TNF-alpha production. The team then tinkered with the drug's structure, adding molecular groups here and there, looking for improvements. "Early on we found that if we changed one of the ring structures of thalidomide, we started to see large increases in [immunomodulatory] activity," Muller says.

Initial tests are not definitive about the safety of the new compounds. But Stirling explains that by studying a family of chemicals in which each member has slightly different properties, chemists can better evaluate which parts of the structure may trigger side effects. Stirling expects the team eventually to "separate the teratogenicity from the immune modulation capabilities" or to improve potency so that lower doses can be given, eliminating harmful effects.

One could, of course, remove the dangers of thalidomide by abandoning the drug entirely. Monoclonal antibodies, for instance, can also be used to lower TNF-alpha levels. According to Stirling, however, the antibodies completely eradicate the protein, instead of lowering its level back to normal as thalidomide and its derivatives do.

Furthermore, Muller says, thalidomide has been studied since the 1960s as a treatment for a variety of diseases; results demonstrate the drug can be a powerful tool against many of these ailments. Modern tests can presumably detect potential teratogens better than those used decades ago—particularly since tests were improved as a direct consequence of the thalidomide tragedy. Indeed, Muller maintains that any adverse effects would show up in laboratory trials—and he will soon find out if this is true for the new family of thalidomide derivatives. Researchers at Johns Hopkins University just began preclinical testing of several thalidomidelike drugs for use in graft versus host disease. —*Sasha Nemecek*

Out of Place

A weed is a valuable crop to some farmers

The fate of a fast-growing shrub in Southeast Asia and tropical Africa could pit small farmers against large plantation managers, with agricultural researchers forced to take sides. *Chromolaena odorata* is not much to look at, but it has spread so rapidly in Africa, according to Joan Baxter of the International Center for Research in Agroforestry (ICRAF) in Nairobi, that local names for it have cropped up: Bokassa (the dictator of the Central African Republic from 1966 to 1979, who had himself crowned emperor in 1977 in a lavish ceremony that bankrupted his subjects), *l'envahisseur* (the invader) and *mighbe* (the plant that crushes all) in Cameroon.

The shrub, which grows up to five meters high, plagues coconut, oil palm and rubber plantations. If it is not suppressed, it can shade infant trees and prevent them from growing. It also creates a wall of impassable undergrowth that makes harvesting mature trees almost impossible. And labor for weeding of enormous tracts is expensive.

So there is little surprise that the *C. odorata Newsletter* should be almost entirely devoted to efforts aimed at the plant's eradication. Since the mid-1960s, one herbicide after another has proved ineffective at targeting the shrub and leaving plantation trees unharmed. But in the past few years researchers at Biotrop in Indonesia have had modest success with a parasitic moth that munches on *C. odorata*'s leaves, slowing its growth and spread dramatically.

There's only one small glitch in this story of agroscience triumphant. Many small farmers depend on *C. odorata* to restore the soil of their fields during fallow years and to crowd out grasses and other weeds that are much more difficult to cut back, reports Simon P. Field of the Fiji Soil and Crop Evaluation Project. Five people can chop down and burn a hectare covered with the shrub and ready it for planting in a week; the job would take a month for a field covered in *Imperata cylindrica,* an invasive grass that grows in the same regions.

Parasitic moths are not known for their ability to distinguish between plantations and small holdings, so large-scale biocontrol of *C. odorata* could leave poor farmers in serious trouble, according to Hubert de Foresta of the Southeast Asian branch of the ICRAF. Avoiding damage to smaller farms could call for plantation managers to return to labor-intensive hand pruning.

Although most fallow crops are of no particular use on plantations, *C. odorata* appears to be the only one actively targeted for destruction, says Miguel A. Altieri of the University of California at Berkeley. (Baxter reports that Australia, for example, lists it among plants to be destroyed on sight.) Field and other researchers are attempting to find other crops that would be as effective at restoring the land and suppressing weeds but that would not threaten plantations. Indonesian farmers already grow several varieties of leguminous trees to prevent weed buildup, but nurturing the trees through their first year can be difficult. *C. odorata,* in contrast, appears able to survive virtually everything but labor-saving research. *—Paul Wallich*

A Never-Ending Feast

Imagine what it would be like if whenever you finished a meal, it magically reappeared. If this sounds like a dream, consult a grasshopper. New findings suggest that every time a grasshopper feeds, it secretes a chemical that encourages the leaves of the plant it is eating to regrow.

Investigations into just what happens to plants when they are consumed have become increasingly common in the past decade as researchers have attempted to address the concerns of environmentalists, evolutionists and farmers. In particular, they have sought to understand vegetation's chemical responses.

Grazing appears to bring about one of two reactions in plants. Herbivores may set in motion a negative feedback system that allows a plant to defend itself. When tomato leaves are damaged, for instance, they produce proteinase inhibitors, which interfere with the predator's digestive system. When attacked by caterpillars, other forms of flora can release chemicals to attract wasps—the natural enemies of the invading caterpillar. Alternatively, a positive feedback system might kick in. In these cases, grazing alters plant metabolism, leading to growth: bison and mouse saliva can stimulate such development. These changes can also protect against further predation; scientists have shown that once attacked, the carbon stores of some greens are moved from stem to root, where they are less vulnerable.

Until recently, however, the mechanism behind such a response remained mysterious. It was thought to depend on a series of chemicals, or perhaps on an electrical signal, elicited by physical damage or by the salivary secretions of the feeding animal. But now Melvin I. Dyer and his colleagues at the University of Georgia have pinpointed a compound from one herbivore, a grasshopper, and detailed its effects. Dyer collected more than 1,000 specimens of *Romalea guttatas,* also known as Lubber grasshoppers (*above*), and purified an extract of their midgut tissue. When applied to sorghum shoots, the concoction fostered growth in 24 hours. This activity suggests that during feeding, the grasshopper may regurgitate to produce "a positive feedback in plant growth," Dyer explains.

MELVIN I. DYER

Although the chemical has not yet been identified, Dyer says it seems similar to epidermal growth factor (EGF), a biochemical messenger found in vertebrate saliva. Dyer has shown that EGF induces changes in the development of plants—as well as in mammals. If EGF-like compounds are also present in invertebrates, it is very likely that Dyer's results could have wide ecological implications, explaining certain aspects of herbivore-plant relations.

Dyer says he hopes to look at the genetics of the system and identify the receptor that binds with the grasshopper's chemical. For now, though, he is pleased the results further confirm the idea of reward feedback. *—Nicola Perrin*

Gay Genes, Revisited

Doubts arise over research on the biology of homosexuality

In recent years, two studies published in *Science* seemed to provide dramatic evidence that male homosexuality has biological underpinnings. In 1991 Simon LeVay, then at the Salk Institute for Biological Studies in San Diego, reported finding subtle but significant differences between the brains of homosexual and heterosexual men. Two years later a group led by Dean H. Hamer of the National Cancer Institute linked male homosexuality to a gene on the X chromosome, which is inherited exclusively from the mother.

Both announcements made headlines worldwide. LeVay and Hamer appeared on talk shows and wrote books. They also co-authored an article published in this magazine in May 1994. But LeVay's finding has yet to be fully replicated by another researcher. As for Hamer, one study has contradicted his results. More disturbingly, he has been charged with research improprieties and is now under investigation by the Federal Office of Research Integrity.

In Hamer's original study, he examined 40 pairs of nonidentical gay brothers and asserted that 33 pairs—a number significantly higher than the 20 pairs that chance would dictate—had inherited the same X-linked genetic markers from their mothers. Sources with knowledge of the investigation say a former colleague has accused Hamer of improperly excluding pairs of brothers whose genetic makeup contradicted his finding. Hamer has declined to comment on the charges, which were first reported in the *Chicago Tribune*.

Hamer has continued to pursue his research in spite of the controversy. With workers at the University of Colorado, Hamer recently performed a study similar to the one reported in 1993, but with 33 pairs of gay brothers instead of 40. Stacey Cherny, one of Hamer's collaborators, says the new study essentially corroborates the original finding of linkage with markers on the X chromosome. The paper has been submitted to a journal.

Elliot S. Gershon of the National Institute of Mental Health is now recruiting 100 pairs of gay brothers for a genetic-marker study similar to Hamer's. But the only independent group that has completed a study like Hamer's failed to replicate his results. George Ebers of the University of Western Ontario says his examination of 52 pairs of gay brothers yielded no evidence for a linkage of homosexuality to markers on the X chromosome or elsewhere. Ebers and an associate, George Rice, have also analyzed the pattern of sexual orientation in 400 families with one or more gay males and found no evidence for the X-linked, mother-to-son transmission posited by Hamer.

Meanwhile one scientist has tried to replicate LeVay's claim about differences between the brains of gay men and their straight counterparts. LeVay asserted that a minute region of the hypothalamus called the interstitial nucleus was smaller in male homosexuals than in straight men and similar in size to the nucleus of females. LeVay speculated that biological factors, possibly genetically based, cause the brains of homosexuals to become "feminized."

One of the premises of LeVay's study was that the interstitial nucleus of males is significantly larger than that of females. William Byne, a psychiatrist at Mount Sinai Medical Center, decided to test LeVay's idea. (In the same issue of *Scientific American* in which LeVay and Hamer argued that homosexuality is a biological condition, Byne challenged their view.) Byne compared the brains of 19 heterosexual men and seven women and found that the male nuclei were larger—as LeVay had found.

But Byne suspects that spurious causes may explain the sexual dimorphism. He notes, for example, that it is much easier to obtain the brains of young males for research, because their mortality rates are so much higher than those of females. As a result, female brains may have been stored longer in a preservative, thus shrinking the interstitial nucleus and other features. Byne has chosen not to publish his results until he can rule out this and other possibilities. He is also collecting brains for a comparison of gay and straight males.

JASON GOLTZ

IDENTICAL TWINS show that some homosexuality cannot be ascribed to genetic factors. While James* (left) *is heterosexual, Jerry is gay.

Evan S. Balaban, a neurobiologist at the Neurosciences Institute in San Diego, notes that the search for the biological underpinnings of complex human traits has a sorry history of late. In recent years, researchers and the media have proclaimed the "discovery" of genes linked to alcoholism and mental illness as well as to homosexuality. None of the claims, Balaban points out, have been confirmed. *—John Horgan*

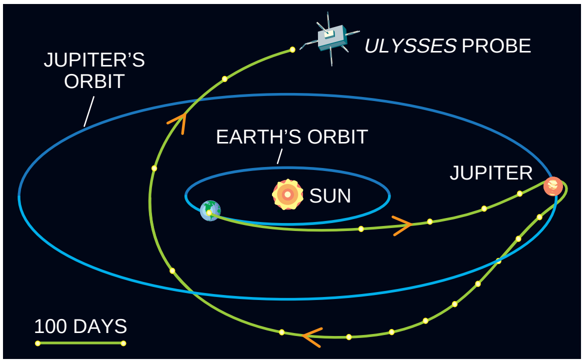
Solar Secrets

More data make for more mystery

Many scientific instruments have been turned on the sun, but until recently all of them have looked at the star from close to the earth's angle of view. A European Space Agency craft called *Ulysses* is now perplexing physicists with measurements from an entirely different perspective.

After a delay of several years, *Ulysses* was launched in 1990 on the space shuttle *Discovery*. During its long voyage, the spacecraft made use of Jupiter's gravity to flip it into an orbit that sent it under the sun. The spacecraft passed below the solar southern pole last year and looped over the northern side this past summer. The spacecraft's unique vantage point enabled it to detect previously unrecorded phenomena.

Some of the key observations relate to the solar wind, a torrent of ionized hydrogen and helium rushing away from the sun that exerts profound effects on the earth's electrical environment (its gusts are responsible for much radio interference). Near the sun's equator, the wind moves relatively slowly and variably at about 450 kilometers per second, but at the higher latitudes now being monitored, its speed changes abruptly to 750 kilometers per second. The boundary between the high- and low-speed winds oscillates like the edge of a spinning ballerina's skirt. The width of the turbulent, low-speed band may depend on the level of sunspot activity—an idea that will be tested after the year 2000 as *Ulysses* makes a second polar pass, which, unlike the first, will occur during a period when many sunspots are expected.



DIMITRY SCHIDLOVSKY

ULYSSES *has given solar scientists new views.*

The fast flow at high latitudes, together with details of the solar wind's composition, fits well with the idea that most of the wind originates in the photosphere, the sun's sharp, bright outer edge, says D. Edgar Page, *Ulysses* science coordinator for the European Space Agency at the Jet Propulsion Laboratory in Pasadena, Calif. Some scientists had thought they would find only occasional high-speed streams, which would have pointed to a different site of origin, Page notes. The fast wind probably escapes through huge holes frequently detected near the sun's poles in the corona, an often invisible gaseous halo that shrouds the visible disk.

Recently David J. Thomson and his colleagues at AT&T Bell Laboratories made the controversial claim that information from *Ulysses* and other satellites reveals a hidden periodicity in the solar wind resulting from oscillations already believed to occur within the sun. Further analysis

Country Music

The natural world is so full of complexity that detection of a regular signal can be startling. Perhaps this is what Vera Schlindwein, Joachim Wassermann and Frank Scherbaum, all then of Ludwig-Maximilians University in Munich, felt as they made seismic recordings along the side of Java's Mount Semeru (*right*) in 1992. That these experiments revealed periodic rumblings is not surprising: seismologists have recognized for decades that volcanoes can generate such vibrations, called harmonic tremors. What seemed strange was that the waves were too regular.

The researchers' instruments recorded ground motion that contained a series of evenly spaced harmonic frequencies—like a musical instrument playing a single note rich in overtones. The fundamental frequency of these subaudible vibrations would often shift slightly up or down, as might a struggling singer trying to stay on key. The frequencies were restricted to below eight hertz, so the song of the mountain, even if amplified, would be inaudible to human ears. Even so, in their recent report in *Geophysical Research Letters,* the team did describe "a variety of acoustic events, among which a regular pumping sound was the most striking feature."

Seismologists have debated whether harmonic tremors such as these arise from peculiarities of the volcanic source—molten magma creeping upward through cracks, perhaps belching up gas now and then—or whether they result from the sound bouncing back and forth along the path between the source and the receiving instrument.

Schlindwein and her co-workers point out that they received the same pattern at different locations, so that echoes along the signal path are not likely to explain the reverberations. They posit instead that these oscillations emanate from a single source—a large, presumably cylindrical gas-filled cavity. The top of the void may be stoppered by a plug of frozen lava; the bottom by a column of molten magma. The lowest frequency in the signal (0.5 hertz) suggests that the chamber could be 500 meters tall.

Bernard A. Chouet, a seismologist at the U.S. Geological Survey in Menlo Park, Calif., remarks that the great difference in physical properties between gas and surrounding rock could explain why the German team detected such a high-quality signal. Most of the acoustic energy would resonate in the cavity at characteristic frequencies without being dampened. "That gives you the same thing as an organ pipe," Chouet explains. The shifts in frequency, the German scientists propose, result from changes in the length of the pipe as the level of magma gradually rises or falls. It is as if they had stumbled on a gargantuan subterranean trombone.

ROGER RESSMEYER *Corbis*

Carrying the musical analogies even further, Schlindwein's team argues that the occasional observation of a set of harmonics without the fundamental note can be accounted for by the same mechanism that controls "overblowing of low tones in a recorder." This phenomenon occurs when pressure pulses in the cavity affect the source (in this case, not quivering lips but bubbling magma).

Whether the basal magma could ever rise to the point where the tones reach audible frequencies is unclear, but should that shift happen, some enterprising local may decide to set up an amplifier and speakers. The attraction might inspire a whole new generation of eco-tourists to visit the peak, saxophone and trumpet in hand. After all, it's not everywhere that you can count on the location itself to provide some good bass riffs. —*David Schneider* of the data may shed light on the matter, says André Balogh of Imperial College, London, a member of the *Ulysses* team. For now, however, he regards the question as unsettled.

What drives the solar wind is also still a mystery, but surprising features of the sun's magnetic field detected by *Ulysses* provide clues. The field's overall form was not the predicted bar-magnet shape, with distinct north and south magnetic poles; rather magnetic-field lines spread out uniformly like the spokes of a tire. According to Balogh, the shape results because the magnetic-field lines near the poles are pushed apart by the solar wind. He envisages the high-speed wind emerging from polar holes in the corona and then being deflected by magnetic forces toward the equator. Powerful, and apparently random, fluctuations in the field over the course of just a few hours may be the energy source for the wind.

The strong fluctuations in the magnetic field probably also keep out most of the cosmic rays that *Ulysses* looked for but that were seen only at low intensity, Page explains. High-intensity rays might have given hints about their origins, which are thought to lie in energetic events elsewhere in the galaxy. But other discoveries compensate, including the first direct detection of neutral atoms from outside the solar system. Their apparent speed of 26 kilometers per second reflects the sun's motion relative to the galactic background. The *Ulysses* data "confirm some of what we expected," Balogh says. "But more than 50 percent of our models were wrong. It's a nice balance." —*Tim Beardsley*

THE ANALYTICAL ECONOMIST

Some Women Are More Equal Than Others

In the days before the current wave of feminism, many economists (most of them male) subscribed to the notion that women's earnings were "pin money"—a luxury that households did not really need. Nowadays, with more than 60 percent of adult women in the labor force (compared with about 75 percent of men), that myth has mostly been banished. Ironically, however, Nada Eissa of the University of California at Berkeley has recently conducted studies showing that for a few women there may be a grain of truth to the old saw after all. In addition, the reaction of women to sudden changes in their effective pay may cast light on how people in general decide how much to work.

Eissa looked at the effects of the 1986 Tax Reform Act, which lowered the tax paid by high-income couples but left middle- and low-income ones essentially unchanged. She found that in households earning more than $130,000 a year, the proportion of women in the labor force—either employed or actively looking for jobs—increased 19.5 percent by 1988, compared with only 7.2 percent for families earning $47,000 annually. High-income women who were already employed worked 12.7 percent more hours each week, compared with 3.6 percent for middle-income women.

Economists have argued for decades over whether wage increases cause people to work more or less, says James M. Poterba of the Massachusetts Institute of Technology. On the one hand, money is considered a good thing, and more of it is generally considered even better. Thus, higher wages should increase the incentives for people to work. On the other hand, leisure is also a good thing, and a higher wage allows people to meet their basic needs more easily, so they could decide to work less and maintain the same standard of living.

Eissa's data suggest that at least for one segment of the population, the lure of extra money outweighs the joys of idleness. Her findings are consistent, Poterba notes, with analyses by Martin Feldstein of Harvard University, who discovered a sharp increase in taxable income among the upper-income brackets in the year that their tax rate fell. About a third of this extra income was the result of people deferring payments from the previous year—in which they would have been taxed more heavily—but the rest does appear to represent real changes, Poterba explains.

KIRK CONDYLES *Impact Visuals*

WOMAN'S WORK is influenced by tax rates, but low- and middle-income women do not reap tax-cut benefits.

Whether such a happy ability, much less desire, to match earnings to tax incentives extends to the rest of the population is very difficult to determine, Eissa says, because there are no statistics collected that address the question directly. There is some evidence to suggest that high-income women, at least, tailor their employment and working habits more closely to tax laws than do working women as a whole, she says, but the issue is far from clear.

Another question that has yet to be decided is whether the behavior of the rich provides any support for the infamous Laffer curve hypothesis, which predicted that cutting taxes would increase government revenues because people who were able to keep more of what they earned would put in longer hours. The numbers appear to bear the now obscure Laffer out, but extrapolating to low incomes could be difficult. Furthermore, Poterba notes, because economists can analyze only reported income, there is no way to tell if people were actually working more or merely switching their portfolios from tax-free municipal bonds to high-yielding taxable investments.

Economists may get a slightly better handle on these points, thanks to the tax counterreformation of 1993, which rescinded some of the breaks that upper-income couples acquired in 1986. Eissa's models suggest that high-income married women should leave jobs and cut back their hours in almost the proportions that they augmented their participation a few years before. This kind of natural, relatively well controlled experiment in the labor market is rare, Poterba says—indeed, he considers the data that have been generated by the policy swings of the 1980s and 1990s something of a windfall for economic research. "It's like a volcano is for geologists," he quips. No one would advocate revamping the tax laws every five years just to gather information, but if Congress is going to do it anyway, some understanding may as well emerge. —*Paul Wallich*

Luddites on the Hill

Congress quietly kills the Office of Technology Assessment

How would a group of lawyers formulate policy on complex technical and scientific issues without a consistent source of in-depth information? It's not another unkind joke at the expense of the legal profession but a real concern in the wake of the U.S. Congress's decision to eliminate its 22-year-old Office of Technology Assessment this past July.

Congress's 535 members, the majority of whom have only legal backgrounds, must regularly formulate legislation on telecommunications, defense, energy, astronautics, health care, basic research, transportation and other technical subjects. For help, the committees on which they serve have often turned to the OTA, which then typically drew on the expertise of specialists in academia, at private think tanks or elsewhere. Such experts offered information, advice and criticism to OTA staffers, who wrote, rewrote and edited reports to elucidate policy options and consequences. Draft reports were reviewed by a bipartisan board of representatives and senators.

TRANS-ALASKA PIPELINE was one of several big technical projects in the early 1970s that compelled the U.S. Congress to seek professional help.

SARAH LEEN *Matrix*

"We have had this agency, which has a $22-million budget, pay for itself hundreds of times over by giving this Congress the kind of advice it needs to prevent mistakes from being made," said Representative Vic Fazio of California in June at a meeting of the committee on legislative branch appropriations. Only last year, supporters say, an OTA report on the Social Security Administration's computer procurement strategy helped to avert a purchase of $2-billion worth of outdated equipment. In the late 1970s the fledgling OTA raised concerns about the synthetic-fuels program, which went on to become what is widely regarded as a multibillion-dollar boondoggle.

But with $200 million needing to be pruned from the $1.3-billion legislative budget, the OTA seemed to some a luxury that was no longer affordable. "I don't think Congress *has* to have a captive agency to advise it on science and technology issues," says John Morgan, a physicist and staff member in the office of Representative Dana Rohrabacher of California. "There are literally hundreds of areas where we have no such agency. I would put economic policy at the head of that list."

"There was a feeling that the information the OTA provides would be available from other sources," adds Mark Mills, a spokesman for Senator Connie Mack of Florida. "With the explosion of technology, there has been an explosion of information on technology."

It is not at all obvious, though, how other sources will compensate for the loss of the OTA. Much of the information that swamps congressional staffs comes from lobbyists and others with specific interests. The organizations most often cited as being able to fill in for the OTA include Congress's own General Accounting Office (GAO) and Congressional Research Service (CRS), executive-branch or other agencies such as the National Research Council (NRC) and private think tanks. None of them, OTA supporters have pointed out, put out information like the OTA's. Besides being tailored to the needs of Congress, OTA reports are peer-reviewed and impartial (insofar as anything is in Washington). Such a combination of attributes is not to be found even in the output of other congressional offices, none of which have anything like the OTA's concentration of technical and scientific expertise. The CRS generally does short, specific studies for individual members, whereas the GAO provides oversight of executive-branch agencies.

The notion that Congress might draw on executive-branch organizations ignores the circumstances of the OTA's establishment in the early 1970s. In dealing with the Nixon administration on such issues as the antiballistic missile system and the Trans-Alaska pipeline, members of Congress and their staffs felt they were at a disadvantage when pitted against the executive branch's parade of technical experts.

The NRC, which is the operating arm of the National Academy of Sciences and the National Academy of Engineering, is probably the most capable in theory of filling in for the OTA. The NRC's detailed studies, however, often take even longer than the 18 to 24 months required for some of the OTA's, and the realities of NRC-congressional cooperation are not encouraging, notes one veteran of both the OTA and CRS. Because of its culture, the "NRC does not often wind up answering the questions Congress asks," he says. "It doesn't know how."

In any case, many observers find the prospect of committee chairmen doggedly pursuing other avenues of technical enlightenment preposterous. "This is a Congress less interested as an institution in being informed than any Congress in the two decades I've been following the legislative branch closely," says the ex-OTA employee. Representative George E. Brown, Jr., of California, a former civil engineer who has a long history of involvement in science and technology issues, agrees. "Many members of Congress do not take advantage of the products the OTA is putting out," he claims. "Politics in Congress today is being driven by ideology, not technology assessments or rational projections." —*Glenn Zorpette*

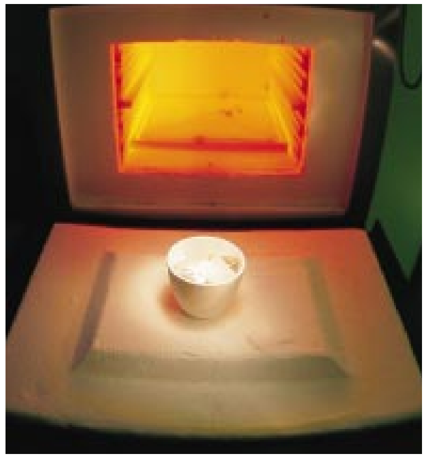
Clearing the Air

Common rocks may deliver cleaner power

The Intergovernmental Panel on Climate Change, an international body reviewing the science of global warming, may soon reach a significant milestone. A draft report from the panel concludes that world average temperature changes over the past century—amounting to an increase of between 0.3 and 0.6 degree Celsius—are "unlikely to be entirely due to natural causes." If that declaration survives in the final report, expected to be published next month, it will mark the panel's first official acknowledgment that humans have very likely contributed to the gradual warming.

That trend is driven by increasing atmospheric levels of greenhouse gases, chiefly carbon dioxide, which is produced when fossil fuels are burned. Researchers everywhere are seeking ways to reduce the amount of the gas released. Power plants, which account for about one third of emissions, are the easiest target. One approach is to increase energy efficiency, reducing the amount of fuel used. An alternative would be to take carbon dioxide out of exhaust gases and sequester it in some safe form. So far, however, nobody has demonstrated an economical way to do so. And Klaus S. Lackner of Los Alamos National Laboratory points out that schemes to extract the gas and bury it are risky, because it could leak—defeating the purpose and posing danger.

But Lackner and his colleagues think there is a solution. They say carbon dioxide from power-plant exhaust can be made to react with abundant, easily accessible minerals to create a harmless waste product, magnesium carbonate. Because the reaction produces heat, which could drive other steps in the operation, the process would largely pay its own energy bills. "We were surprised that nobody else had thought of this," Lackner says. The scheme uses rocks that contain magnesium oxide. Two kinds, in particular, show promise: serpentinite and olivine. Serpentinite could be simply ground up and heated to start the reaction while carbon dioxide is passed over it; olivine would have to be pretreated to make it reactive enough.



CHIP SIMONS

GROUND ROCKS could be an answer to global warming.

As envisioned by the Los Alamos team, the operation would not be small: six tons of rocks would be needed to absorb the carbon dioxide from every one ton of coal burned. Having to transport the rocks would make the process impossibly expensive, but Lackner says carbon dioxide could be piped from power plants to absorbing facilities sited near mines. Others who have examined the proposal wonder, however, whether the process can be made as energy efficient—and hence economical—as Lackner assumes. "The ideas are important, but the scheme is optimistic," says Roddie R. Judkins of Oak Ridge National Laboratory. "None of the necessary technology exists now."

But Lackner thinks modern heat exchangers make the technique financially feasible. The cheapest electricity available costs about three cents per kilowatt-hour. Lackner's calculations suggest carbon dioxide could be extracted and stored on an industrial scale for an additional six cents per kilowatt-hour—roughly tripling the cost. Although that price might sound unpromising, Lackner points out that nuclear power costs about eight cents per kilowatt-hour. If concerns about carbon dioxide levels grow, "having some solution available will be critical," he says. The team is seeking grants to scale up the experiments—a challenge, as funds for energy research are being cut. *—Tim Beardsley*

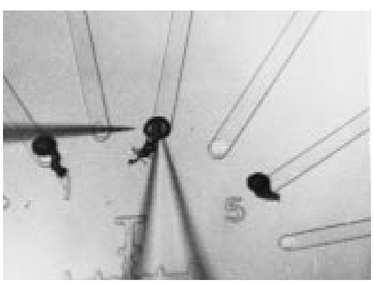
Mind Meets Machine, Sort of

Taking a modest step closer to the science-fiction staple of melding the human brain with the computer, researchers in Germany can now control a single neuron via a silicon chip connected to it. Granted, the neuron belongs to a leech. Still, the achievement may give biologists a new tool to investigate how neural networks grow and communicate.

Of course, scientists playing with electricity have, since the late 18th century, been able to set nerves and muscles atwitter using microelectrodes. Yet that approach has significant problems, says Peter Fromherz of the Max Planck Institute of Biochemistry near Munich. The current flow can initiate chemical reactions that can damage the cells, corrode the electrical contacts and form toxic by-products.

To avoid these problems, Fromherz and his colleagues relied on a capacitative effect—that is, using a nearby electric field to induce current flow in another element. They crafted a silicon chip with insulated "stimulation spots" about 10 to 50 microns wide. The workers then extracted from leeches individual neurons, which are large and hence easy to isolate, and plopped each one onto a stimulation spot. A voltage applied to the spot caused a buildup of positive charge in the nerve cell without any electricity actually flowing between the silicon and the cell. Above 4.9 volts, the neuron fired.

The work complements research Fromherz had conducted a few years ago, when he was able to register neuronal activity with a silicon chip. He recently succeeded in combining both detection and stimulation devices so that they can connect to the same neuron. His group has even fabricated stimulation spots in the two-micron range, small enough to be used for neurons in rats and even humans. Still, "it is most difficult to handle them individually," Fromherz remarks. And it is not clear how the system would work once taken out of the petri dish. "I do not know how to make such contacts in a tissue at the moment," Fromherz admits, noting that the researchers are only at the stage of developing the tools for experiments that might record and stimulate neural networks. The brain prosthesis will have to wait. *—Philip Yam*



PETER FROMHERZ

LEECH NERVES* (black spots) *sit on silicon channels and are probed by microelectrode tips.

Meta-Virus

Breaking the hardware species barrier

When computer diagnostician Angela Bennett (played by Sandra Bullock) disabled a mainframe computer with a virus-infected disk slipped into a Macintosh in this past summer's nerd thriller, *The Net,* most computer aficionados chuckled knowingly. One of the fundamentals of computer viruses is that malicious programs designed to paralyze one kind of hardware become ineffective gibberish when aimed at the wrong machine.

Those were the good old days. In August thousands of Microsoft Word users' computers were infected with a virus that spread equally fast regardless of whether they were using Macintoshes or Intel-style PCs. The offending code was a macro—a miniature program—whose instructions were carried out by an interpreter that Microsoft had built into the newest version of the word-processing software. This "virtual machine" was independent of the underlying hardware. The macro was designed to run automatically when a document containing it was opened for reading or editing. (Instead of performing any illicit deed, however, the main body of the virus consisted of a statement: "REM That's enough to prove my point.") Although Microsoft quickly released software to contain the virus, contributors to the Usenet newsgroup comp.security.misc pointed out that the antidote neither completely excises the offending code nor guards against trivially modified versions.

JOYCE RUDOLPH *Sony Pictures Entertainment Company*

ART ANTICIPATES LIFE in* The Net, *as Sandra Bullock plays a hacker who meets a universal computer virus.

"I was not surprised," says security expert William Cheswick of AT&T Bell Laboratories somewhat wearily. Computer scientists have been toying with the viral possibilities of macro languages for at least seven years, he notes; the only puzzle is why it took this long for one to start spreading. Cheswick speculates the reason is more epidemiological than technical: not enough machines running the right software and no good method for transmitting the infection from one machine to another. The combination of local-area network file servers and Microsoft's market dominance appears to have supplied both factors.

Many other programs—and computer operating systems—are acquiring macro capabilities, sometimes also known as scripting. These simple programming languages can make use of the capabilities of the applications in which they are embedded: a word-processing macro, for example, might use the search-and-replace function in conjunction with the word-counting command to adjust a text for the available space. Any repetitive task is easy to automate; indeed, Microsoft has proposed making the language in which the Word virus was written a standard for the rest of its software and for other companies.

Luckily, most of these potential digital breeding grounds are crippled by the difficulty of communicating infectious content. The real potential for "geometric increase," according to Cheswick, lies with software that combines simple programming tools and capabilities for sending and receiving data over the Internet. Instead of waiting for users to exchange files or floppy disks, such a program can reach out to kindred machines in a few hundred milliseconds.

"Virus Implementation Language" is Cheswick's private name for Hot Java, a World Wide Web scripting tool developed by Sun Microsystems. The language lets programmers embed small pieces of software in World Wide Web documents; these customized programs run not on the Web server (a machine that responds to requests for information sent over the World Wide Web) but rather on the computer that belongs to the person looking for information. This technique makes it easier to process complex exchanges of information.

Although Sun's engineers have installed a number of security features to reduce the chances that rogue Java code—downloaded with a single click of a mouse—will run amok over the Internet, some of the features that make it dangerous are precisely the ones that make it useful. If a Java program can access users' files to help bring order to their electronic life, it can as easily wreak disorder; if it can reach out to other machines on the Internet to retrieve valuable information, it may also be able to spawn copies of itself and bring the Net to its collective knees. Careful attention to the rules governing what files a program can manipulate or how freely it can access the Internet can minimize the risks and still allow Java programs to perform useful work, but Cheswick and others are doubtful that most users will know how to configure their machines correctly.

And Hot Java is only one of many methods under development for sending programs across the Net and executing them remotely. General Magic's Telescript is based on the notion of software "agents" prowling in search of the best airfare from Phoenix to Fiji, the e-mail address of an old college buddy or whatever else their owners may want. In theory, strict cryptographic safeguards should prevent mischief, but the system has yet to be thoroughly tested. Microsoft's own proprietary network, a sort of shadow of the World Wide Web, allows users to e-mail programs to one another in a special format so that a program will run automatically when the recipient reads an incoming message. Even Mime, a multimedia extension for conventional Internet mail programs, is designed to decode and execute simple programs sent via e-mail.

With so many attractive choices facing them simultaneously, hackers' to-do list may be getting long enough that any given loophole is less likely to be cracked, Cheswick suggests hopefully. He recalls his surprise earlier this year when no one exploited a bug that made it possible to commandeer Web servers simply by sending a message that was too long for their input buffers. (Ironically, this same class of bug was responsible for the spread of the Internet worm that nearly shut down the Net in 1988.) Then again, Cheswick says, the fact that so many security holes have gone unused for so long could mean that there are far fewer malicious hackers on the Internet than the din of dire public pronouncements would have people think. Unfortunately, as Cornell University graduate student Robert Morris, Jr., and his self-reproducing programs dramatically showed seven years ago, it takes only one. *—Paul Wallich*

Rights of Privacy

Technology has its eyes on you

Privacy, as George Orwell pointed out, rests on some level on a bargain between people and their machines. Long before 1984, communications technology had the potential to become surveillance technology. Now it is. Not, as Orwell might have predicted, because Big Brother wants to keep his subjects in thrall but simply because most people want it to be. By giving up some protective anonymity, people get safety and service. A majority seem to think the bargain a very good one—which is why everybody should look very carefully at the fine print.

Somewhat ironically for the nation that gave birth to Orwell, Britain is leading the way in creating the kind of society that he taught the world to fear. More than 300 British city streets are wired for 24-hour surveillance by closed-circuit television cameras. From control rooms, police and private security officers scan everything that moves, or doesn't, and dispatch police officers to investigate anything suspicious.

More cities are getting wired all the time, often by popular demand. Whatever qualms Britons have about privacy, they are more concerned about crime. The cameras do seem to reduce crime—at least in the areas underneath the cameras. Academics point out that surveillance seems to have no impact whatsoever on the overall level of crime, which is rising, but people just don't seem to care about where the muggers go when they leave their neighborhood—particularly when their neighborhood wasn't too good to begin with.

Safety is not the only reason to embrace surveillance. At the Olivetti Research Laboratory in Cambridge, for instance, Andy Hopper and his staff have for years worn tiny badges that inform their computers where they are each minute. The point is convenience. Computers automatically bring to the screen the work of the person sitting in front of them. Calls are forwarded to the telephone nearest wherever they happen to be—unless the computers detect three or more badge wearers gathered in the same office, in which case they are assumed to be in a meeting, and calls are forwarded to their voice mail.

To make life more convenient still, Hopper is trying even cleverer technologies. Some chairs now contain compasses that monitor whether they are pointed at a screen, and, if not, the screen is dimmed to save power. Such devices, Hopper reckons, are crucial to making computers effortlessly easy to use. As he puts it, "You can't have personalization without identification."

But the search for personalization in a high-tech world may create an uncomfortable situation in the global village. Villages are safe places but not very private ones. Mrs. Grundy, peering from behind her lace curtains, did stop housebreakers, but she also tried to halt many other things of which she disapproved. There are signs that Grundyism is returning to Britain. Many of the crimes recorded by surveillance cameras are worryingly petty. Arrests for urinating in public have soared. For better and for worse, cameras that can see in the dark now line romantic walks to the beaches in seaside towns.

In Britain, as elsewhere, technology and politicians are about to deepen the privacy dilemma. Cameras are being linked to smarter computers that can identify people. Some drivers receive tickets without human intervention. Video cameras check their speed and read their license plates. Along with a ticket, the owner is sent a photograph of the car and driver at the time the speeding was clocked. A number of companies are touting technology that can recognize faces by matching video images to digitized photographs (from, say, drivers' licenses).

The British government, like many others, is also discussing plans for a national identity card that would, by giving everyone a number, make it easier to keep track of personal data. The selling point is convenience. Much of the work of filling out forms in bureaucratic Britain is simply to give one branch of government information that another part already has—or to correct information that bureaucrats have got wrong.

Convenient though it may be in theory, the combination of national identity schemes and surveillance cameras promises to give governments many of the powers of an all-seeing God. And there are many reasons to worry that mere humans would not be as merciful or as competent. Two aspects of surveillance will prove crucial in determining the practical terms of the new privacy bargain now being struck: choice and reciprocity.

Unlike the subject of video surveillance, the wearer of one of Olivetti's badges can remove the device and disappear from the system. His electronic identity is entirely a voluntary one: if he wishes to forward all the telephone calls the old-fashioned way, by hand, there is nothing to stop him. Surveillance becomes less intrusive if it is optional. But choice cannot be a cure for all the potential ills of surveillance. As electronic personalization makes electronic identification more important, that choice becomes harder to manage.

One problem is forgery. If electronic identities can be taken on and off like sweaters, the risk that fraudsters will be able to put on somebody else's identity rises. Besides, as such identification becomes more important, the sheer effort required to live anonymously will render choice moot. Anonymity will simply become too much work.

Real village traditions offer hope for the lazy and the identifiable. In village life, surveillance was reciprocal: if Mrs. Grundy knew a lot about you, you also knew a lot about her—and you knew what she knew about you. Technology should further extend this reciprocity. The badges in the Olivetti lab provide a way of locating any badge wearer. But they also allow badge wearers to track

REMI BENALI *Gamma Liaison*

VIDEO CAMERAS will scan the crowd at the 1996 Olympic Games in Atlanta. The security system can transmit images for identification.

anybody who is trying to locate them.

There can indeed be no personalization without identification, but there is increasingly little excuse for identification without notification. The same computers and networks that send faces, names and numbers whizzing around the world could also be required to send notification back to each of those identified, each time they have been spotted. Even as the world becomes more personalized and less private, there is no reason for the electronic global village to become less personable than a thatched one, or less fair. *—John Browning*

Sewage Treatment Plants

Algae offer a cheaper way to clean up wastewater

Andile Tiyani wrinkles his nose in distaste as he points to a listing outhouse patched together from scraps of wood and corrugated metal. The tiny shack, huddled among thousands of other slightly larger shacks that house the black residents of the Crossroads township outside of Cape Town, South Africa, is just large enough to accommodate a toilet seat mounted over a bucket. The bucket is overflowing.

LOUISE GUBB *JB Pictures*

PETER D. ROSE believes algae-filled ponds may bring affordable waste treatment to South African townships.

"In better areas, they periodically take these buckets to the edge of town and dump them," Tiyani explains. "When the rains come, it all runs into the streams, where people wash their clothes, and it contaminates the groundwater, which lies just four meters below the surface here." In five neighboring townships, home to some one million black South Africans, conditions vary only slightly. In Harare, residents share pit toilets. Tiyani's house in the middle-class district of Guguletu is among the most hygienic around, sporting a septic tank.

Bringing basic sanitation services to the millions who lack them is a top public health priority for the new South African government. It is also a huge fiscal challenge. As in so many other poor countries, expensive Western technologies are simply not an option.

One cheap Western technology may be, though. Nearly 500 miles to the east of Cape Town, Peter D. Rose of Rhodes University is adapting an American algae-based system to meet the needs of sub-Saharan Africa. In a nearby pilot plant, due to be completed next year, the waste of 500 to 1,000 people will be pumped through 1,000 square meters of ponds and raceways full of *Spirulina,* a single-celled plant that thrives on salty, nutrient-rich sewage. Exposed to sunlight and stirred gently, algae ingest most of the waste. A small remainder of heavy metals and other inorganic detritus sinks to the bottom of the pits.

Ponds replete with algae have been used to treat waste for at least a century. But it is only in the past decade that advanced algal systems, in which just certain species are actively cultivated, have begun to challenge the activated-sludge techniques commonly used in industrial nations.

Advanced algal ponding processes now offer several advantages, says William J. Oswald of the University of California at Berkeley, who has worked on the technology since the 1950s. The equipment and power used in conventional plants to mix incoming sewage with pressurized air and bacteria-rich sludge are avoided in algal systems, so the latter cost about one half as much to build and operate. They can run on less water—important in arid climes such as South Africa's. They produce far less sludge, which is generally trucked to landfills or dumped at sea. In fact, the main product is tons upon tons of dead algae, which when dried makes a good fertilizer or additive for fish food. And because the plants produce lots of oxygen, they don't stink. "We had a wine tasting not long ago at the [algal pond] plant in St. Helena," which processes 500,000 gallons of sewage a day in the heart of California wine country. "It was very picturesque," Oswald says.

For Rose, the technology holds a dual attraction. The potential for improving community sanitation throughout the Third World is obvious. (Researchers in Kuwait and Morocco are also running tests.) "But it has allowed us to do some very interesting fundamental research as well," Rose says, donning his biochemist's cap. As South African science budgets are increasingly squeezed by a government facing more urgent needs, many scientists there are scrambling to find relevant applications to justify their basic research.

"One of the future benefits of the process is that once you have this algal biomass, you might be able to engineer it to produce by-products that are more valuable than just animal feed," Rose continues. His team recently elucidated the biochemical mechanism by which another algae, *Dunaliella salina,* produces massive amounts of beta carotene (the nutrient used by the body to make vitamin A) when stressed by excessive salt or heat.

Rose has also demonstrated that *Spirulina* ponds can treat industrial waste, particularly from tanneries. "The tanning industry is set to explode in Africa," says Randall Hepburn, Rhodes's dean of science. "The reason is simple: we kill 650 million sheep, goats, pigs and cows each year. But the hides of all but 3 percent of those are left to rot. That is going to change."

The possibility of a tanning boom worries some African environmentalists. "Tanneries produce some of the worst effluents of any industry: sulfides, ammonia, heavy metals," Rose says. "It's shocking stuff." So he was a bit surprised several years ago when he noticed giant blooms of *Spirulina* forming in a tannery's evaporation pond. The discovery has led to test projects at tanneries near Cape Town, in Namibia and in the Transvaal, where algal treatment systems are successfully—and inexpensively—squelching odors and reclaiming water that was previously wasted through evaporation.

"Rapid industrialization in Third World countries is very often done at the expense of the environment, because the costs of First World remediation technologies cannot be afforded simultaneously," Rose says. "To come up with a low-cost method that turns waste into something not only safe but useful—well, that's the first prize in biotechnology." *—W. Wayt Gibbs*

PROFILE: KAY REDFIELD JAMISON

Coming through Madness

Kay Redfield Jamison's musical voice sounds above the din in the midtown Manhattan restaurant where we are eating lunch. It is the confident voice of a seasoned lecturer. But Jamison, a professor of psychiatry at the Johns Hopkins University School of Medicine, is not at this moment setting forth the symptoms of manic-depressive illness, her area of expertise. Instead she is telling me about the reactions to her latest book. It is, to be certain, quite different from what she has published in the past. In 1990 Jamison co-authored *Manic-Depressive Illness,* considered the definitive clinical text, and in 1993 wrote *Touched with Fire,* a look at the disease's influence on great artists. Her new offering, *An Unquiet Mind,* describes manic-depression from another vantage altogether: her own.

Jamison was diagnosed with the illness some 20 years ago but only now has found the conviction—and, more important, time away from her intense schedule—to write about it. "Basically, people have been very supportive," she says, nodding her head as though she is still trying to decide. "But you are not aware of the people who aren't saying anything. So you're sort of left at the mercy of what other people's opinions of the disease are." It is, as she well knows, an illness that frightens many, conjuring up bleak images of locked psychiatric wards. It is also strongly genetic, running through families and too often stigmatizing affected and unaffected members alike. Left untreated, manic-depressive illness precipitates violent, psychotic manias and black suicidal depressions. Yet, as Jamison can testify, the disease is highly treatable. Lithium and psychotherapy have ably secured her life and sanity for many years.

JASON GOLTZ

JAMISON has sought to change how manic-depressive illness is perceived and treated.

She has also benefited from terrific strength and luck. Lithium was approved by the Food and Drug Administration for treating manic-depression in 1970, only four short years before her condition became a medical emergency. Her very first attack had come 10 years earlier, when she was a senior in high school. Jamison's family had recently left Washington, D.C. Her father, a meteorologist and manic-depressive as well, retired from the U.S. Air Force and took a job at the Rand Corporation in Santa Monica. Although Jamison had moved many times before—she attended four schools by the fifth grade—California proved to be a difficult adjustment. Her brother, on whom she doted and would later depend, had left for college, and her father fell into depression and heavy drinking.

Initially, she experienced a brief, very mild mania. "I raced about like a crazed weasel, bubbling with plans and enthusiasms," she writes. But these high-flying emotions soon gave way to despair. For months, she thought constantly about death, often drank vodka in her morning orange juice and felt "virtually inert, with a dead heart and a brain cold as clay." Then, as swiftly as her moods had come, they lifted. During her undergraduate years at the University of California at Los Angeles, however, the illness returned in force.

As her temperament worsened and graduation grew near, Jamison shifted her career goals from medicine to psychology and, in 1971, began studying for a doctorate at U.C.L.A. "Despite the fact that we were being taught how to make clinical diagnoses, I still did not make any connection in my own mind between the problems I had experienced and what was described as manic-depressive illness in the textbooks," she writes. Though disruptive, her moods were not unrelenting. In fact, they had vanished during a junior year abroad at the University of St. Andrews in Scotland. "Throughout and beyond a long North Sea winter," she writes, "it was the Indian summer of my life."

In her writing and teaching, Jamison has long emphasized how seductive mild manias and respites from depression can be during the early stages of the disease. As such, they explain in part why so many manic-depressives—more than two thirds—go untreated. It is a critical point. During lunch, she pauses on it, using the blunt side of her knife to impress a timeline on the stretch of linen between our plates. "The natural course of the disease is to have an initial episode, say, at 18," she says, making one invisible notch near the breadbasket. "Then you have maybe a year and a half or two before another episode," she adds, scoring the cloth again, "and then another year or so of free time." Toward the edge of the table, her hand is recording stripes of psychosis, spaced a year or less apart.

Once manic-depression enters such a regular cycle, it is often less responsive to medication, and the moods it brings begin to overlap. Indeed, mania and depression do not lie on opposite ends of the emotional spectrum, as the blanched name "bipolar disorder" implies. In mixed states—filled with manic energy and morbid thoughts—people are most likely to attempt suicide; without treatment, one in five succeed. "It sounds like a terrible thing to say," Jamison remarks, "but when you most want people to have a whole lot of episodes so that if they stop taking their medication they'll get sick again, they actually face the greatest probability that they are going to stay well for a long time. So many people delude themselves into thinking that the illness won't come back."

She herself fell into this trap. In July 1974 Jamison joined the psychiatry faculty at U.C.L.A. "Summer, a lack of sleep, a deluge of work, and exquisitely vulnerable genes eventually took me to the back of beyond, past my familiar levels of exuberance and into florid madness," she writes. One evening in the early fall, as she watched the sun set over the Pacific from her living room, she suddenly "felt a strange sense of light at the back of my eyes and almost immediately saw a huge black centrifuge inside my head." A tall figure, whom she slowly recognized as herself, placed a large tube into the centrifuge. "Then, horrifyingly, the image that previously had been inside my head now was completely outside of it." The whirring machine splintered, spewing blood onto the walls, carpets and window, where it merged into the sunset. "I screamed again and again. Slowly the hallucinations receded. I telephoned a colleague for help, poured myself a large scotch, and waited for his arrival."

This colleague insisted she see a psychiatrist, persuaded her to leave U.C.L.A. for a while and prescribed an array of antipsychotic medications. "Endless and terrifying days of endlessly terrifying drugs—Thorazine, lithium, Valium and barbiturates—finally took effect." But in the spring, when she again felt well, she ceased taking lithium. Many of her reasons were medical: The high doses that were regularly prescribed in the 1970s blurred her vision and made her horribly nauseated. When the dose reached toxic levels, she became ataxic, or uncoordinated. Lithium further faulted her memory and concentration. She was also loath to relinquish the addictive thrill of her manias. And she was scared that lithium might not work. Today anticonvulsant drugs can level extreme moods in many patients, she explains, but 10 and 20 years ago, "if you didn't respond to lithium, you were just out of luck." It was a costly gamble.

> In a rage I pulled the bathroom lamp off the wall and felt the violence go through me but not yet out of me. "For Christ's sake," he said, rushing in—and then stopping very quietly. Jesus, I must be crazy, I can see it in his eyes: a dreadful mix of concern, terror, irritation, resignation, and why me, Lord? "Are you hurt?" he asks. Turning my head with its fast-scanning eyes I see in the mirror blood running down my arms, collecting into the tight ribbing of my beautiful, erotic negligee, only an hour ago used in passion of an altogether different and wonderful kind. "I can't help it. I can't help it," I chant to myself, but I can't say it; the words won't come out, and the thoughts are going by far too fast. I bang my head over and over against the door. God make it stop. I can't stand it, I know I'm insane again. He really cares, I think, but within ten minutes he too is screaming, and his eyes have a wild look from contagious madness, from the lightning adrenaline between the two of us. "I can't leave you like this," but I say a few truly awful things and then go for his throat in a more literal way, and he does leave me, provoked beyond endurance and unable to see the devastation and despair inside. I can't convey it and he can't see it; there's nothing to be done. I can't think, I can't calm this murderous cauldron, my grand ideas of an hour ago seem absurd and pathetic, my life is in ruins and—worse still—ruinous; my body is uninhabitable. It is raging and weeping and full of destruction and wild energy gone amok. In the mirror I see a creature I don't know but must live and share my mind with.
>
> I understand why Jekyll killed himself before Hyde had taken over completely. I took a massive overdose of lithium with no regrets.

Jamison had in fact planned the attempt well in advance, obtaining antiemetic medication to prevent her body from vomiting up the deadly dosage. She also placed her telephone far from her bed so she would not answer it and attract any unwanted help. Nevertheless, when it did ring, her half-drugged brain instinctively responded. Her brother, checking in from Paris, heard her slurred speech, hung up and called her psychiatrist. "The debt I owe my psychiatrist is beyond description," she writes. "He taught me that the road from suicide to life is cold and colder and colder still, but—with steely effort, the grace of God, and an inevitable break in the weather—that I could make it."

When Jamison finally resolved that lithium was, for her, a matter of survival, she returned to academia determined "to make a difference in how the illness was seen and treated." With two colleagues, she set up an outpatient clinic at U.C.L.A. in 1977 specializing in the treatment of mood disorders. Within a few years, it became a large teaching and research facility. Jamison, not surprisingly, emphasized the value in treating manic-depression with drugs and psychotherapy at once, which was not then the norm. "When medications first became available, there was a tendency to say, well, you can just take your lithium and be happy as a clam, and clearly that's the wrong approach," she says. "It does no good to have a drug that works, if people don't take it."

Also at the clinic, Jamison began giving talks on musical composers, such as Robert Schumann, who had suffered from mood disorders. These lectures led to a series of concerts—the first of which she produced with the Los Angeles Philharmonic in 1985—and to a series of television specials on the link between manic-depressive illness and the arts. In 1982 she surveyed the high prevalence of mood disorders in British artists and writers while on sabbatical at the University of Oxford and St. George's Hospital Medical School in London. She later found evidence that a disproportionately high number of eminent writers and artists of the 18th and 19th centuries, including Lord Byron, Vincent van Gogh and Alfred, Lord Tennyson, had very likely suffered from manic-depressive illness.

Certainly most artists are not mad, and most manic-depressives are not especially artistic, but Jamison suggests that heightened mood swings may afford some people greater creativity [see "Manic-Depressive Illness and Creativity," by Kay Redfield Jamison: SCIENTIFIC AMERICAN, February]. Such an advantage raises difficult questions, given that manic-depressive illness is genetic. Workers at Stanford University, Cold Spring Harbor Laboratory and Johns Hopkins University, as part of the Dana Consortium, are collaborating to find the genes and to consider the ethical ramifications of success: "Do we risk making the world a blander, more homogenized place if we get rid of the genes for manic-depressive illness?" Jamison asks in her book. "What are the dangers in prenatal diagnostic testing?" She herself never had children, but not because she feared they might well inherit her illness. Rather the man in her life at the time she was ready died unexpectedly, and her current husband, Richard Wyatt, a schizophrenia researcher at the National Institute of Mental Health, already had three children when they met. A pilot study of 50 manic-depressives and their spouses at Johns Hopkins has found that most couples would not abort an affected fetus.

Aside from early diagnosis, Jamison believes that finding the genes will help scientists uncover the biochemistry of manic-depression. "There are a lot of theories about neurotransmitters, but at the end of the day, when they find the genes, they're going to be able to trace back what is out of whack." Meanwhile new imaging techniques are yielding intriguing clues. Both magnetic resonance imaging and positron emission tomographic scans show structural abnormalities called hyperintensities, referred to as unidentified bright objects (UBOs), in the brains of many manic-depressives. No one has looked for UBOs in children at risk for the disease who have not yet been treated. Until then, it will remain unknown whether UBOs are etiologic. "It is clear that the UBOs are related," Jamison says, adding with a quick smile, "I'm not playing with a full deck." It is also clear that she has played her hand well. *—Kristin Leutwyler*

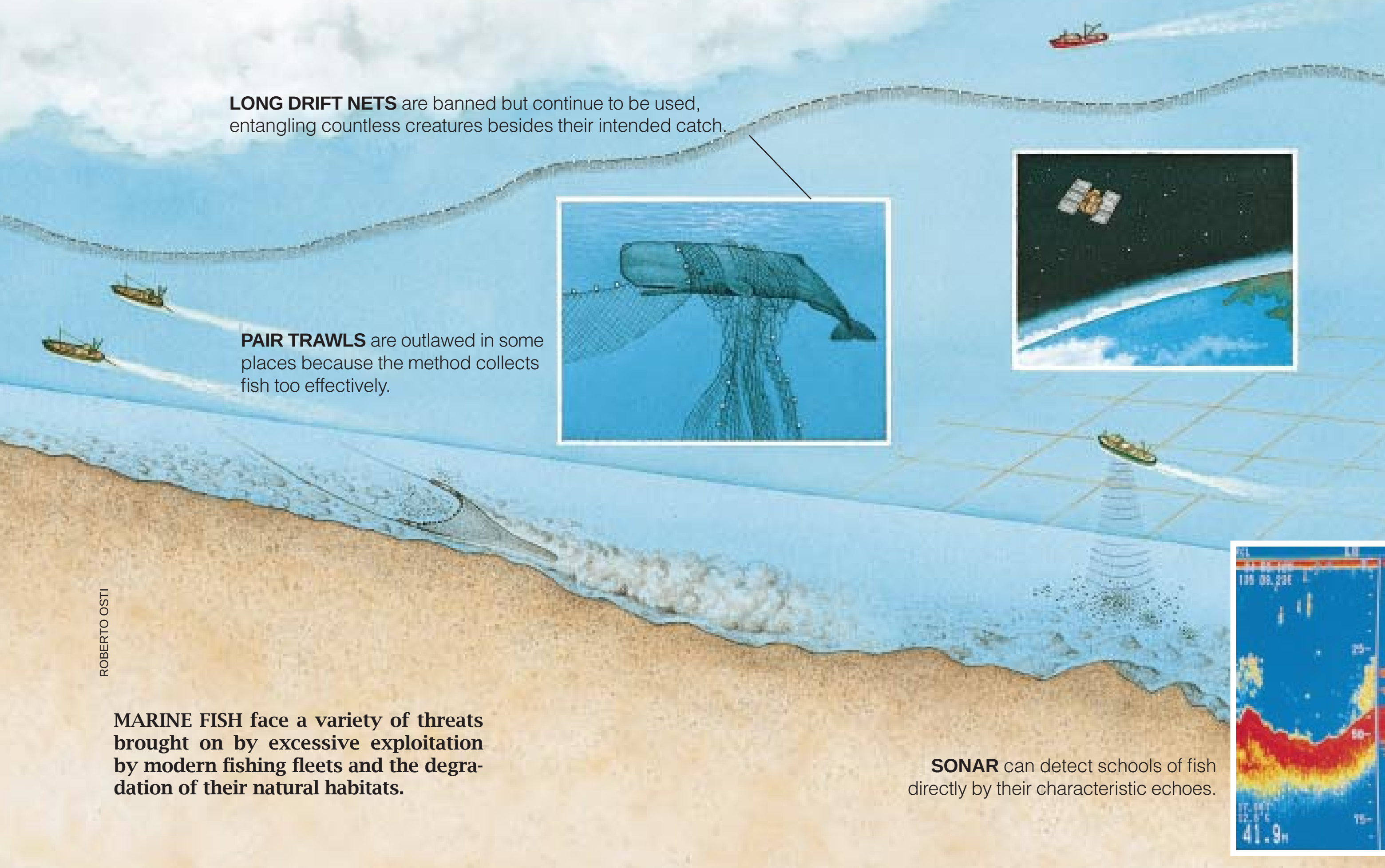
The World's Imperiled Fish

Wild fish cannot survive the onslaught of modern industrial fishing. The collapse of fisheries in many regions shows the danger plainly

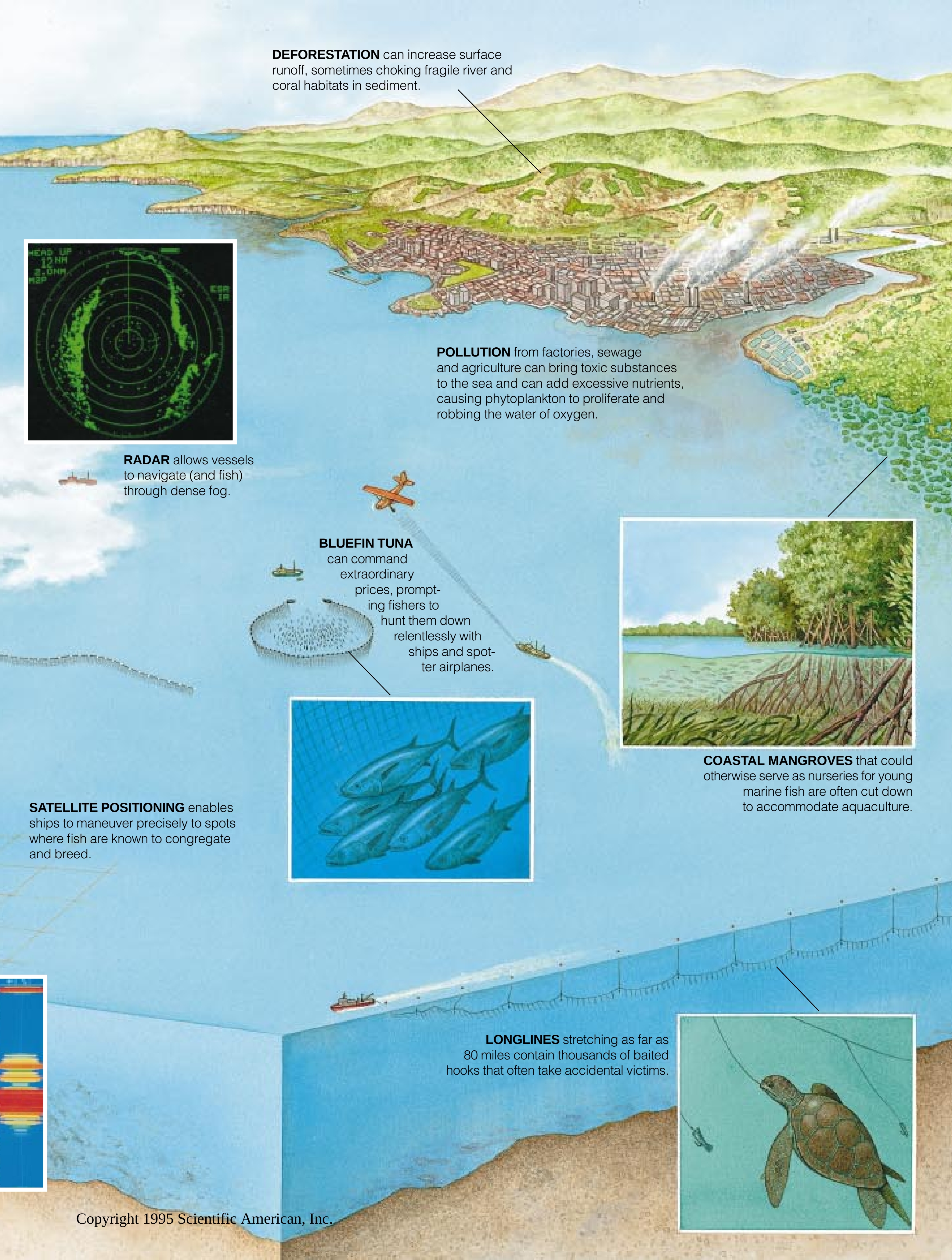
by Carl Safina

The 19th-century naturalist Jean-Baptiste de Lamarck is well known for his theory of the inheritance of acquired characteristics, but he is less remembered for his views on marine fisheries. In pondering the subject, he wrote, "Animals living in . . . the sea waters . . . are protected from the destruction of their species by man. Their multiplication is so rapid and their means of evading pursuit or traps are so great, that there is no likelihood of his being able to destroy the entire species of any of these animals." Lamarck was also wrong about evolution.

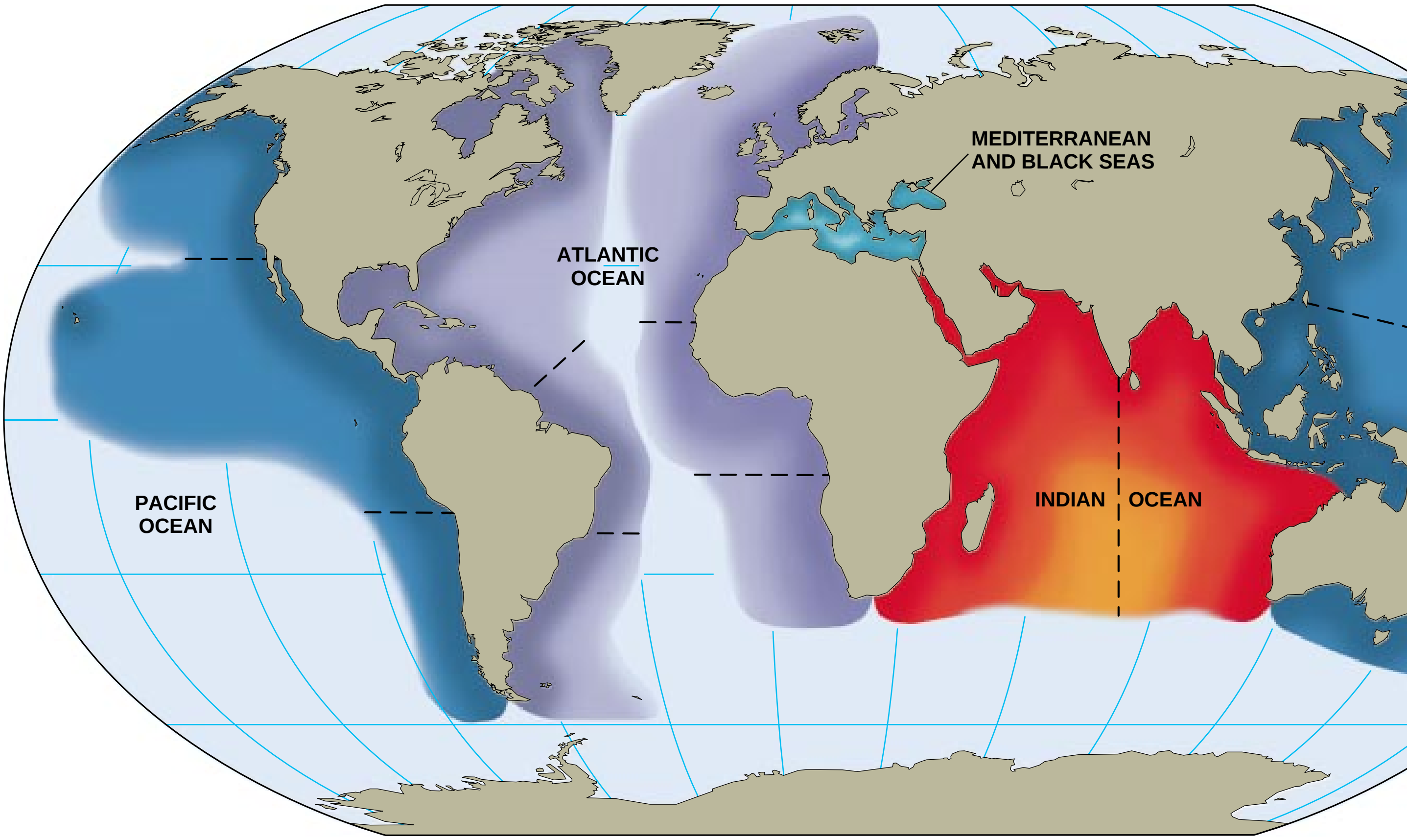
One can forgive Lamarck for his inability to imagine that humans might catch fish faster than these creatures could reproduce. But many people—including those in professions focused entirely on fisheries—have committed the same error of thinking. Their mistakes have reduced numerous fish populations to extremely low levels, destabilized marine ecosystems and impoverished many coastal communities. Ironically, the drive for short-term profits has cost billions of dollars to businesses and taxpayers, and it has threatened the food security of developing countries around the world. The fundamental folly underlying



MARINE FISH face a variety of threats brought on by excessive exploitation by modern fishing fleets and the degradation of their natural habitats.


DEFORESTATION can increase surface runoff, sometimes choking fragile river and coral habitats in sediment.
POLLUTION from factories, sewage and agriculture can bring toxic substances to the sea and can add excessive nutrients, causing phytoplankton to proliferate and robbing the water of oxygen.
RADAR allows vessels to navigate (and fish) through dense fog.
BLUEFIN TUNA can command extraordinary prices, prompting fishers to hunt them down relentlessly with ships and spotter airplanes.
COASTAL MANGROVES that could otherwise serve as nurseries for young marine fish are often cut down to accommodate aquaculture.
SATELLITE POSITIONING enables ships to maneuver precisely to spots where fish are known to congregate and breed.
LONGLINES stretching as far as 80 miles contain thousands of baited hooks that often take accidental victims.

Major Fishing Regions of the World: Changes in Catch



the current decline has been a widespread failure to recognize that fish are wildlife—the only wildlife still hunted on a large scale.

Because wild fish regenerate at rates determined by nature, attempts to increase their supply to the marketplace must eventually run into limits. That threshold seems to have been passed in all parts of the Atlantic, Mediterranean and Pacific: these regions each show dwindling catches. Worldwide, the extraction of wild fish peaked at 82 million metric tons in 1989. Since then, the long-term growth trend has been replaced by stagnation or decline.

In some areas where the catches peaked as long ago as the early 1970s, current landings have decreased by more than 50 percent. Even more disturbingly, some of the world's greatest fishing grounds, including the Grand Banks and Georges Bank of eastern North America, are now essentially closed following their collapse—the formerly dominant fauna have been reduced to a tiny fraction of their previous abundance and are considered commercially extinct.

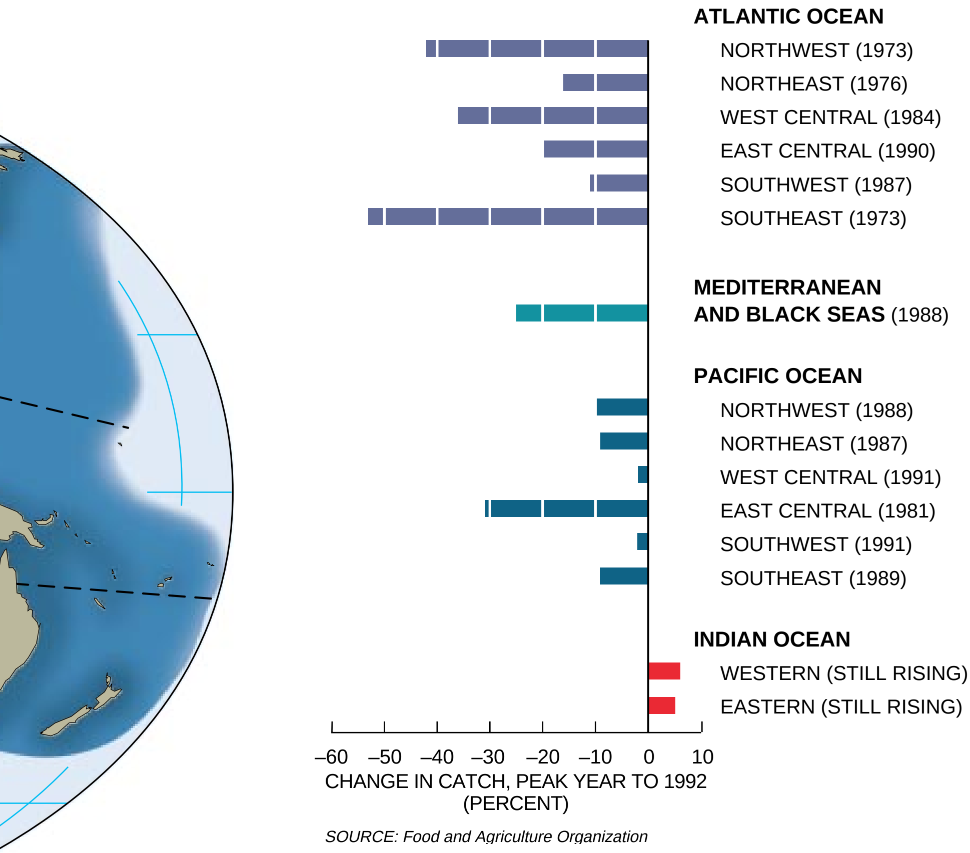
Recognizing that a basic shift has occurred, the members of the United Nations's Food and Agriculture Organization (a body that encouraged the expansion of large-scale industrial fishing only a decade ago) recently concluded that the operation of the world's fisheries cannot be sustained. They now acknowledge that substantial damage has already been done to the marine environment and to the many economies that depend on this natural resource.

Such sobering assessments are echoed in the U.S. by the National Academy of Sciences. It reported this past April that human actions have caused drastic reductions in many of the preferred species of edible fish and that changes induced in composition and abundance of marine animals and plants are extensive enough to endanger the functioning of marine ecosystems. Although the scientists involved in that study noted that fishing constitutes just one of the many human activities that threaten the oceans, they ranked it as the most serious.

Indeed, the environmental problems facing the seas are in some ways more pressing than those on land. Daniel Pauly of the Fisheries Center at the University of British Columbia and Villy Christensen of the International Center for Living Aquatic Resources Management in Manila have pointed out that the vast majority of shallow continental shelves have been scarred by fishing, whereas large untouched tracts of rain forest still exist. For those who work with living marine resources, the damage is not at all subtle. Vaughn C. Anthony, a scientist formerly with the National Marine Fisheries Service, has said simply: "Any dumb fool knows there's no fish around."

A War on Fishes

How did this collapse happen? An explosion of fishing technologies occurred during the 1950s and 1960s. During that time, fishers adapted various military technologies to hunting on the high seas. Radar allowed boats to navigate in total fog, and sonar made it possible to detect schools of fish deep under the oceans' opaque blanket. Electronic navigation aids such as LORAN (Long-Range Navigation) and satellite positioning systems turned the trackless sea into a grid so that vessels could return to within 50 feet of a chosen location, such as sites where fish gathered and bred. Ships can now receive



LAURIE GRACE

REGIONAL TAKES of fish have fallen in most areas of the globe, having reached their peak values anywhere from four to 22 years ago. (The year of the peak catch is shown in parentheses.) Only in the Indian Ocean region, where modern mechanized fishing is just now taking hold, have marine catches been on the increase. (Red bars show average annual growth since 1988.)

satellite weather maps of water-temperature fronts, indicating where fish will be traveling. Some vessels work in concert with aircraft used to spot fish.

Many industrial fishing vessels are floating factories deploying gear of enormous proportions: 80 miles of submerged longlines with thousands of baited hooks, bag-shaped trawl nets large enough to engulf 12 jumbo jetliners and 40-mile-long drift nets (still in use by some countries). Pressure from industrial fishing is so intense that 80 to 90 percent of the fish in some populations are removed every year.

For the past two decades, the fishing industry has had increasingly to face the result of extracting fish faster than these populations could reproduce. Fishers have countered loss of preferred fish by switching to species of lesser value, usually those positioned lower in the food web—a practice that robs larger fishes, marine mammals and seabirds of food. During the 1980s, five of the less desirable species made up nearly 30 percent of the world fish catch but accounted for only 6 percent of its monetary value. Now there are virtually no other marine fish that can be exploited economically.

With the decline of so many species, some people have turned to raising fish to make up for the shortfall. Aquaculture has doubled its output in the past decade, increasing by about 10 million metric tons since 1985. The practice now provides more freshwater fish than do wild fisheries. Saltwater salmon farming also rivals the wild catch, and about half the shrimp now sold are raised in ponds. Overall, aquaculture supplies one fifth of the fish eaten by people.

Unfortunately, the development of aquaculture has not reduced the pressure on wild populations. Strangely, it may do the opposite. Shrimp farming has created a demand for otherwise worthless catch because it can be used as feed. In some countries, shrimp farmers are now investing in trawl nets with fine mesh to catch everything they can for shrimp food, a practice known as biomass fishing. Much of the catch are juveniles of valuable species, and so these fish never have the opportunity to reproduce.

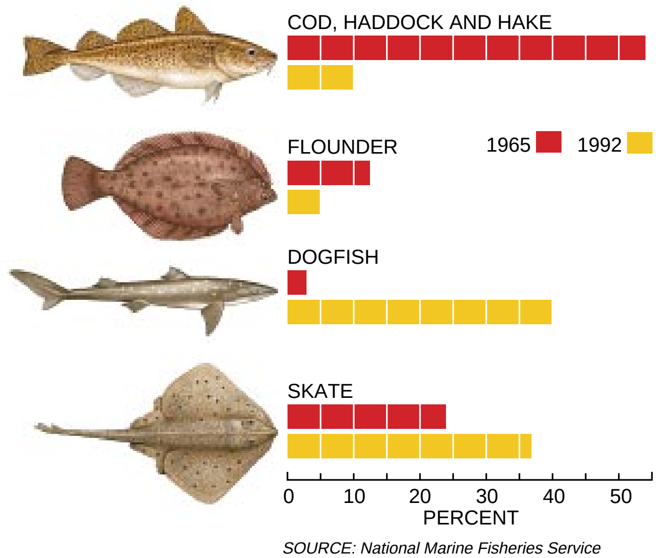
Fish farms can hurt wild populations because the construction of pens along the coast often requires cutting down mangroves—the submerged roots of these salt-tolerant trees provide a natural nursery for shrimp and fish. Peter Weber of the Worldwatch Institute reports that aquaculture is one of the major reasons that half the world's mangroves have been destroyed. Aquaculture also threatens marine fish because

NIGEL BROTHERS *Parks and Wildlife Service, Tasmania*

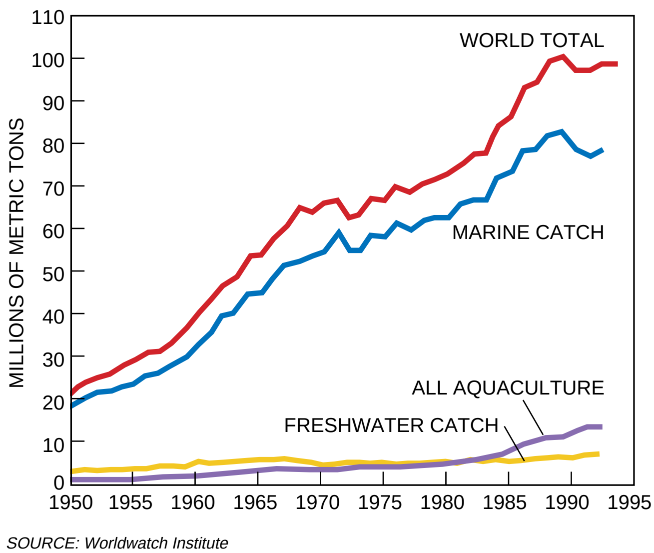
ALBATROSS are killed in tremendous numbers because they frequently grab at bait on longlines that are being set for tuna. Such losses are threatening the survival of several species of these wide-ranging seabirds.

some of its most valuable products, such as groupers, milkfish and eels, cannot be bred in captivity and are raised from newly hatched fish caught in the wild: the constant loss of young fry then leads these species even further into decline.

Aquaculture also proves a poor replacement for fishing because it requires substantial investment, land ownership and large amounts of clean water. Most of the people living on the crowded coasts of the world lack all these resources. Aquaculture as carried out in many undeveloped nations often produces only shrimp and expensive types of fish for export to richer countries, leaving most of the locals to struggle for their own needs with the oceans' declining resources.



RELATIVE ABUNDANCE of common fishes in the Gulf of Maine has changed drastically because of overfishing. Bars indicate the level of each of these species in 1965 (*red*) as compared with 1992 (*yellow*).



FISH SUPPLIES from aquaculture continue to rise, but marine fisheries (which provide the greatest share of the global yield) peaked in 1989. Total world catch has since entered a period of stagnation or decline.

Madhouse Economics

If the situation is so dire, why are fish so available and, in most developed nations, affordable? Seafood prices have, in fact, risen faster than those for chicken, pork or beef, and the lower cost of these foods tends to constrain the price of fish—people would turn to other meats if the expense of seafood far surpassed them.

Further price increases will also be slowed by imports, by overfishing to keep supplies high (until they crash) and by aquaculture. For instance, the construction of shrimp farms that followed the decline of many wild populations has kept prices in check.

So to some extent, the economic law of supply and demand controls the cost of fish. But no law says fisheries need to be profitable. To catch $70-billion worth of fish, the fishing industry recently incurred costs totaling $124 billion annually. Subsidies fill much of the $54 billion in deficits. These artificial supports include fuel-tax exemptions, price controls, low-interest loans and outright grants for gear or infrastructure. Such massive subsidies arise from the efforts of many governments to preserve employment despite the self-destruction of so many fisheries.

These incentives have for many years enticed investors to finance more fishing ships than the seas' resources could possibly support. Between 1970 and 1990, the world's industrial fishing fleet grew at twice the rate of the global catch, fully doubling in the total tonnage of vessels and in number. This armada finally achieved twice the capacity needed to extract what the oceans could sustainably produce. Economists and managers refer to this situation as overcapitalization. Curiously, fishers would have been able to catch as much with no new vessels at all. One study in the U.S. found that the annual profits of the yellowtail flounder fishery could increase from zero to $6 million by removing more than 100 boats.

Because this excessive capacity rapidly depletes the amount of fish available, profitability often plummets, reducing the value of ships on the market. Unable to sell their chief asset without major financial loss, owners of these vessels are forced to keep fishing to repay their loans and are caught in an economic trap. They often exercise substantial political pressure so that government regulators will not reduce allowable takes. This common pattern has become widely recognized. Even the U.N. now acknowledges that by enticing too many participants, high levels of subsidy ultimately generate severe economic and environmental hardship.

A World Growing Hungrier

While the catch of wild marine fish declines, the number of people in the world increases every year by about 100 million, an amount equal to the current population of Mexico. Maintaining the present rate of consumption in the face of such growth will require that by 2010 approximately 19 million additional metric tons of seafood become available every year. To achieve this level, aquaculture would have to double in the next 15 years, and wild fish populations would have to be restored to allow higher sustainable catches.

Technical innovations may also help produce human food from species currently used to feed livestock. But even if all the fish that now go to these animals—a third of the world catch—were eaten by people, today's average consumption could hold for only about 20 years. Beyond that time, even improved conservation of wild fish would not be able to keep pace with human population growth. The next century will therefore witness the heretofore unthinkable exhaustion of the oceans' natural ability to satisfy humanity's demand for food from the seas.

To manage this limited resource in the best way possible will clearly require a solid understanding of marine biology and ecology. But substantial difficulties will undoubtedly arise in fashioning scientific information into intelligent

LAURIE GRACE (*graphs*); ROBERTO OSTI (*drawings*) policies and in translating these regulations into practice. Managers of fisheries as well as policymakers have for the most part ignored the numerous national and international stock assessments done in past years.

Where regulators have set limits, some fishers have not adhered to them. From 1986 to 1992, distant water fleets fishing on the international part of the Grand Banks off the coast of Canada removed 16 times the quotas for cod, flounder and redfish set by the Northwest Atlantic Fisheries Organization. When Canadian officials seized a Spanish fishing boat near the Grand Banks early this year, they found two sets of logbooks—one recording true operations and one faked for the authorities. They also discovered nets with illegally small mesh and 350 metric tons of juvenile Greenland halibut. None of the fish on board were mature enough to have reproduced. Such selfish disregard for regulations helped to destroy the Grand Banks fishery.

Although the U.N. reports that about 70 percent of the world's edible fish, crustaceans and mollusks are in urgent need of managed conservation, no country can be viewed as generally successful in fisheries management. International cooperation has been even harder to come by. If a country objects to the restrictions of a particular agreement, it just ignores them.

In 1991, for instance, several countries arranged to reduce their catches of swordfish from the Atlantic; Spain and the U.S. complied with the limitations (set at 15 percent less than 1988 levels), but Japan's catch rose 70 percent, Portugal's landings increased by 120 percent and Canada's take nearly tripled. Norway has decided unilaterally to resume hunting minke whales despite an international moratorium. Japan's hunting of minke whales, ostensibly for scientific purposes, supplies meat that is sold for food and maintains a market that supports illegal whaling worldwide.

No Place Like Home

Although much of my work has been focused on overfishing, I have also come to see that marine habitats are being destroyed or degraded in numerous ways. In many temperate regions the larger, bottom-dwelling animals and plants—which feed and shelter fish—have been heavily damaged by trawling, a form of fishing that rakes nets over the shallow continental shelves. In the tropical Indo-Pacific, many people catch fish by stunning them with cyanide—a poison that kills the coral that makes up the fishes' habitat. Some fishers herd their prey into nets by pounding the corals with stones; a boat fishing in this way can destroy up to a square kilometer of living reef every day.

Marine habitats also suffer assaults from aquaculture, agriculture and clear-cutting for logging. In the Pacific Northwest of the U.S. and Canada, intensive deforestation, hydroelectric dams and water diversion have destroyed thousands of miles of salmon habitat. Most species of sturgeon are also becoming endangered in this way throughout the Northern Hemisphere. Profuse sedimentation following deforestation degrades habitats in many parts of the tropics as well. Sediments can kill coral reefs by clogging them, blocking sunlight and preventing settlement of larvae.

In 1989 the tropical marine ecologist Robert Johannes helped to select the tiny Pacific island country of Palau as one of the world's seven undersea wonders—akin to the seven wonders of the ancient world—because of its spectacular and largely unspoiled coral reefs. When I visited him in Palau early this year, I frequently witnessed long plumes of red sediment bleeding off new, poorly made roads into coral lagoons after every heavy rain. Runoff from intact jungle was, in contrast, as clear as the rain itself. Untreated sewage was also flowing into reefs near the capital's harbor. Such nutrient-rich pollution allows algae to grow at unnatural rates, killing corals by altering their delicate balance with internal symbiotic algae. *—C.S.*

Innocent Bystanders

In virtually every kind of fishery, people inadvertently capture forms of marine life that, collectively, are known as "bycatch" or "bykill." In the world's commercial fisheries, one of every four animals taken from the sea is unwanted. Fishers simply discard the remains of these numerous creatures overboard.

Bycatch involves a variety of marine life, such as species without commercial value and young fish too small to sell. In 1990 high-seas drift nets tangled 42 million animals that were not targeted, including diving seabirds and marine mammals. Such massive losses prompted the U.N. to enact a global ban on large-scale drift nets (those longer than 2.5 kilometers)—although Italy, France and Ireland, among other countries, continue to deploy them.

In some coastal areas, fishing nets set near the sea bottom routinely ensnare small dolphins. Losses to fisheries of

KAKU KURITA *Gamma Liaison*

WHALE MEAT sold in Japan includes many different species from all over the world, although the legal catch (taken nominally for scientific purposes) is limited to minke whales.

Economies of Scales

Fishing adds only about 1 percent to the global economy, but on a regional basis it can contribute enormously to human survival. Marine fisheries contribute more to the world's supply of protein than beef, poultry or any other animal source.

Fishing typically does not require land ownership, and because it remains, in general, open to all, it is often the employer of last resort in the developing world—an occupation when there are no other options. Worldwide, about 200 million people depend on fishing for their livelihoods. Within Southeast Asia alone, more than five million people fish full-time. In northern Chile 40 percent of the population lives off the ocean. In Newfoundland most employment came from fishing or servicing that industry—until the collapse of the cod fisheries in the early 1990s left tens of thousands of people out of work.

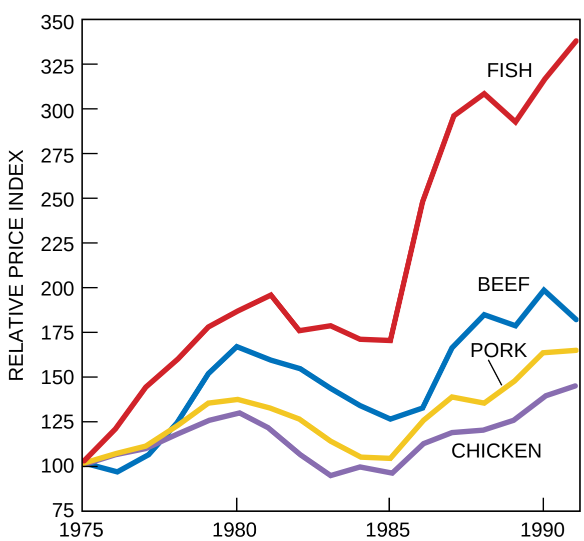
Although debates over the conservation of natural resources are often cast as a conflict between jobs and the environment, the restoration of fish populations would in fact boost employment. Michael P. Sissenwine and Andrew A. Rosenberg of the U.S. National Marine Fisheries Service have estimated that if depleted species were allowed to rebuild to their long-term potential, their sustainable use would add about $8 billion to the U.S. gross domestic product—and provide some 300,000 jobs. If fish populations were restored and properly managed, about 20 million metric tons could be added to the world's annual catch. But reinstatement of ecological balance, fiscal profitability and economic security will require a sub-

DAVID W. HARP

several marine mammals—the baiji of eastern Asia, the Mexican vaquita (the smallest type of dolphin), Hector's dolphins in the New Zealand region and the Mediterranean monk seal—put those species' survival at risk. Seabirds are also killed when they try to eat the bait attached to fishing lines as these are played out from ships. Rosemary Gales, a research scientist at the Parks and Wildlife Service in Hobart, Tasmania, estimates that in the Southern Hemisphere more than 40,000 albatross are hooked and drowned every year after grabbing at squid used as bait on longlines being set for bluefin tuna. This level of mortality endangers six of the 14 species of these majestic wandering seabirds.

In some fisheries, bykill exceeds target catch. In 1992 in the Bering Sea, fishers discarded 16 million red king crabs, keeping only about three million. Trawling for shrimp produces more bykill than any other type of fishing and accounts for more than a third of the global total. Discarded creatures outnumber shrimp taken by anywhere from 125 to 830 percent. In the Gulf of Mexico shrimp fishery 12 million juvenile snappers and 2,800 metric tons of sharks are discarded annually. Worldwide, fishers dispose of about six million sharks every year—half of those caught. And these statistics probably underestimate the magnitude of the waste: much bycatch goes unreported.

There remain, however, some glimmers of hope. The bykill of sea turtles in shrimp trawls had been a constant plague on these creatures in U.S. waters (the National Research Council estimated that up to 55,000 adult turtles died this way every year). But these deaths are being reduced by recently mandated "excluder devices" that shunt the animals out a trap door in the nets.



LAURIE GRACE

SOURCE: Food and Agriculture Organization

EXPORT PRICES for fish have exceeded those for beef, chicken and pork by a substantial margin over the past two decades. To facilitate comparison, the price of each meat is scaled to 100 for 1975.

Perhaps the best-publicized example of bycatch involved up to 400,000 dolphins killed annually by fishers netting Pacific yellowfin tuna. Over three decades since the tuna industry began using huge nets, the eastern spinner dolphin population fell 80 percent, and the numbers of offshore spotted dolphin plummeted by more than 50 percent. These declines led to the use of so-called dolphin-safe methods (begun in 1990) whereby fishers shifted from netting around dolphin schools to netting around logs and other floating objects.

This approach has been highly successful: dolphin kills went down to 4,000 in 1993. Unfortunately, dolphin-safe netting methods are not safe for immature tuna, billfish, turtle or shark.


DAVID W. HARP

stantial reduction in the capacity of the commercial fishing industry so that wild populations can recover.

The necessary reductions in fishing power need not come at the expense of jobs. Governments could increase employment and reduce the pressure on fish populations by directing subsidies away from highly mechanized ships. For each $1 million of investment, industrial-scale fishing operations require only one to five people, whereas small-scale fisheries would employ between 60 and 3,000. Industrial fishing itself threatens tens of millions of fishers working on a small scale by depleting the fish on which they depend for subsistence.

For some fisheries, regulators have purposefully promoted inefficiency as a way to limit excessive catches and maintain the living resource. For example, in the Chesapeake Bay, law requires oyster-dredging boats to be powered by sail (*left*), a restriction on technology that has helped this fishery survive. In New England, regulators outlawed the use of nets pulled between two boats ("pair trawls") because this technique was too effective at catching cod. Managers of the U.S. bluefin-tuna fishery allocate 52 percent of the catch to commercial boats that deploy the least capable gear—handlines or rod and reel—even though the entire allowed amount could easily be extracted with purse-seine nets. In this instance, vessels with the more labor-intensive tackle account for nearly 80 percent of direct employment; those that have large nets provide only 2 percent. Numerous other regulations on sizes and total amount of the catch, as well as allocation and allowable equipment, can be viewed as acknowledgments of the need to curb efficiency in order to achieve wider social and ecological benefits. *—C.S.*

On average, for every 1,000 nets set around dolphin herds, fishers inadvertently capture 500 dolphins, 52 billfish, 10 sea turtles and no sharks. In contrast, typical bycatch from the same number of sets around floating objects includes only two dolphins but also 654 billfish, 102 sea turtles and 13,958 sharks. In addition, many juvenile tuna are caught under floating objects.

One solution to the bycatch from nets would be to fish for tuna with poles and lines, as was practiced commercially in the 1950s. That switch would entail hiring back bigger crews, such as those laid off when the fishery first mechanized its operations.

The recent reductions in the bycatch of dolphins and turtles provide a reminder that although the state of the world's fisheries is precarious, there are also reasons for optimism. Scientific grasp of the problems is still developing, yet sufficient knowledge has been amassed to understand how the difficulties can be rectified. Clearly, one of the most important steps that could be taken to prevent overfishing and excessive bycatch is to remove the subsidies for fisheries that would otherwise be financially incapable of existing off the oceans' wildlife—but are now quite capable of depleting it.

Where fishes have been protected, they have rebounded—along with the social and economic activities they supported. The resurgence of striped bass along the eastern coast of the U.S. is probably the best example in the world of a species that was allowed to recoup through tough management and an intelligent rebuilding plan.

During the past year, the U.N. has been making historic progress in forging new conservation agreements dealing with high-seas fishing. Such measures, along with regional and local efforts to protect the marine environment, should help guide the world toward a sane and sustainable future for life in the oceans.

The Author

CARL SAFINA earned his doctorate in ecology in 1987 at Rutgers University, where he studied natural dynamics among seabirds, prey fishes and predatory fishes. He founded and now directs the National Audubon Society's Living Oceans Program. He also serves as deputy chair of the World Conservation Union's Shark Specialist Group, is a founding member of the Marine Fish Conservation Network and was formerly on the Mid-Atlantic Fisheries Management Council. Safina received the Pew Charitable Trust's Scholars Award in Conservation and the Environment. He has fished commercially and for sport.

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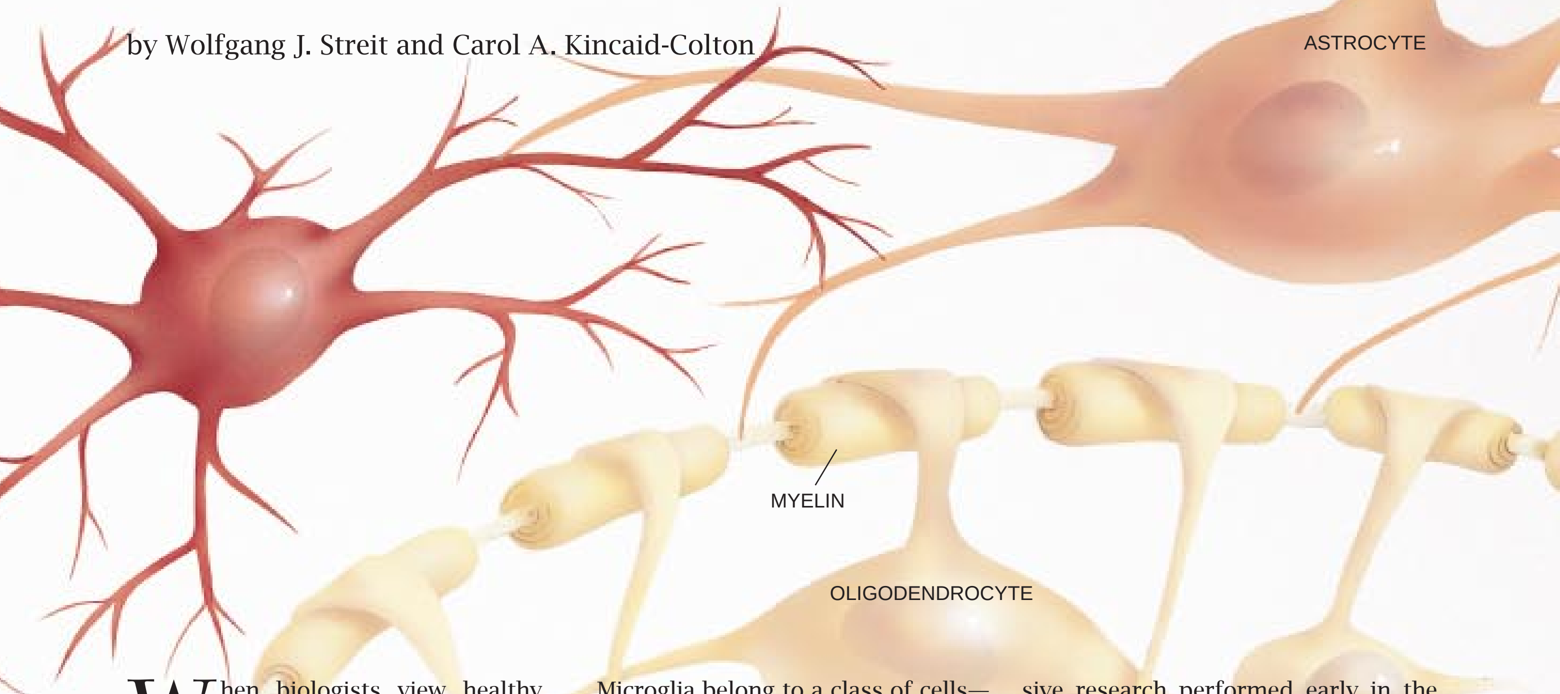
The Brain's Immune System

It consists of cells called microglia that are normally protective but can be surprisingly destructive. The cells may contribute to neurodegenerative diseases and to the dementia of AIDS

by Wolfgang J. Streit and Carol A. Kincaid-Colton



When biologists view healthy tissue from the brain or spinal cord under a microscope, they rarely see white blood cells, the best known sentries of the immune system. And for good reason. Although white blood cells defend against infection and cancer, they also can secrete substances capable of killing irreplaceable nerve cells, or neurons. The body minimizes such destruction by restricting the passage of immune cells out of blood vessels and into the central nervous system; white cells generally escape into the nerve tissue only when blood vessels are damaged by trauma or disease.

Such observations led to the once widespread belief that the central nervous system lacks immune protection. Recently, however, investigators have demonstrated that fascinating cells called microglia form an extensive defensive network there. Most of the time, microglia serve without harming neurons. Yet mounting evidence suggests they occasionally lose their benign character. In fact, there are intimations that the cells can help cause or exacerbate several disabling conditions, among them, stroke, Alzheimer's disease, multiple sclerosis and other neurodegenerative disorders.

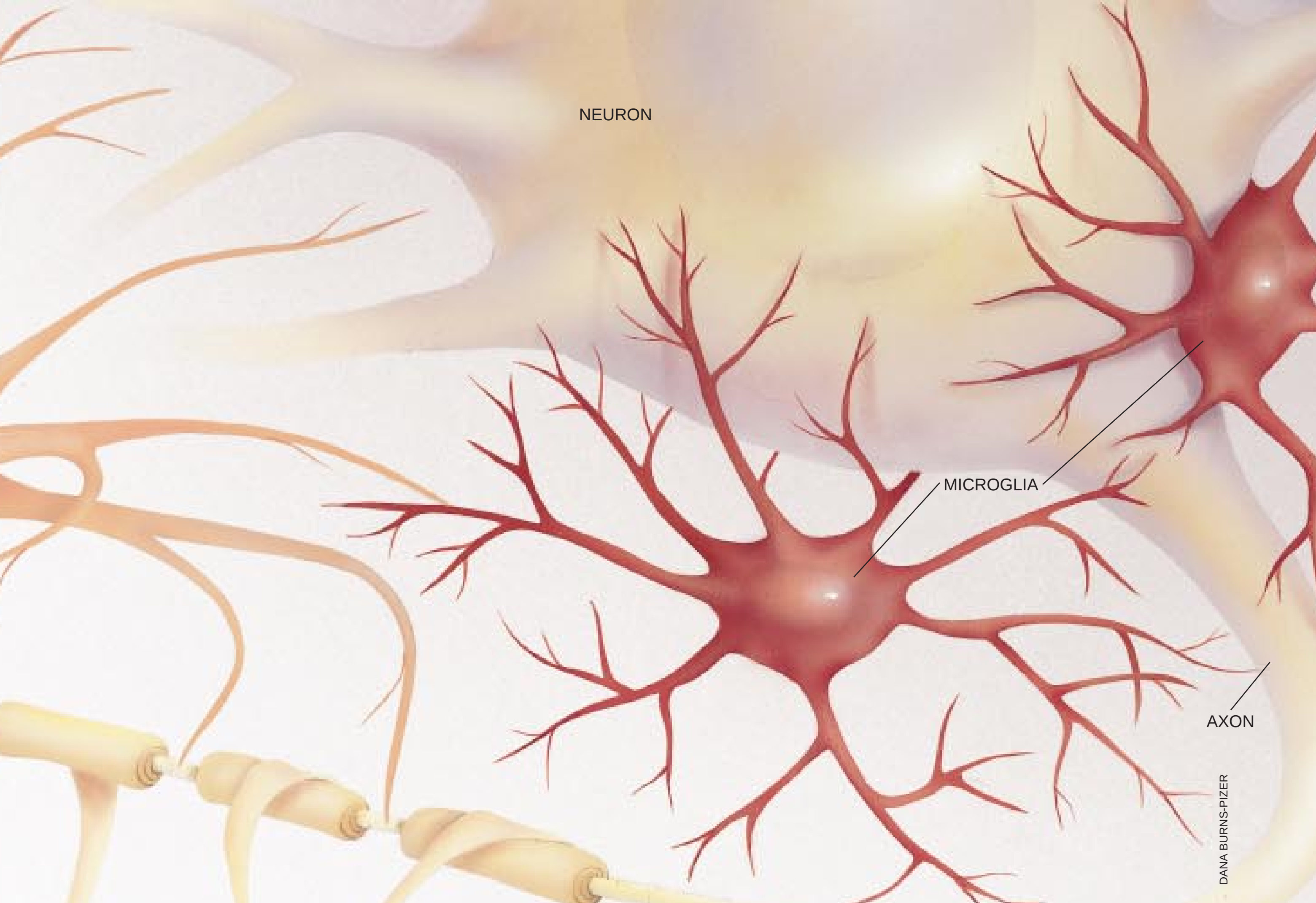
Microglia belong to a class of cells—the glia (from Greek, meaning "glue")—that was first recognized in the 1800s. Initially, biologists mistakenly thought of the glia as a single unit that served only as the uninteresting putty between neurons in the brain and spinal cord. But by the 1920s microscopists had identified three kinds of glial cell: astrocytes, oligodendrocytes and microglia. By the 1970s it was evident the first two types, at least, had profound responsibilities.

For instance, the star-shaped astrocyte, which has the largest cell body, had been found to sop up extra neurotransmitter molecules around neurons, thereby protecting nerve cells from receiving too much stimulation [see "Astrocytes," by Harold K. Kimelberg and Michael D. Norenberg; SCIENTIFIC AMERICAN, April 1989]. And the oligodendrocyte, the next largest glial cell, had been shown to produce the myelin sheath that insulates axons (long projections that extend from neuronal cell bodies and carry electrical signals). Some researchers suspected the more diminutive, microglial cell also had a special—immunologic—role, but until the 1980s, the tools needed to validate this speculation were lacking.

The idea grew primarily out of intensive research performed early in the 20th century by Pio del Río-Hortega, a former student of the famous Spanish neuroanatomist Santiago Ramon y Cajal. In 1919 del Río-Hortega developed a stain, based on silver carbonate, that made it possible to distinguish microglia from neurons, astrocytes and oligodendrocytes in thin slices of the mammalian brain. He then spent more than a decade learning all he could about these odd cells.

He determined that microglia first appear in the developing brain as amorphous bodies. Eventually, though, they differentiate into extensively branched, or ramified, forms that populate every region of the brain and touch neurons and astrocytes (but not one another). He also saw that the cells responded dramatically when the brain was injured severely. For instance, he noted that in reaction to a stab wound, the ramified cells retracted their delicate branches, or processes, and seemed to return to their rounder, immature conformation.

Del Río-Hortega recognized that microglia in this last state resembled macrophages, a form of white blood cell found in tissues outside the brain. He knew as well that when macrophages sensed that tissues were hurt or in-



MICROGLIAL CELLS (*red*) in their resting state touch the cells around them and monitor their health, ready to respond quickly to injury or disease. Microglia are as numerous as neurons in the central nervous system and are dispersed throughout it.

fected, they usually migrated to the affected areas, proliferated and became highly phagocytic—that is, they became garbage collectors, capable of ingesting and degrading microbes, dying cells and other debris. By 1932 he was able to postulate that the rounding of mature microglia reflected a metamorphosis to a phagocytic state. In other words, he thought microglia functioned as the macrophages of the central nervous system.

Support for an Immune Role

Although del Río-Hortega's ideas made sense, few investigators followed up on them during the next 50 years, largely because his staining method proved unreliable. Without a dependable way of distinguishing microglia from other cells, no one could learn much about their functions. This barrier came down only in the 1980s, after V. Hugh Perry and his colleagues at the University of Oxford began screening monoclonal antibodies for their ability to bind to microglia. Monoclonal antibodies each recognize a highly specific protein target, or antigen. Perry's group knew that if such antibodies found their targets on microglia but not on other cells of the central nervous system, the antibodies could be exploited as a new kind of "stain." The microglia would stand out from other cells if the workers simply linked the bound antibodies to some detectable label, such as a fluorescent compound.

In 1985 Perry's team demonstrated that various monoclonals produced by other groups could indeed pinpoint microglia in brain tissue. Soon, even more antibodies able to serve this purpose became available. Their introduction, together with the advent in the mid-1980s of methods for maintaining pure populations of microglia in culture dishes, finally made it possible to examine the activities of the cells in detail.

The antibodies did more than highlight microglia; they provided strong circumstantial support for the assertion that those cells could operate as immune defenders in the brain and spinal cord. Notably, various antibodies that recognize proteins occurring exclusively on cells of the immune system were able to find their targets on microglia. Further, certain antibodies demonstrated that the cells probably behaved like macrophages.

Macrophages and some of their kin are antigen presenters: they chop up proteins made by invading microbes and display the pieces in molecular showcases known as class II major histocompatibility antigens. Such displays help to induce additional immune cells to launch a full-fledged attack against an invader. Between 1985 and 1989, researchers from around the world demonstrated that monoclonal antibodies able to latch on to class II major histocompatibility antigens often bound well to microglia. This behavior meant that, contrary to prevailing views, microglia produced class II major histocompatibility antigens; hence, they were probably antigen-presenting cells themselves.

The antibody results dovetailed with work by Georg W. Kreutzberg and his colleagues at the Max Planck Institute for Psychiatry in Martinsried. The German group, one of the few with a long-standing interest in microglial function,

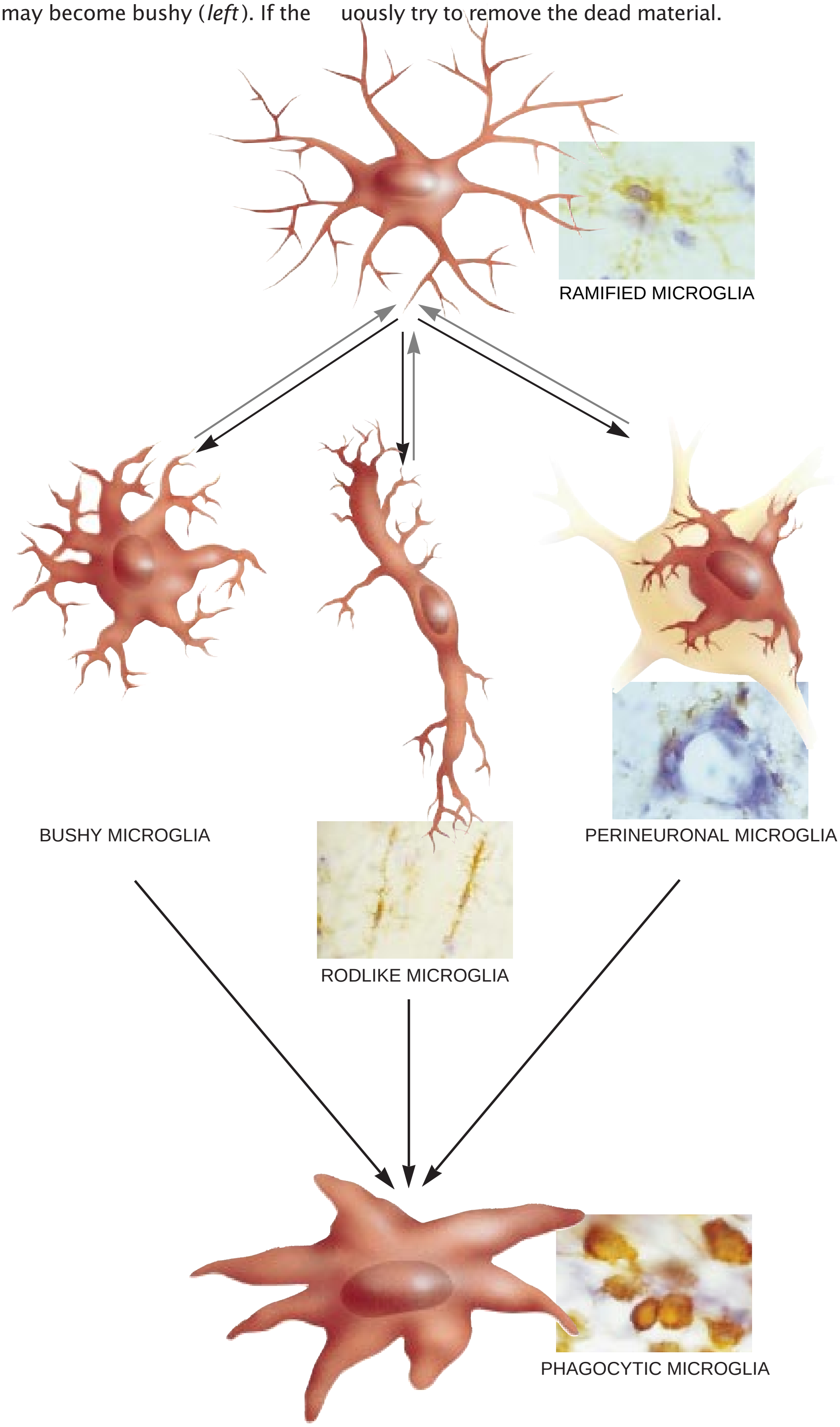
The Many Guises of Microglia

Microglia (*golden brown in micrographs*) are often found in their resting, highly ramified state (*top*). But when they sense a neuron is in trouble, they begin to retract their branches. They also migrate to the site of danger and take on a new conformation (*middle*). The precise shape usually depends on the architecture of the brain region in which the microglia find themselves. If the cells have enough space, they may become bushy (*left*). If the cells have to fit in among long, thin neuronal projections, they tend to become rodlike (*center*). Other times, they prefer to conform to the surface of injured neurons, as is the case when motor neurons are damaged (*right*). If disordered neurons recover, microglia may revert to their resting state (*gray arrows*). If neurons die, however, microglia progress to a phagocytic state (*bottom*) and assiduously try to remove the dead material.

State 1:
Resting
Ramified microglia constantly monitor the health of cells around them.

State 2:
Newly Activated
Microglia change shape when they first detect a disturbance in their microenvironment, such as injury to a neuron.

State 3:
Phagocytic
Cells in this state are reacting to the death of other cells; they change shape again and attempt to degrade the dead matter.



DANA BURNS-PIZER (*drawings*); WOLFGANG J. STREIT (*micrographs*) tested the ability of microglia in the rodent brain to behave like macrophages when confronted with severely injured neurons. At the same time, the workers looked into the contention of some investigators that microglia did not live in the central nervous system at all, that they were nothing more than monocytes that flooded into the brain or spinal cord when blood vessels in the nerve tissue were damaged. This last assertion had been difficult to refute because then, as now, the antibodies and stains that recognized microglia also recognized macrophages derived from blood-borne monocytes.

Kreutzberg and his colleagues applied a simple method to resolve both issues. As a start, they focused on neurons whose cell bodies were located in the brain but whose axons terminated at muscles outside the brain. They injected a toxin into a site near the ends of the axons and allowed the poison to diffuse through—and kill—the neurons without affecting any blood vessels. This maneuver ensured that any macrophagelike cells responding to the damage would be residents of the brain tissue, not interlopers from the blood. Finally, they examined the brain region containing the remains of the affected nerve cells. Analyses of tissue from many animals revealed that microglia do in fact migrate to dead neurons, proliferate and remove dead cells. In short, microglia are, indeed, the brain's own kind of macrophages.

Experiments on pure populations of microglia in culture have now helped convince even the greatest skeptics that microglia are the immune warriors del Río-Hortega thought them to be. These studies have confirmed that the cells are extremely mobile—a property essential for cells that supposedly move easily to injured areas within the brain. The work has also established that microglia can be induced to produce a wide array of chemicals made by macrophages in other tissues.

How Normal Microglia Behave

It appears, then, that modern research has finally justified del Río-Hortega's belief in the immunologic properties of microglia. The studies have also clarified the operation of the cells in the healthy, as well as the diseased, central nervous system.

Microglia are critical to proper development of the embryo. They may secrete growth factors important to the formation of the central nervous system, but another role has been identified more definitively. The growing fetus generates many more neurons and glial cells than it needs. Over time, the unused cells die, and young microglia, still in their initial, nonramified conformation, remove the dead matter.

As the sculpting of the central nervous system is completed, the need to degrade large numbers of cells disappears, and microglia differentiate into their extensively ramified, resting state. This conformation enables the cells to keep close tabs on the health of many cells in their vicinity. No one yet knows much about the other functions of resting microglia, but indirect evidence implies the cells release low levels of growth factors, which at this stage would help mature neurons and glia survive. Those substances may include fibroblast growth factor and nerve growth factor—two proteins that investigators have prodded cultured microglia to secrete.

Investigations of cultured microglia and of diseased brains suggest the cells sometimes damage the neurons they are meant to protect.

What is more certain is that resting microglia respond almost instantly (within minutes) to disturbances in their microenvironment and prepare to surround damaged neurons or other cells. The outward signs of such activation are retraction of their branches, other changes in shape, production of proteins not found in the resting state, and stepped-up synthesis of proteins formerly made only in small amounts. For example, expression of major histocompatibility antigens is enhanced markedly. We do not yet know whether the cells release higher amounts of growth factors, but they may well do so in an attempt to repair injured neurons.

The conformation of the newly activated microglia seems to depend a great deal on the architecture of the region in which the cells live. If the area is filled mainly with axons, the cells tend to become long and thin, in order to fit between the cables. If there is room to maneuver, as is the case in much of the brain, the cells often become bushy.

Activated cells do not automatically become phagocytic; they can revert to the resting state if the injury they have detected is mild or reversible. If the injury is severe and kills neurons, however, microglia begin to function as full-fledged, phagocytic macrophages. The ultimate fate of the phagocytes is unclear, but investigations of cultured microglia and of diseased brains suggest the cells sometimes go on to damage the neurons they are meant to protect.

Suspicion that microglia might contribute to neurologic disorders was aroused in part by the discovery, mentioned earlier, that microglia can release many of the same chemicals emitted by macrophages outside the central nervous system. Some of those substances are dangerous to cells and, if made in excessive amounts, could surely kill neurons. For example, one of us (Kincaid-Colton) and her colleagues at Georgetown University have found that when activated microglia in culture are exposed to particular bacterial components, the cells, like other macrophages, generate extremely destructive molecules known as reactive oxygen species. The compounds go by such names as the superoxide anion, the hydroxyl radical (one of the most toxic compounds in the body) and hydrogen peroxide. Along with killing microbes, they can damage membranes, proteins and DNA in neurons and other cells.

Additional, potentially destructive compounds manufactured by strongly activated microglia and other macrophages include enzymes called proteases that digest proteins and can chew holes in cell membranes. They further encompass at least two versatile messenger molecules, or cytokines, that can increase inflammation. That is, these cytokines—among them, interleukin-1 and tumor necrosis factor—often help to recruit other components of the immune system to a site of injury [see "Tumor Necrosis Factor," by Lloyd J. Old; SCIENTIFIC AMERICAN, May 1988]. Inflammation can be important for eradicating infections and incipient cancers, but it can have serious "bystander" effects by which uninfected cells are harmed. Under some circumstances, the cytokines can also damage neurons directly, and tumor necrosis factor can kill oligodendrocytes.

That microglia can synthesize all these substances in culture is not proof that the cells can disrupt the living brain. Indeed, the central nervous system apparently holds microglia on a tight leash, forcing them to keep worrisome secretions to a minimum, even when responding to injury and disease; otherwise no one would survive having microglia everywhere in the brain. Nevertheless, research into a number of neurological disorders suggests that in some patients the leash is loosened, either because a defect exists in the microglia themselves or because some other disease process undermines the normal controls on the behavior of the cells.

Microglia and Disease

Excessive microglial activity has certainly been implicated in the dementia that sometimes arises in patients suffering from AIDS. The human immunodeficiency virus, which causes the disease, does not attack neurons, but it does infect microglia. Such invasion has been shown to spur microglia to make elevated levels of inflammatory cytokines and other molecules that are toxic to neurons.

Disturbed regulation of microglia could play a part in Alzheimer's disease as well. The brains of Alzheimer's patients are marked by large numbers of senile plaques: abnormal regions in which deposits of a protein fragment known as beta amyloid mingle with microglia, astrocytes and the endings of injured neurons. Such plaques are thought to contribute to the neuronal death that underlies the deterioration of the mind. Exactly how they hurt nerve cells is unclear and a matter of heated argument. Many investigators suspect beta amyloid is the agent of trouble. We think beta amyloid might do its mischief by affecting microglia. It is now evident, for instance, that the levels of interleukin-1 and other cytokines known to be made at times by microglia are elevated in senile plaques. Such elevation implies that something—perhaps beta amyloid—pushes the microglia in plaques into a highly active state. In that condition, the cells would presumably also release oxygenated species and protein-degrading enzymes and could thereby disrupt neurons.

Other findings suggest that microglia might even contribute to the formation of plaques. It seems microglia respond to injury in the central nervous system by making one form of the amyloid precursor protein—the molecule that, when cleaved in a particular way, yields beta amyloid. Moreover, studies of cells in culture have shown that interleukin-1 causes various other cells, possibly including neurons, to produce amyloid precursor molecules. Finally, the reactive oxygen species made by activated microglia promote the aggregation of amyloid fragments.

It is easy to imagine that a vicious cycle could ensue after some trigger pushed microglia into a hyperactive state. If the cells made the amyloid precursor protein, their proteases could well cleave the molecule to produce beta amyloid. At the same time, interleukin-1 might induce other cells to make amyloid as well. Then reactive oxygen species could cause the amyloid released by microglia or neighboring cells to clump together. Such clustering, in turn, could lead to activation of additional microglia, production of more amyloid, formation of more plaques, and so on.

People born with Down's syndrome acquire elevated numbers of senile plaques in their brains, albeit earlier than do patients with Alzheimer's disease. Because the brain changes are so alike in the two conditions, Kincaid-Colton and her colleagues have begun exploring the possibility that microglia damage brain tissue in these patients. They have uncovered some support for the concept in studies of mice bearing a genetic defect analogous to that responsible for Down's syndrome in humans. Microglia in such fetuses are unusually reactive and abundant; additionally, the microglia in the "Down's" mice release increased amounts of reactive oxygen species, interleukin-1 and other cytokines that might affect nerve tissue adversely.

Stroke victims, too, might lose neurons to overzealous microglia, according to experiments performed in rats by one of us (Streit) and his co-workers at the University of Florida. When a major blood vessel feeding the forebrain is shut down, the brain tissue dependent on the vessel dies quickly. Over the next several days, particularly vulnerable neurons in a part of the surrounding area—the so-called CA1 region of the hippocampus—die as well. Interestingly, Streit's group has discovered that microglia are activated within minutes after onset of such a stroke, long before the hippocampal neurons die. (This activation is made evident by changes in cell shape and by enhanced stainability.) It is conceivable that the microglia, sensing danger, attempt to protect the

The Controversial Origin of Microglia

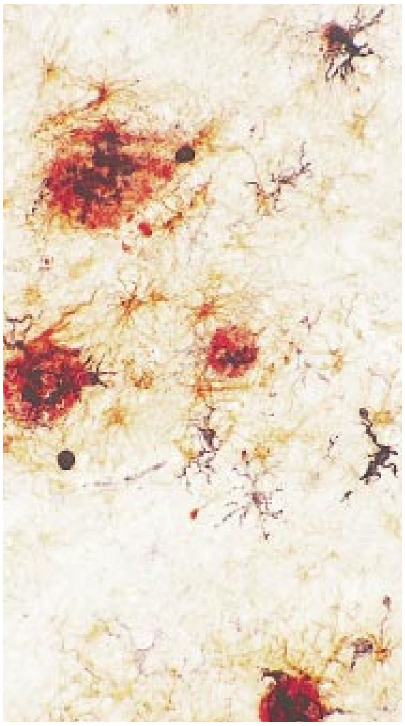
In 1932 Pio del Río-Hortega, the pioneer of microglial research, ignited a controversy that preoccupied most investigators interested in microglia for more than 50 years. In the same paper in which he proposed that microglia were the immune defenders and garbage collectors of the central nervous system, he suggested that the cells did not originate in the same embryonic tissue—the ectoderm—that gives rise to nerve cells. He concluded that microglia derived instead from the mesoderm, the layer of embryonic germ cells that forms the bone marrow, blood, blood vessels and lymphatics. He could not decide, however, on the precise mesodermal lineage of the cells. Did microglia descend from white blood cells called monocytes and enter the brain and spinal cord from the fetal blood circulation? Or did they descend from noncirculating cousins of monocytes and migrate to the central nervous system directly, without passing through the bloodstream?

For a time, the monocytic origin was favored, and the majority opinion held that the precursors of microglia were monocytes attracted to the developing nervous system by neurons that died during the sculpting of the brain and spinal cord. But new findings contradict that view. For instance, Jutta Schnitzer of the Max Delbrück Center for Molecular Medicine in Berlin and Ken W. S. Ashwell of the University of Sydney in Australia have shown that the retina of the eye, a part of the central nervous system, is "seeded" with microglia quite early in development, well before neurons begin to die. In fact, the weight of evidence now favors the "cousin" hypothesis.

The photograph at the left was taken in 1924 by Wilder G. Penfield, before Penfield gained renown as a neurosurgeon. —*W.S. and C.K.-C.*

Courtesy of William Feindel *The Penfield Archive*

Pio del Río-Hortega



HARUHIKO AKIYAMA *Tokyo Institute of Psychiatry*

Microglial Products: Double-Edged Swords

Chemical	Beneficial Effects	Harmful Effects
Amyloid precursor protein	Unknown	When cleaved, may give rise to beta amyloid
Cytokines (messenger molecules of the immune system)	Recruit other cells to sites of infection; some promote the survival and repair of astrocytes; some combat tumors	Can harm healthy cells and induce other immune cells to secrete cell-damaging substances
Growth factors	Promote the survival and repair of neurons	Unknown
Protein-cleaving enzymes	Help to degrade microbes and damaged cells	Can degrade membranes of healthy cells; may contribute to formation of beta amyloid
Reactive oxygen species	Can damage membranes, proteins and DNA in microbes	Can damage healthy cells; can promote the aggregation of beta amyloid

SENILE PLAQUES (*round regions in micrograph*) are thought to cause the neuronal damage underlying memory impairment in patients with Alzheimer's disease and Down's syndrome. At their core, the plaques consist mainly of protein fragments called beta amyloid (*red*), known to be harmful to neurons, and microglia (*deep purple*). The plaques also include other glial cells called astrocytes (*golden brown "stars"*) as well as damaged axons and dendrites (*not visible*). New evidence suggests microglia promote plaque formation. It is also possible that activated microglia disrupt neurons directly, by secreting chemicals that can be toxic to cells. Some of the chemicals made by microglia are listed in the table.

neurons, perhaps by initiating or increasing secretion of growth factors potentially able to repair injuries. It is equally likely, however, that the altered chemistry in the region eventually releases the normal brakes on microglial behavior, propelling the cells into a state in which they become dangerous.

Preliminary evidence points as well to microglia as possible participants in multiple sclerosis, Parkinson's disease and amyotrophic lateral sclerosis (Lou Gehrig's disease). Microglia also change with age, as is evident in the increased display of major histocompatibility antigens. This display could be a sign that the normal inhibitions on progression to the dangerous, highly active state relax with time. Easing of these controls would undoubtedly promote neuronal destruction and could thus contribute to memory declines and senility.

The Good News

A good deal of research into the link between microglia and disorders of the brain casts microglia as villains, but the data do have some encouraging implications. If microglia are indeed central players in neurological diseases, it might be possible to ameliorate these conditions by specifically inhibiting microglia or by blocking the activity of their products. Drug therapies with these aims are already beginning to be tested in patients with Alzheimer's disease. For example, small trials are under way to examine the safety and effectiveness of an anti-inflammatory agent capable of quieting activated microglia. Conversely, scientists might be able to take advantage of the cells' protective aspects and boost microglial production of growth factors.

Ten years ago some investigators denied that microglia even existed. Five years ago most physicians would have laughed if anyone hinted that microglia could be major participants in Alzheimer's disease and other degenerative conditions of the brain. Today the skepticism is evaporating. Indeed, many workers are confident that study of microglia will eventually yield new therapies for some of the most heartbreaking diseases afflicting humankind.

The Authors

WOLFGANG J. STREIT and CAROL A. KINCAID-COLTON conduct separate research programs but have collaborated on developing a symposium on microglia. Streit, who earned his Ph.D. in experimental neuropathology at the Medical University of South Carolina, is associate professor of neuroscience at the University of Florida Brain Institute. He joined the university after working as a staff scientist at the Max Planck Institute for Psychiatry in Martinsried, Germany. Kincaid-Colton is associate professor of physiology and biophysics at the Georgetown University School of Medicine. She holds a doctorate in physiology from Rutgers University and was on staff at the Laboratory of Biophysics at the National Institutes of Health before taking her post at Georgetown.

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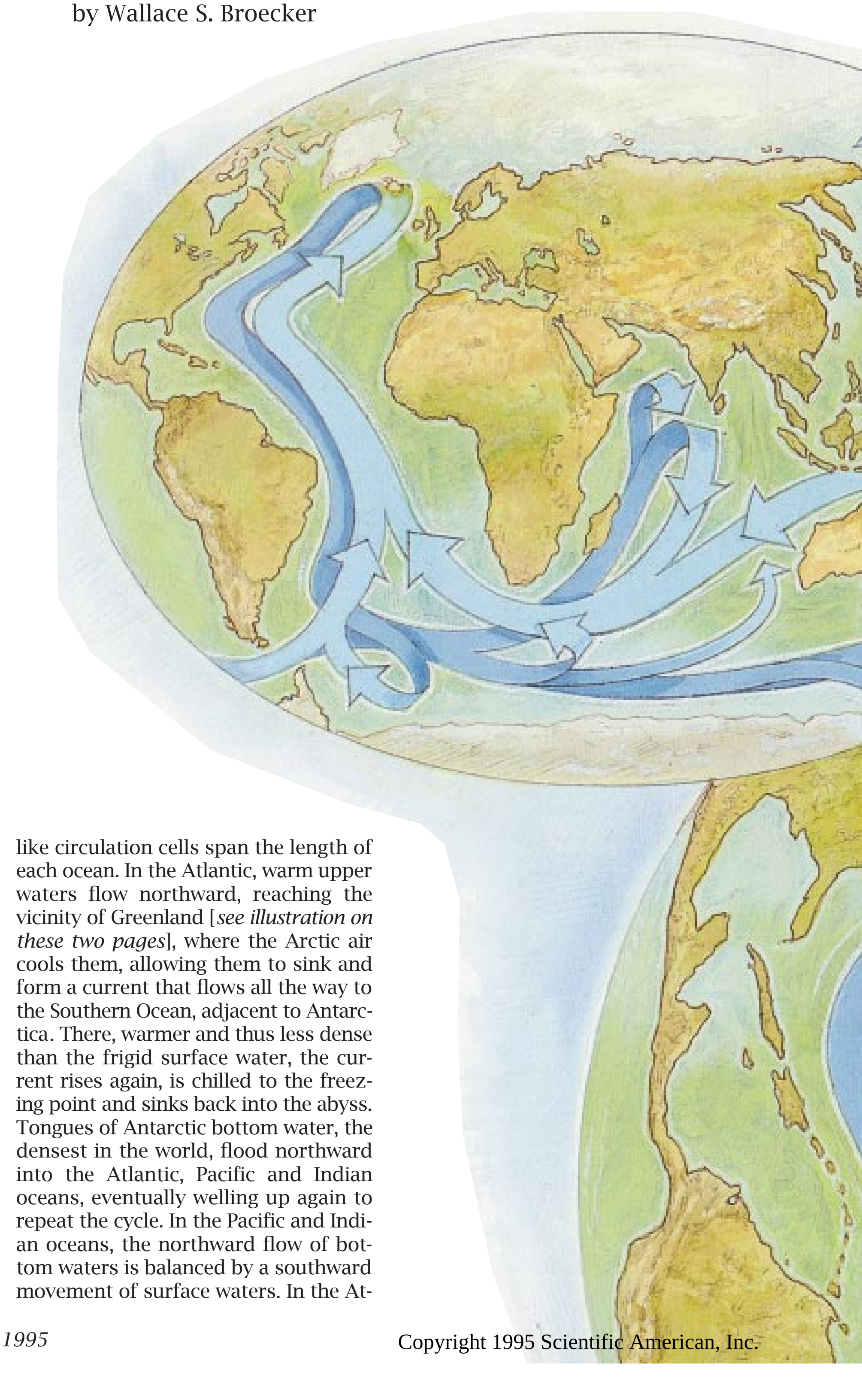
Chaotic Climate

Global temperatures have been known to change substantially in only a decade or two. Could another jump be in the offing?

by Wallace S. Broecker



The past 10,000 years are anomalous in the history of our planet. This period, during which civilization developed, was marked by weather more consistent and equable than any similar time span of the past 100 millennia. Cores drilled through several parts of the Greenland ice cap show a series of cold snaps and warm spells—each lasting 1,000 years or more—that raised or lowered the average winter temperature in northern Europe by as much as 10 degrees Celsius over the course of as little as a decade. The signs of these sudden changes can be read in the records of atmospheric dust, methane content and precipitation preserved in the annual ice layers.

The last millennium-long cold period, known as the Younger Dryas (after a tundra flower whose habitat expanded significantly), ended about 11,000 years ago. Its marks can be found in North Atlantic marine sediments, Scandinavian and Icelandic glacial moraines, and northern European and maritime Canadian lakes and bogs. New England also cooled significantly.

Further evidence is accumulating that the Younger Dryas's effects were global in scope. The postglacial warming of Antarctica's polar plateau came to a halt for 1,000 years; at the same time, New Zealand's mountain glaciers made a major advance, and the proportions of different species in the plankton population of the South China Sea changed markedly. The atmosphere's methane content dropped by 30 percent. Only pollen records from parts of the U.S. fail to show the period's impact.

The Great Conveyor

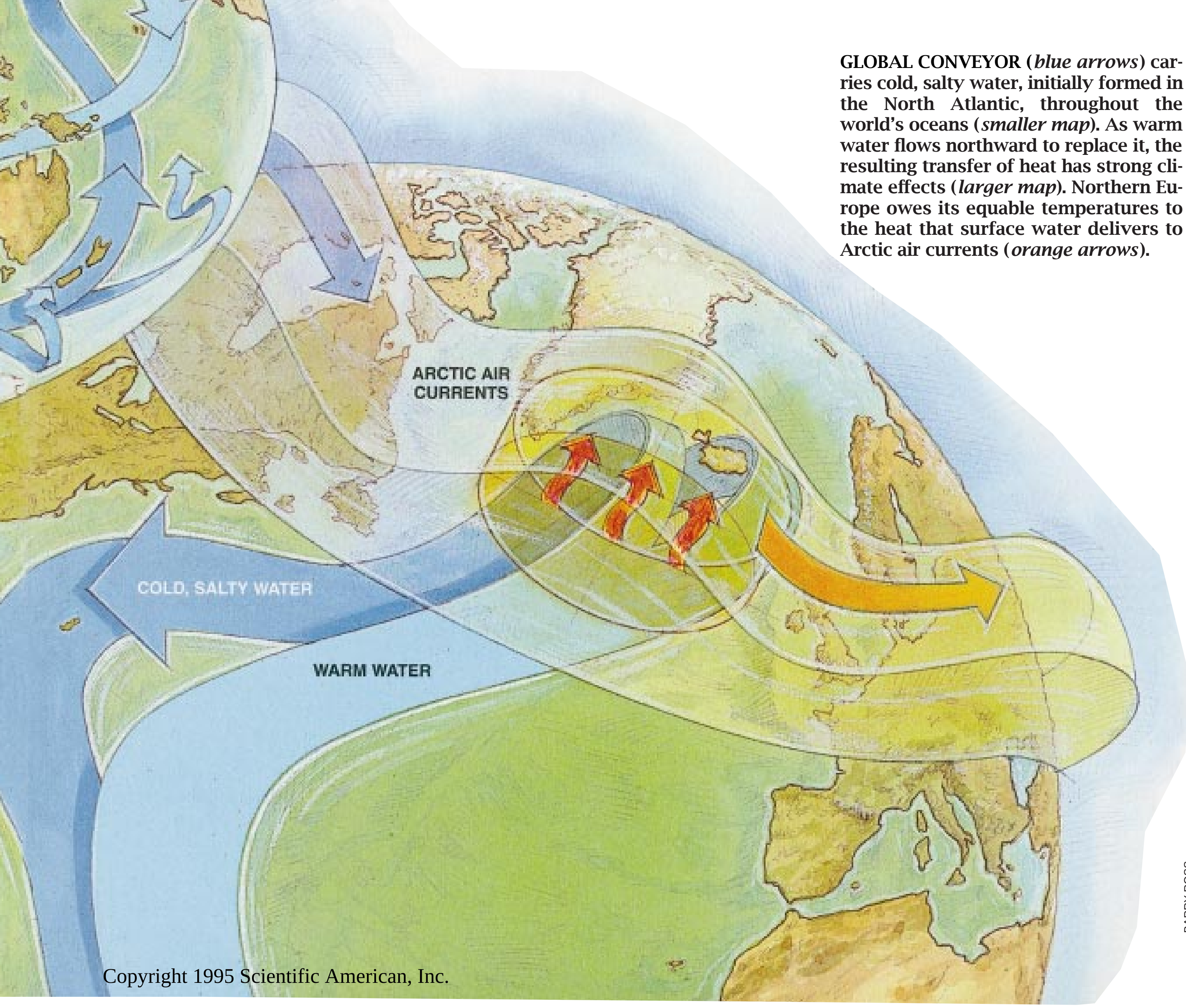
What lies behind this turbulent history, and could it repeat itself? Although no one knows for sure, there are some very powerful clues. A variety of models suggest that the circulation of heat and salt through the world's oceans can change suddenly, with drastic effects on the global climate. Giant, conveyor-like circulation cells span the length of each ocean. In the Atlantic, warm upper waters flow northward, reaching the vicinity of Greenland [*see illustration on these two pages*], where the Arctic air cools them, allowing them to sink and form a current that flows all the way to the Southern Ocean, adjacent to Antarctica. There, warmer and thus less dense than the frigid surface water, the current rises again, is chilled to the freezing point and sinks back into the abyss. Tongues of Antarctic bottom water, the densest in the world, flood northward into the Atlantic, Pacific and Indian oceans, eventually welling up again to repeat the cycle. In the Pacific and Indian oceans, the northward flow of bottom waters is balanced by a southward movement of surface waters. In the Atlantic, this northward counterflow is rapidly entrained into the much stronger southward current of the conveyor.

This so-called deep water forms in the North Atlantic—but not the Pacific—because surface waters in the Atlantic are several percent saltier than those in the Pacific. The locations of large mountain ranges in the Americas, Europe and Africa lead to weather patterns that cause the air leaving the Atlantic basin to be wetter than when it enters; the resulting net loss of water from the surface leads to an excess of salt. Salt makes the upper layers of water denser; as a result, they descend in the North Atlantic and begin a global circulation pattern that effectively redistributes the salt throughout the world's oceans.

The Atlantic's conveyor circulation, which has a flow equal to that of 100 Amazon Rivers, results in an enormous northward transport of heat. The water flowing north is, on average, eight degrees warmer than the cold water flowing south. The transfer of this heat to Arctic air masses over the North Atlantic accounts for the anomalously warm climate enjoyed by Europe.

This pattern, however, is vulnerable to disruption by injections of excess freshwater into the North Atlantic. Precipitation and continental runoff exceed evaporation at high latitudes, and so the salinity of North Atlantic surface waters depends on the rapidity with which the conveyor sweeps away the excess freshwater delivered by rain and rivers. Any shutdown of the conveyor system would tend to perpetuate itself. Were the conveyor to stop, winter temperatures in the North Atlantic and its surrounding lands would abruptly fall by five or more degrees. Dublin would acquire the climate of Spitsbergen, almost 1,000 kilometers north of the Arctic Circle. Furthermore, the shift would occur in 10 years or less. (Ice cores and other records suggest that the average temperature throughout the North Atlantic basin dropped about seven degrees during ancient cold snaps.)

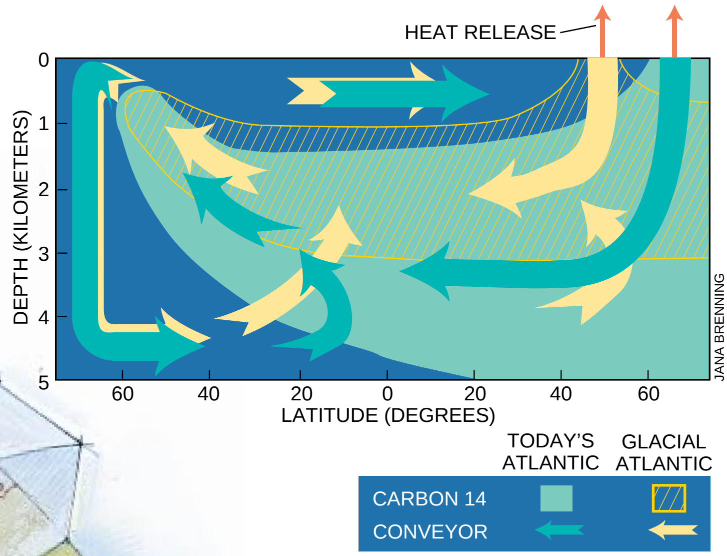
Ocean modelers have shown that the oceanic conveyor would come back to life, but only after hundreds or thousands of years had passed. Heat mixed down from warm parts of the sea surface and diffusion of salt from the bottom toward the surface would eventually reduce the density of the stagnated deep water, to the point where surface waters from one or the other polar region could once again penetrate into the abyss, reestablishing the circulation of heat and salt. The pattern of this rejuvenated circulation need not be the

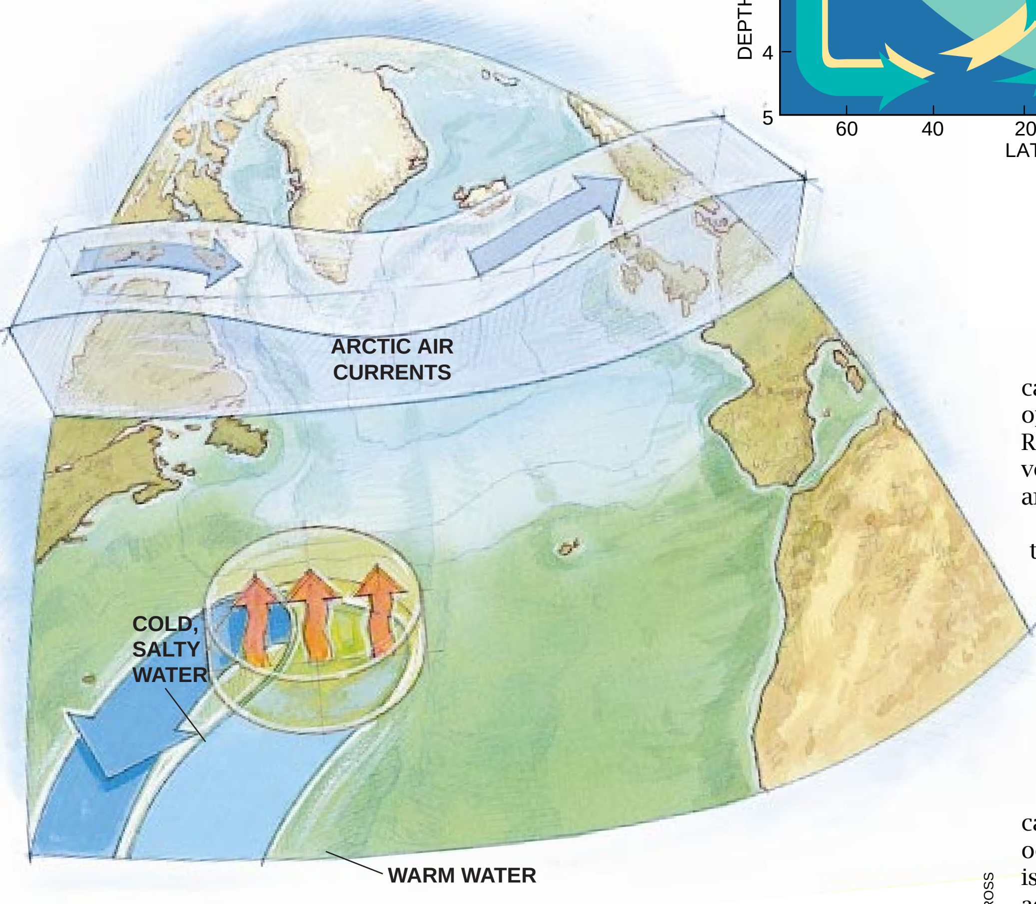


GLOBAL CONVEYOR (*blue arrows*) carries cold, salty water, initially formed in the North Atlantic, throughout the world's oceans (*smaller map*). As warm water flows northward to replace it, the resulting transfer of heat has strong climate effects (*larger map*). Northern Europe owes its equable temperatures to the heat that surface water delivers to Arctic air currents (*orange arrows*).

BARRY ROSS

ALTERNATE CONVEYOR proposed by Stefan Rahmstorf of the University of Kiel (*below*) would operate at the latitude of southern Europe and so would not transfer heat effectively to North Atlantic winds. Temperatures in Europe during glacial times, when this conveyor was running, averaged as much as 10 degrees lower than today's. Shallow circulation characterized this alternate conveyor (*right*).





same as that which existed before the shutdown, however. Instead it would depend on the details of the freshwater runoff patterns for each polar region.

More recently, modeling work by Stefan Rahmstorf of the University of Kiel has suggested that the shutdown of the primary conveyor system may be followed by the formation of an alternate circulation pattern that operates at a shallower depth, with deep water forming north of Bermuda instead of near Greenland. This shift renders the heat released far less effective in warming northern Europe. Rahmstorf's shallow conveyor can be knocked out of action by a pulse of freshwater, just like the primary one, but his model predicts a spontaneous reactivation after only a few decades. It is still not clear, however, how the ocean circulation might switch back from the shallow conveyor to the deeper one that operates today.

Two properties of Rahmstorf's model catch the eye of paleoclimatologists. First, the shallow draft of the alternate conveyor reproduces the ice age distribution of cadmium and carbon isotopes captured in the shells of tiny bottom-dwelling creatures called benthic foraminifera. Today the waters of the North Atlantic conveyor are poor in cadmium and rich in carbon 13, whereas deep waters in the rest of the ocean are rich in cadmium and poor in carbon 13.

This contrast reflects the fact that respiration by aquatic organisms depletes carbon 13 and enhances the concentration of cadmium (and other constituents whose history is not recorded in benthic shells). During cold episodes, cadmium levels dropped in the mid-depth Atlantic waters and rose dramatically in the bottom waters; the ratio of carbon 13 to carbon 12 displayed the opposite pattern—consistent with Rahmstorf's conclusion that the conveyor operated at a shallower depth and bypassed the bottommost water.

Second, the alternate conveyor maintains the movement of radiocarbon into the deep sea. If this transfer had ceased, radiochemical-dating methods based on carbon 14 decay would show huge distortions; in fact, the radiocarbon clock has been calibrated by other means and found to be imperfect but still basically valid.

Only about a quarter of the world's carbon currently resides in the upper ocean and atmosphere. The remainder is in the abyss. The distribution of radioactive carbon 14, which is formed in the atmosphere by cosmic rays, depends on the rate of oceanic circulation. In today's ocean, most of the radiocarbon reaching the deep sea does so via the Atlantic's conveyor circulation. During their traverse up the Atlantic, waters in the conveyor's warm upper limb are recharged with radiocarbon by absorption from the air. The conveyor then carries this radiocarbon down to the ocean depths. Although the deep water resurfaces briefly in the region around the Antarctic continent, little radiocarbon finds its way into solution there.

This state of affairs implies that even a slowdown of the conveyor would have a significant effect on the abundance of carbon 14 in both the atmosphere and the ocean. The ratio of carbon 14 to stable carbon 12 in the deep ocean is at present approximately 12 percent lower than the average for the upper ocean and the atmosphere because of the radioactive decay that takes place while the deep water is circulating. Meanwhile cosmic rays replenish 1 percent of the world's radiocarbon inventory every 82 years. As a result, if exchanges between the upper and deep ocean were to cease, the carbon 14 ratio in the upper ocean and the atmosphere would rise at the rate of 5 percent every century because carbon 14 was being added but not swept down into the deep sea. After a millennium of isolation, the atmosphere's carbon 14 ratio would rise by a third of its original value.

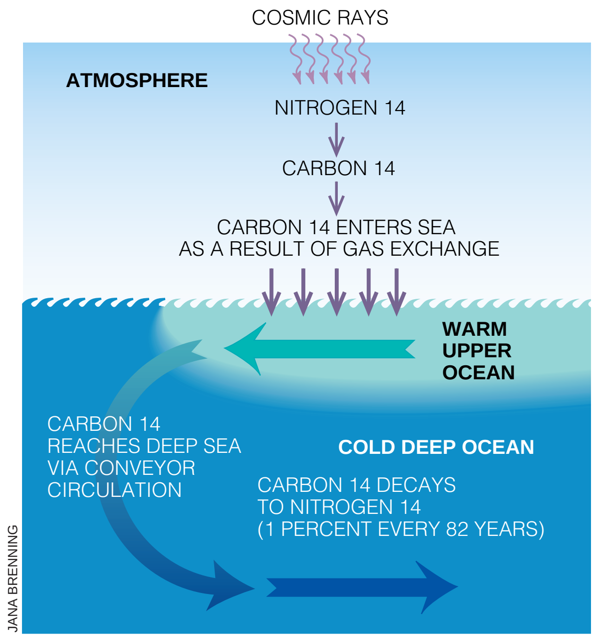
Such an occurrence would lead to a radical disturbance of the radiocarbon-dating record. Paleontologists determine the age of organic materials by measuring their residual carbon 14 content. The amount incorporated into a plant's structure while it is alive depends on the proportion of radiocarbon in the atmosphere (or ocean) at the time; the less carbon 14 that remains, the older a specimen must be. Plants that grew during a conveyor shutdown would incorporate the extra carbon 14 and appear younger than their true age. Then, when the conveyor started up again and brought atmospheric carbon 14 back down near its current level, the anomaly would disappear. Thus, plants from the cold times would appear—according to carbon dating—to be contemporary with warm-weather specimens that lived more than 1,000 years later.

Although the amount of carbon 14 in the atmosphere has varied somewhat over time, sequences of radiocarbon dates from marine sediments likely to have accumulated at a nearly uniform rate clearly demonstrate that no such sudden shock took place at any time during the past 20,000 years. Indeed, measurements on corals whose absolute ages have been established by uranium-thorium dating imply that during the end of the last ice age, when the conveyor should have been starting up again and drawing carbon 14 out of the atmosphere, the radiocarbon content of the atmosphere increased.

This record seems to be telling us that any conveyor shutdowns must have been brief—a century or less—and that they must have been matched by intervening intervals of rapid mixing. In particular, the Younger Dryas was apparently a time when overall ocean circulation increased rather than decreased, as would be expected if the cold snap were caused by a complete halt of the Atlantic conveyor. If the conveyor did shut down, some other method of transporting carbon 14 to the deep sea must have been in operation.

A Fleet of Icebergs

Assuming that changes in the conveyor mechanism did drive the abrupt changes found in the Greenland ice cores and other climate records, what might supply the excess freshwater needed to shut down transport of water into the abyss? The polar ice caps are the obvious sources for the jolts of freshwater needed to upset ocean circulation. Moreover, sudden changes appear to be confined to times when large ice sheets covered Canada and Scandinavia. Since the ice ages ended, global climate has remained locked in its present mode.



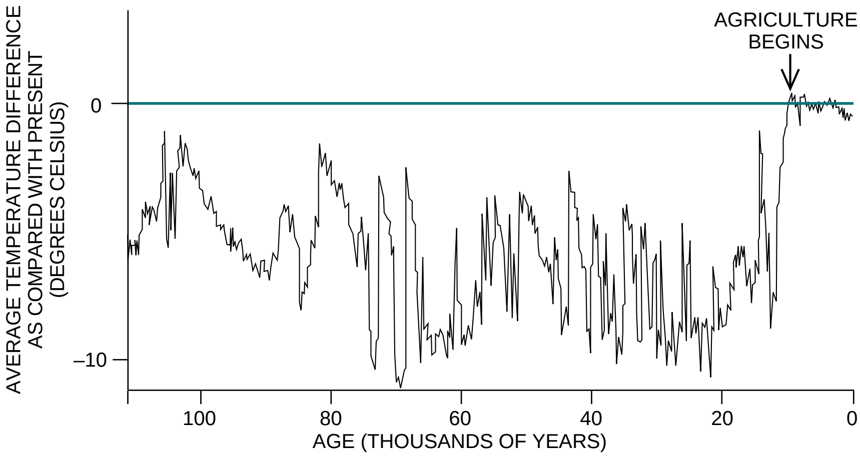
DEEPWATER FORMATION PROCESS carries radioactive carbon 14, formed by cosmic rays, out of the atmosphere and upper ocean and into the abyss. Radiocarbon dating indirectly measures the state of the oceanic conveyor because any prolonged shutdown causes a buildup of carbon 14 in the atmosphere and scrambles the apparent ages of organic remains.

There is evidence of at least eight invasions of freshwater into the North Atlantic: seven armadas of icebergs released from the eastern margin of the Hudson Bay ice cap and a flood of meltwater from a huge lake that marked the southern margin of the ice sheet during glacial retreat. In the early 1980s, while he was a graduate student at the University of Göttingen, Hartmut Heinrich discovered a curious set of layers in the sediments of the North Atlantic. The layers stretch from the Labrador Sea to the British Isles, and their characteristics are most plausibly explained by the melting of enormous numbers of icebergs launched from Canada.

The debris dropped from this flotilla thins eastward from half a meter in the Labrador Sea to a few centimeters in the eastern Atlantic. Rock fragments characteristic of the sedimentary limestones and igneous bedrock from Hudson Bay and the surrounding area constitute most of the larger particles of the sediments. Shells of foraminifera are found only rarely in these layers, suggesting an ocean choked with sea ice; the low ratio of oxygen 18 to oxygen 16 in those shells that do appear provides an unambiguous marker that the animals lived in water much less salty than usual. (Rain and snow at high latitudes is depleted in oxygen 18 because the "heavy" water containing it condenses out of the atmosphere preferentially as air masses cool.)

The eighth freshwater pulse came from Lake Agassiz, a very large lake trapped in the topographic depression created by the weight of the retreating ice cap. Initially, the water from the lake spilled over a rock sill into the Mississippi River watershed and thence the Gulf of Mexico. About 12,000 years ago the retreat of the ice front opened a channel to the east, triggering a catastrophic drop in lake level. The water released during this breakthrough flooded across southern Canada into the valley now occupied by the St. Lawrence River and discharged directly into the region where deep waters now form.

The connection between these events and local climate changes is clear. Four occurred at times corresponding to significant changes in the climate of the North Atlantic basin. One of Heinrich's layers marks the end of the second-to-last major glacial cycle, and another that of the most recent cycle. A third layer appears to match the onset of glacial conditions in the North Atlantic, and the catastrophic release of water from Lake Agassiz coincided with the onset of the Younger Dryas. Each of the four remaining pulses caps a climate subcycle. Gerard C. Bond of the Lamont-Doherty Earth Observatory of Columbia University correlated Heinrich layers with the Greenland ice core record and found that the millennia-long cold events come in groups characterized by progressively more severe cold snaps, culminating with a Heinrich event that is followed in turn by a signif-



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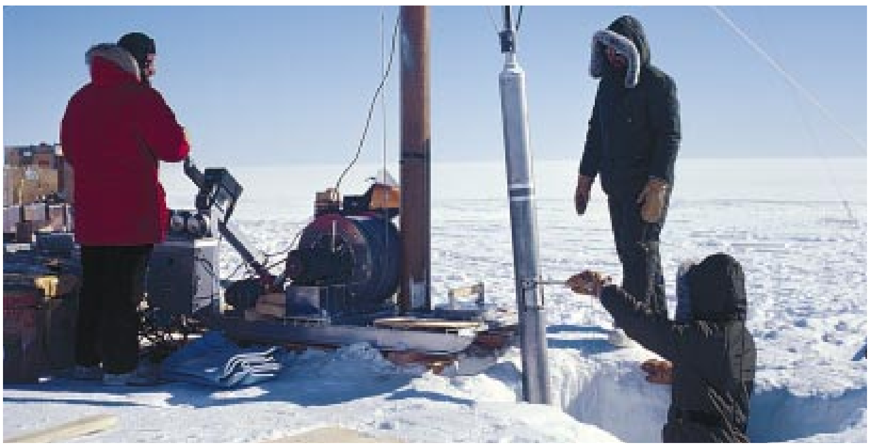

RICHARD B. ALLEY *Pennsylvania State University*

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ICE CORE DATA (*top left*) show the variability of the earth's climate during the past 100,000 years. Researchers drilled down to bedrock near the center of the Greenland ice cap (*above*) and measured the relative concentration of oxygen 18 and oxygen 16 in the samples they retrieved. (Cores awaiting analysis are shown in cold storage at the right.) The amount of oxygen 18 in atmospheric water vapor depends on air temperature: the colder the climate, the less water containing the heavy isotope is present. Microscopic views of an ice core section (*top right*) make individual ice crystals visible through their differing transmission of polarized light and highlight the trapped air bubbles that record the composition of the prehistoric atmosphere (*middle right*). The lowest layers (*bottom right*) have been distorted by the ice cap's flow over Greenland's uneven ground, making accurate measurements difficult or impossible.

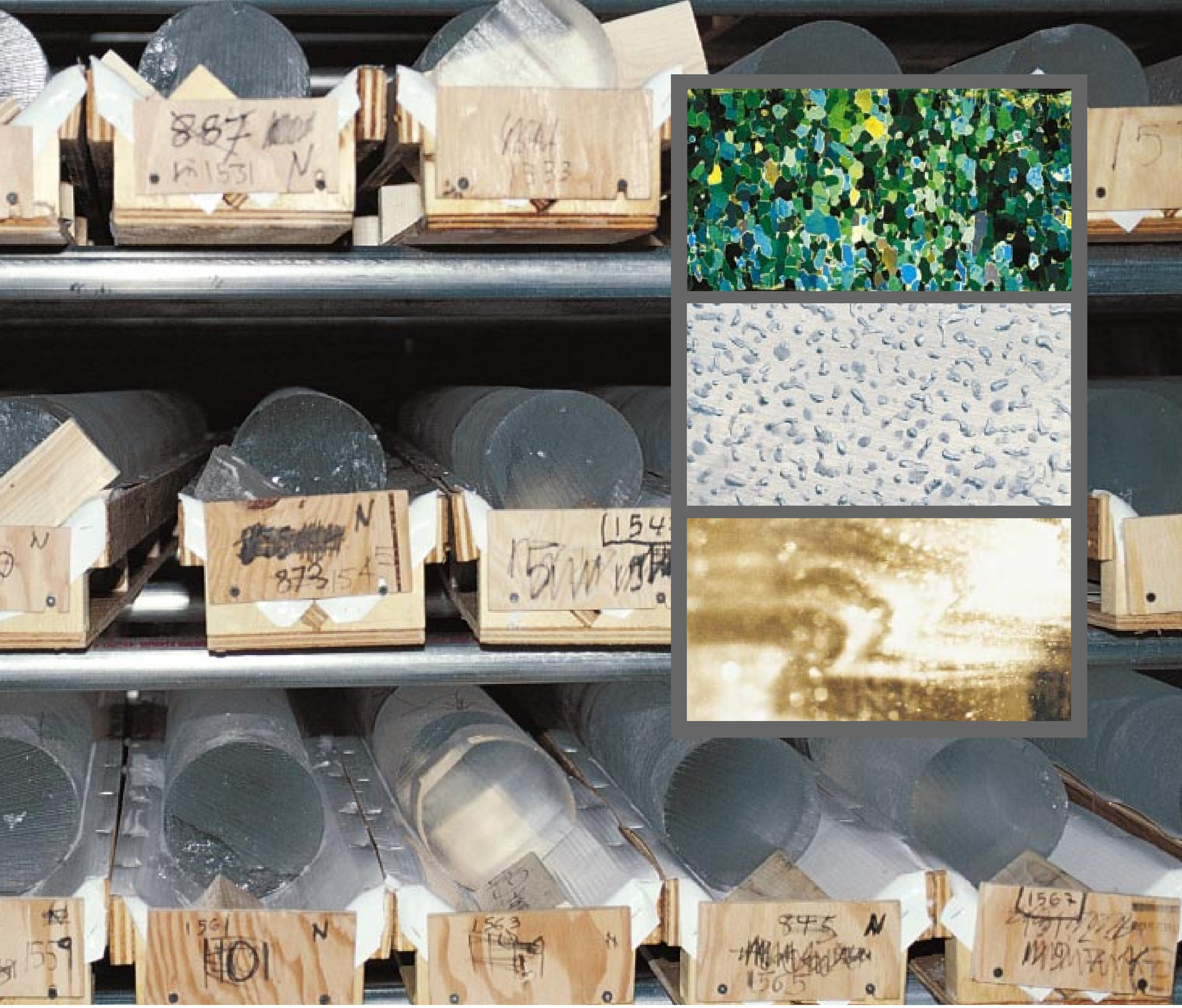
icant warming that begins a new cycle.

The climate shifts of the Younger Dryas period were felt around the world. Is the same true of the 15 or so similar events that appear earlier in the ice core record? So far only two pieces of evidence point in that direction, but they are convincing ones. First, Jerome A. Chappellaz of the Laboratory of Glaciology and Geophysics of the Environment near Grenoble has analyzed air trapped in Greenland ice cores and found that cold periods were accompanied by drops in the atmosphere's methane content. Methane is produced mostly in swamps and bogs. Because those of the northern temperate region were either frozen or buried underneath ice during glacial times, methane present in the atmosphere must have come from the tropics. The fluctuations in the methane record imply that the tropics dried out during each of the northern cold intervals.

The second clue is an as yet unpublished study by James P. Kennett and Richard J. Behl of the University of California at Santa Barbara of a sediment core recovered from 500 meters below sea level in the Santa Barbara basin. The two found that bands of undisturbed sediment with clear annual layers alternated with sections more or less disturbed by burrowing worms. The presence of worms implies that the bottom water in the area contained significant amounts of oxygen, enough to support life; such periods display an uncanny correlation with cold spells in Greenland, implying that changes in ocean circulation reached around the globe.

More surprising is the finding that Heinrich events also appear to have had a worldwide imprint. Eric Grimm of the Illinois State Museum and his colleagues sampled pollen in the sediments of Lake Tulane in Florida and found one prominent peak in the ratio of pine to oak for each Heinrich event. Pine trees prosper in relatively wet climates, whereas oaks prefer dryer ones. Although the exact relation between pine-rich intervals and Heinrich events awaits more accurate radiocarbon dating, the Lake Tulane record suggests one wet interval per cycle. George H. Denton of the University of Maine and his co-workers found an even more distant connection: each of the four Heinrich events falling within the range of radiocarbon dating matches a sharp maximum in the extent of Andean mountain glaciers.

The finding that the massive calving



of Canadian glaciers caused global impacts creates a paradox. Atmospheric models indicate clearly that climate shifts related to changes in the amount of heat delivered to the atmosphere over the North Atlantic would be limited to the surrounding regions. The evidence that has been found, however, demands a mechanism for extending these effects to the tropics, the southern temperate region and even the Antarctic.

The symmetrical distribution of these climate changes around the equator points to the tropics. Changes in the dynamics of the tropical atmosphere could easily have a far-reaching effect. The towering convection cells that form in the tropical atmosphere where the trade winds meet feed the atmosphere with its dominant greenhouse gas: water vapor. Although the link between ocean circulation and tropical convection is tenuous, it seems plausible that changed circulation patterns might alter the amount of cold water upwelling to the surface along the equator in the Pacific. This upwelling is an important part of the region's heat budget and thus its overall climate. Reduction of the equatorial upwelling, as occurs now during so-called El Niño periods, can cause droughts in some areas and floods in others.

Global Shifts

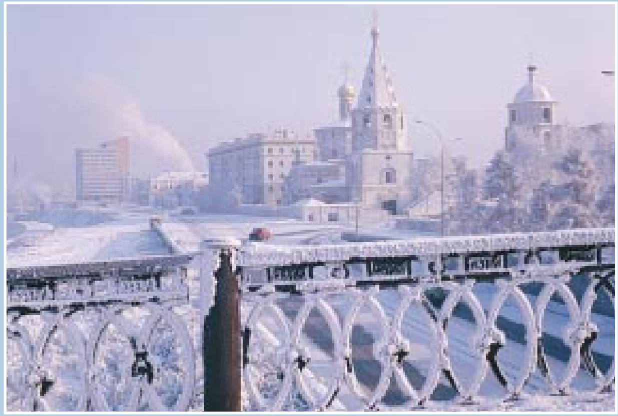
Support for such a scenario comes not only from Chappellaz's data showing drying in the tropics but also from the moisture histories of Nevada, New Mexico, Texas, Florida and Virginia. The most dramatic evidence comes from the Great Basin area of the western U.S.: immediately after the last Heinrich event about 14,000 years ago, Lake Lahontan in Nevada achieved its greatest size, an order of magnitude larger than today's remnant. Supporting such a large body of water requires immense amounts of precipitation, of the magnitude experienced during the record El Niño winter of 1982–1983. One way of thinking about the impact of these earlier occurrences, then, is as changes in the pattern of ocean circulation that led to El Niños lasting 1,000 years.

More recent findings, from Lonnie G. Thompson of Ohio State University, reinforce the evidence that tropical weather was extremely different during glacial times. Ancient ice cores from 6,000 meters up in the tropical Andes contain 200 times as much fine dust as more

NORMAN TOMALIN *Bruce Coleman, Inc.*

STEFAN LUNDGREN *The Wildlands Collection*

FRIDMAR DAMM *Leo de Wys*



BORIS DMITRIEV

IMPACT ON EUROPE of a disruption in deepwater formation would be drastic and unpleasant. Dublin (*top left*) would have a summer climate of the kind currently characteristic of Spitsbergen in the high Arctic, and London (*bottom left*) would experience the winter cold that now grips Irkutsk in Siberia.

recent samples—dust probably carried by winds blowing up from an arid Amazonia. The older ice is also depleted in oxygen 18 as compared with ice formed more recently than 10,000 years ago, implying a temperature about 10 degrees lower than today. Taken with the observation that the Andean snow line reached down a full 1,000 meters closer to sea level during the ice ages, these data suggest that the tropics of glacial times were both colder and drier.

The conclusion that the earth's climatic system has occasionally jumped from one mode of operation to another is rock solid. Unfortunately, researchers have yet to pin down the cause of these abrupt shifts. Although large-scale reorganizations of the ocean's circulation seem the most likely candidate, it is possible that atmospheric triggers may be discovered as well.

A Fragile Balance

This situation leaves us in limbo with regard to climatic prediction. Might the current buildup of greenhouse gases set in motion yet another reorganization of the deepwater conveyor and the weather patterns that depend on it? On the one hand, the paleographic record suggests that jumps have been confined to times when the North Atlantic was surrounded by huge ice sheets, a situation that is now further from the case than ever. On the other hand, the greenhouse nudge promises to be far larger than any other forcing experienced during an interglacial interval, and there is no certainty that the system will remain locked in its present relatively benign mode.

A conveyor shutdown or comparable drastic change is unlikely, but were it to occur, the impact would be catastrophic. The likelihood of such an event will be highest between 50 and 150 years from now, at a time when the world will be bulging with people threatened by hunger and disease and struggling to maintain wildlife under escalating environmental pressure. It behooves us to take this possibility seriously. We should spare no effort in the attempt to understand better the chaotic behavior of the global climatic system.

The Author

WALLACE S. BROECKER has been studying climatic change and ocean circulation for more than 40 years. He is professor of geology at the Lamont-Doherty Earth Observatory of Columbia University, where in 1958 he received his Ph.D. Broecker pioneered radiochemical and isotopic analysis of seawater and has spent much of the past decade investigating the stability of the mechanisms that led to the formation of deep water in the North Atlantic Ocean.

Further Reading

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Holographic Memories

After more than 30 years, researchers are on the verge of using holograms to store data in memories that are both fast and vast

by Demetri Psaltis and Fai Mok

Optical storage of data has been one of the bright spots in technology over the past 15 years. Compact discs, for example, dominate the market for musical recordings and are now also the standard medium for multimedia releases, which combine text, images and sound. Video games, entire journals, encyclopedias and maps are among the multimedia products available on CDs to users of personal computers.

Without a doubt, optical memories store huge amounts of digitized information inexpensively and conveniently. A compact disc can hold about 640 million bytes—enough for an hour and a quarter of high-fidelity music or more than 300,000 pages of double-spaced, typewritten text. All indications are, however, that these large memories have stimulated demand for even more capacious and cheaper media. Executives in the entertainment industry would like to put one or more motion pictures on a single optical disk the same size as a CD, and so great are the data storage needs of some hospitals, law firms, government agencies and libraries that they have turned to so-called jukeboxes that have robotic arms to access any one of hundreds of disks.

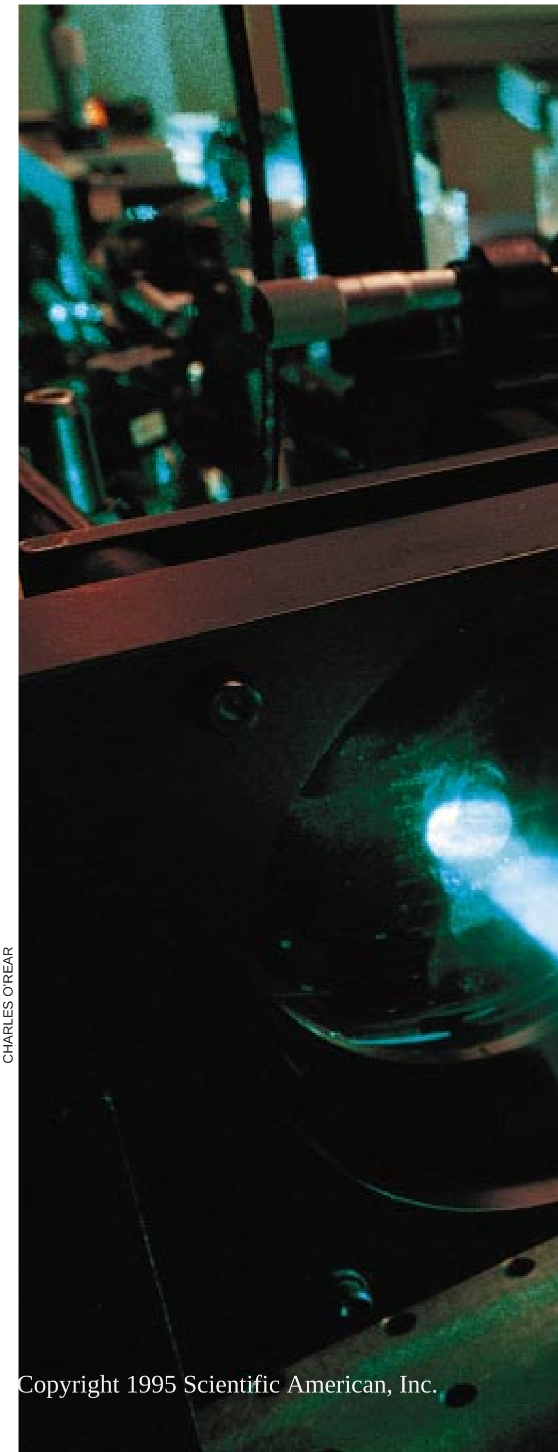
Engineers have responded by trying to wring the most out of CD systems. Some are working on semiconductor lasers with shorter wavelengths (in effect, these will be finer styli that permit closer spacing of bits on a CD). Others are investigating techniques of data compression and "super-resolution" that also allow higher density (the latter at the expense of increased background noise). Another promising development has been multiple-level CDs, in which two or more data-containing tracks are stacked and read by an optical system that can focus on one level at a time. Such schemes are expected to push the capacity of CDs into the tens of billions of bytes within five years or so.

But to pack a CD-size disk with much more data—hundreds of billions of bytes, say—will require a fundamentally different approach: holography. The idea dates back to 1963, when Pieter J. van Heerden of Polaroid first proposed using the method to store data in three dimensions.

Holographic memories, it is now believed, could conceivably store hundreds of billions of bytes of data, transfer them at a rate of a billion or more bits per second and select a randomly chosen data element in 100 microseconds or less. No other memory technology that offers all three of these advantages is as close to commercialization—a fact that has compelled such large companies as Rockwell, IBM and GTE in the past two years to launch or expand efforts to develop holographic memories.

Initially, the expense and novelty of the technology will probably confine it to a handful of specialized applications demanding extraordinary capacity and speed. Such uses are already attempting to carve out little niches—one recently offered product holographically stores the fingerprints of those entitled to enter a restricted area, permitting access when a matching finger is placed on a glass plate. If in meeting such needs the technology matures and becomes less expensive, it might supersede the optical disk as a high-capacity digital storage medium for general-purpose computing.

The main advantages of holographic storage—high density and speed—come



CHARLES O'REAR

HOLOGRAPHIC MEMORY stores data in a crystal of lithium niobate not much larger than a sugar cube (*foreground*). The hologram is created in the crystal by the meeting of a reference laser beam, shown thick and bright in this photograph, and a signal beam, fainter and thinner, which contains the data.

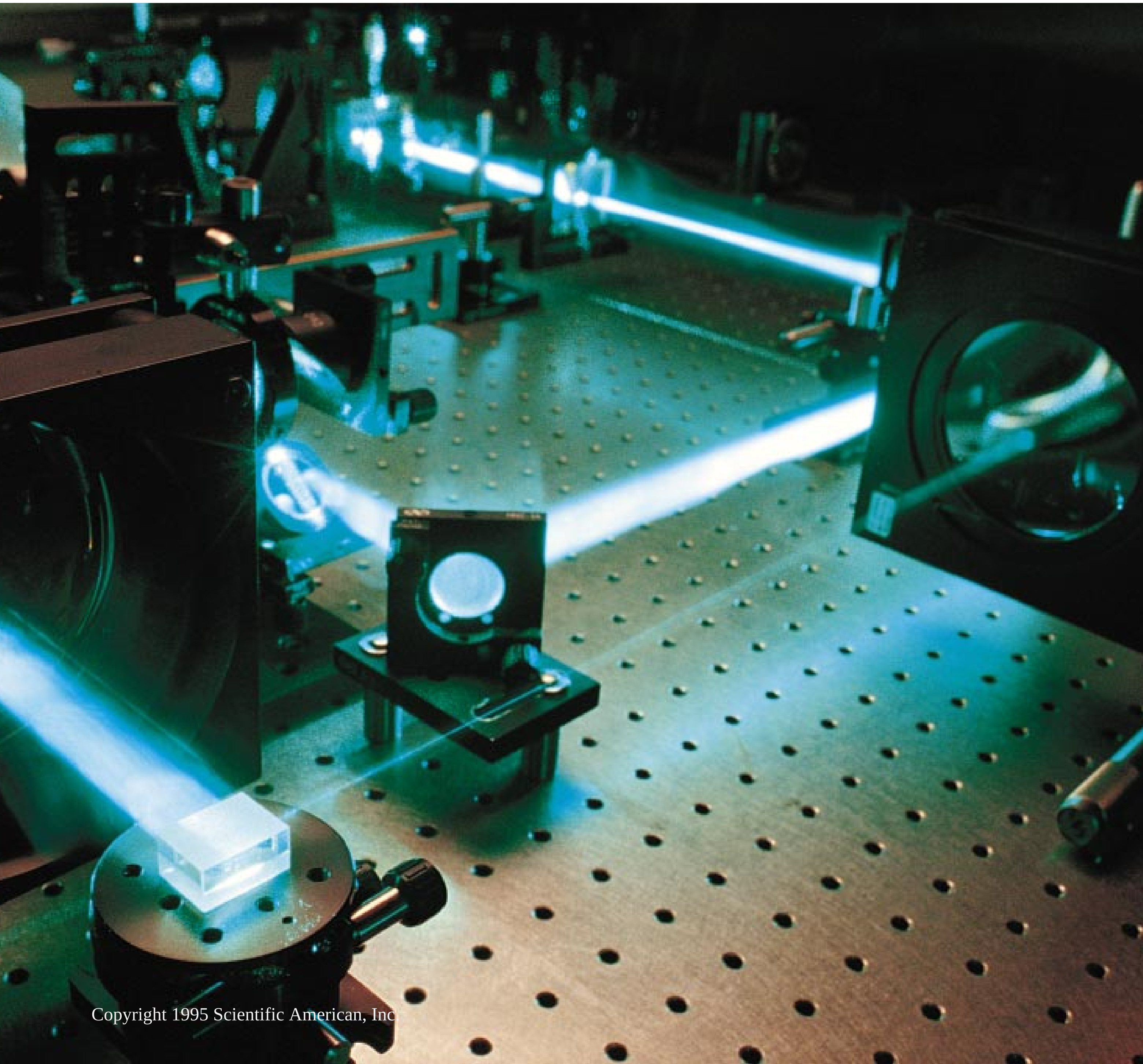
from three-dimensional recording and from the simultaneous readout of an entire page of data at one time. Uniquely, holographic memories store each bit as an interference pattern throughout the entire volume of the medium.

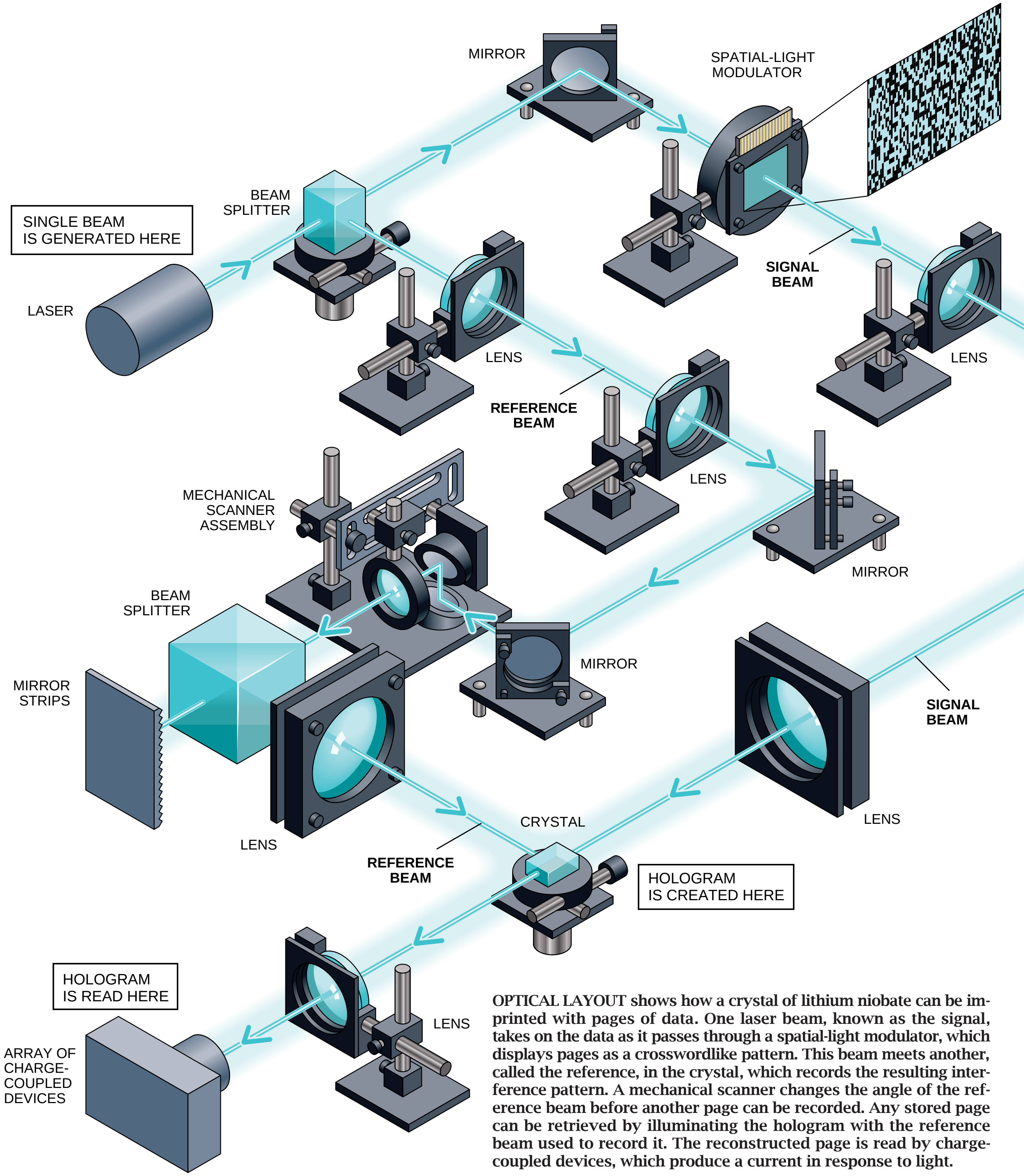
How Holographic Memories Work

The pattern, also known as a grating, forms when two laser beams interfere with each other in a light-sensitive material whose optical properties are altered by the intersecting beams.

Before the bits of data can be imprinted in this manner in the crystal, they must be represented as a pattern of clear and opaque squares on a liquid-crystal display (LCD) screen, a miniature version of the ones in laptop computers. A blue-green laser beam is shined through this crossword-puzzle-like pattern, or page, and focused by lenses to create a beam known as the signal. A hologram of the page of data is created when this signal beam meets another one, called the reference, in the photosensitive crystal. The reference beam, in this case, is collimated, which means that all its light waves are synchronized, with crests and troughs passing through a plane in lockstep (indeed, such waves are known as plane waves). The grating created when the signal and reference beams meet is captured as a pattern of varying refractivity in the crystal.

After being recorded like this, the page can be holographically reconstructed by once again shining the reference beam into the crystal from the same angle at which it had entered the material to create the hologram. As it passes through the grating in the crystal, the reference beam is diffracted in such a way that it re-creates the image of the original page and the information contained on it. The reconstructed page is then projected onto an array of electro-optical detectors that sense the light-and-dark pattern, thereby reading all





OPTICAL LAYOUT shows how a crystal of lithium niobate can be imprinted with pages of data. One laser beam, known as the signal, takes on the data as it passes through a spatial-light modulator, which displays pages as a crosswordlike pattern. This beam meets another, called the reference, in the crystal, which records the resulting interference pattern. A mechanical scanner changes the angle of the reference beam before another page can be recorded. Any stored page can be retrieved by illuminating the hologram with the reference beam used to record it. The reconstructed page is read by charge-coupled devices, which produce a current in response to light.

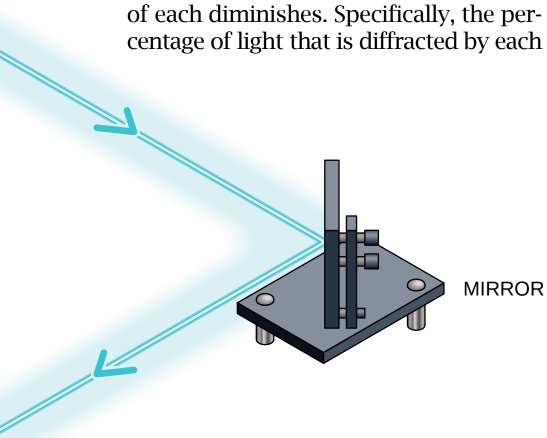
the stored information on the page at once. The data can then be electronically stored, accessed or manipulated by any conventional computer.

The key characteristic is the accuracy with which the "playback" reference beam must match the original one that recorded the page. This precision depends on the thickness of the crystal—the thicker the crystal, the more exactly the reference beam must be repositioned. If the crystal is one centimeter thick and the illumination angle deviates by one thousandth of a degree, the reconstruction disappears completely. Far from being an inconvenience, this basic mechanism is exploited in almost all holographic memories. The first page of data is holographically recorded in the crystal. The angle of the reference beam is then increased until the recon-

JARED SCHNEIDMAN JSD

struction of the first hologram disappears. Then a new page of data is substituted and holographically recorded. The procedure, known as angle multiplexing, is repeated many times. Any of the recorded holograms can be viewed by illuminating the crystal with the reference beam set at the appropriate angle.

How many pages can be imprinted into a single crystal? The number is limited mainly by the dynamic range of its material: as more holograms share the same crystalline volume, the strength of each diminishes. Specifically, the percentage of light that is diffracted by each hologram (and therefore sensed by the electro-optical detectors) is inversely proportional to the square of the number of holograms superimposed.



If 10 holograms in a crystal yield a diffraction efficiency equal to 1 percent, 1,000 holograms will have a diffraction efficiency of only 0.0001 percent. This effect determines the maximum number of holograms that can be stored, because the drop in diffraction efficiency ultimately makes the reconstructions too weak to be detected reliably amid the noise in the system—fluctuations in the brightness of the lasers, scattering from the crystal, thermally generated electrons in the detector, and so on. This maximum number of holograms can be determined by measuring the optical properties of the crystal material and the various noise sources in the system. In practice, when the diffraction efficiency has dropped too low for the pages to be reliably reconstructed, the rate at which erroneous data are detected—the bit-error rate—becomes unacceptably high.

Stronger Signals

Much of the work in developing holographic memories comes down to the application of new techniques to strengthen, against the background noise, the optical signals representing pages of data. Better technologies have allowed fainter and fainter signals to be reliably detected, and improvements in holographic recording methods have strengthened the recorded signals, enabling more pages to be imprinted into the crystal.

The first attempts to store many holograms date back to the early 1970s. Juan J. Amodei, William Phillips and David L. Staebler of RCA Laboratories recorded 500 holograms of plane waves in an iron-doped lithium niobate crystal. Robert A. Bartolini and others, also at RCA, stored 550 holograms of high-resolution images in a light-sensitive polymer material, and Jean-Pierre Huignard's group at Thomson-CSF in Orsay, France, engineered a memory with 256 locations, each capable of storing 10 holograms. Besides storing relatively many holograms, Huignard's system was exceptionally well engineered.

Impressive though some of these early efforts were, none of them led to a practical system. Semiconductor and magnetic memories were progressing quite rapidly at the time, making more exotic technologies seem unworthy of pursuit. Gradually, holographic memories fell out of the limelight.

A renaissance began in 1991, when one of us (Mok), with funding from the U.S. Air Force and the Department of Defense's Advanced Research Projects Agency, demonstrated the storage and high-fidelity retrieval of 500 high-resolution holographic images of tanks, jeeps and other military vehicles in a crystal of lithium niobate with trace amounts of iron.

Several new theories and experiments followed. In 1992 we stored 1,000 pages of digital data in a one-cubic-centimeter, iron-doped lithium niobate crystal. Each stored page contained 160 by 110 bits obtained from the ordinary electronic memory of a digital personal computer. We then copied segments of the stored data back to the memory of the digital computer—and detected no errors. This experiment demonstrated for the first time that holographic storage can have sufficient accuracy for digital computers.

A similar setup was used to store 10,000 pages, the most in a single crystal so far. Each of these pages measured 320 bits by 220 bits, so all told the system could store a little less than 100 million bytes (100 megabytes). We performed this experiment in 1993 at the California Institute of Technology in collaboration with Geoffrey Burr.

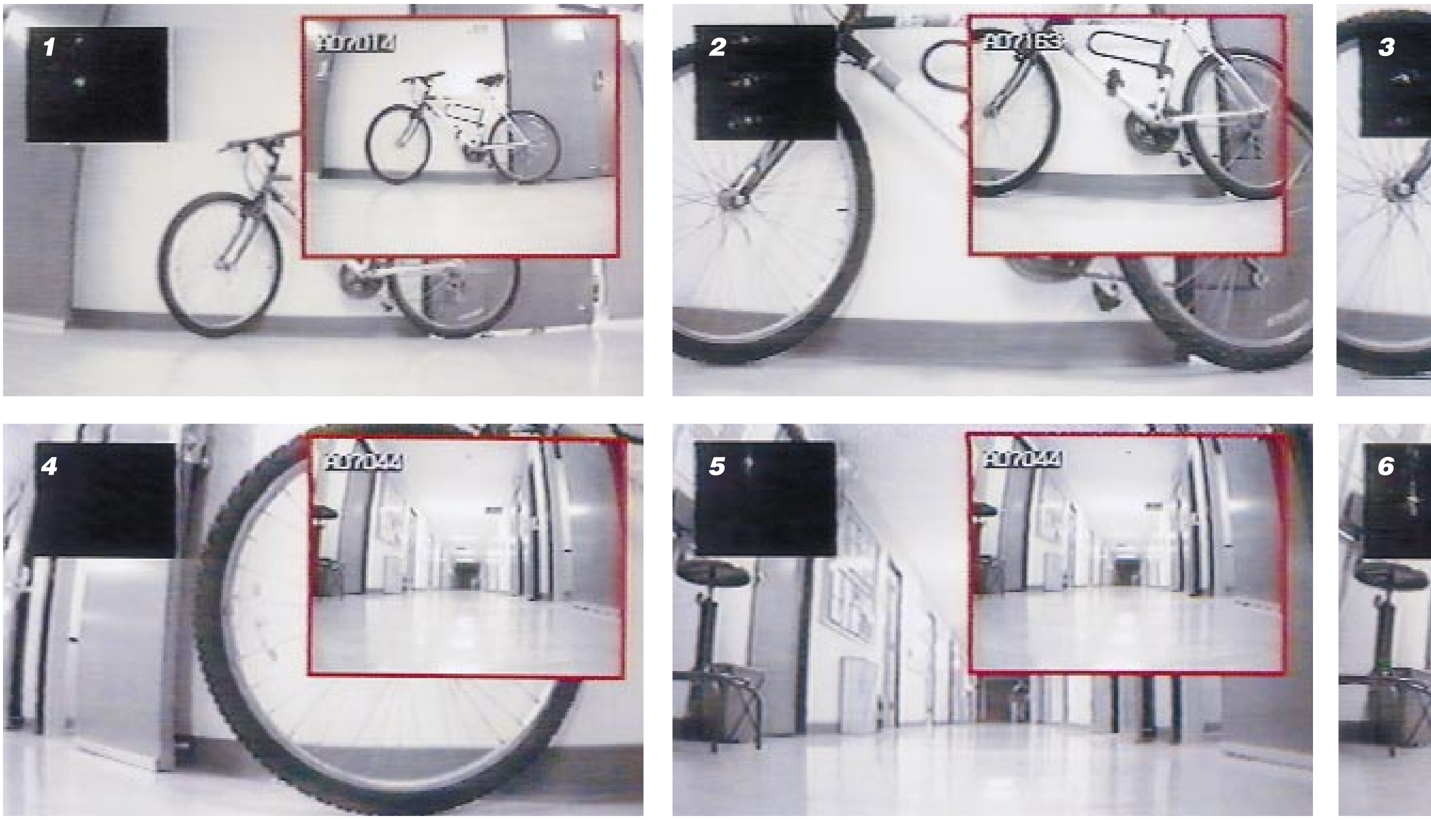
The majority of the 10,000 stored holograms were random binary patterns, similar to the data that can be stored by a conventional computer. The raw (uncorrected) error rate was one bad bit out of every 100,000 evaluated. Such a rate suffices to store image data, particularly if they have not been compressed or manipulated to reduce the number of bits needed to represent the image. Several photographs of faces and of the Caltech logo were also included among the pages to demonstrate that images and data can be easily combined in a holographic memory. The information contained in the 10,000 holograms would fill only one eighth of the capacity available in a conventional compact disc. But holographic memories that have a much higher capacity can be made by storing holograms at multiple locations in the crystal. For instance, we demonstrated a system in which 10,000 data pages are stored in each of 16 locations, for a total of 160,000 holograms.

In 1994 John F. Heanue, Matthew C. Bashaw and Lambertus Hesselink, all at Stanford University, stored digitized, compressed images and video data in a holographic memory and recalled the information with no noticeable loss of picture quality. They stored 308 pages, each containing 1,592 bits of raw data, in four separate locations in the same crystal. The Stanford group combined several techniques, some electronic, others optical, to keep the bit-error rates under control. For instance, they appended a few bits to each string of eight bits to correct a single erroneous bit anywhere in the group. This error-correcting code reduced the error rate from about one bit in every 10,000 or less to about one bit per million.

Another important potential advantage of holographic storage is rapid random access by nonmechanical means. For example, high-frequency sound waves in solids can be used to deflect a reference light beam in order to select and read out any page of data in tens of microseconds—as opposed to the tens of milliseconds typical of the mechanical-head movements of today's optical and magnetic disks. At Rockwell's research center in Thousand Oaks, Calif., John H. Hong and Ian McMichael have designed and implemented a compact system capable of storing 1,000 holograms in each of 20 locations. An arbitrary page can be accessed in less than 40 microseconds, and its data are retrieved without errors.

Promising Polymers

As with the original experiments in the 1970s, these recent demonstrations used a crystal of lithium niobate with trace amounts of iron. When illuminated with an optical pattern—such as a hologram created by the intersection of two laser beams—charged particles migrate within the crystal to produce an internal electric field whose



modulation closely matches that of the optical pattern. The way the crystal then diffracts light depends on this electric field: when the crystal is illuminated again at the correct angle, light is diffracted in such a way that the original hologram is reconstructed. The phenomenon is known as the photorefractive effect [see "The Photorefractive Effect," by David M. Pepper, Jack Feinberg and Nicolai V. Kukhtarev; SCIENTIFIC AMERICAN, October 1990].

A different type of holographic material became commercially available for the first time last year. This material, known as a photopolymer, was developed at Du Pont and undergoes chemical rather than photorefractive changes when exposed to light. Electrical charges are not excited, and the photochemical changes are permanent—information cannot be erased and rewritten. The medium is therefore suitable only for write-once or read-only memories. The material does, however, have a diffraction efficiency 2,500 times greater than a lithium niobate crystal of the same thickness. One of us (Psaltis) collaborated with Allen Pu of Caltech and Kevin Curtis of AT&T Bell Laboratories on an experiment in which we stored 1,000 pages of bit patterns in a polymer film 100 microns thick. We retrieved the data without any detected errors.

In recent years, researchers at IBM and at the University of Arizona have begun experimenting with polymer films that, like lithium niobate crystals, exhibit the photorefractive effect. Promising though the developments in polymeric holographic materials are, it is too soon to count out lithium niobate, which has lately also shown greater versatility. For instance, crystals of lithium niobate doped with trace amounts of both cerium and iron—which are sensitive to red light rather than green—recently became available. They point the way to crystals that can be imprinted with inexpensive and tiny semiconductor lasers, instead of the much more costly green or blue-green ones.

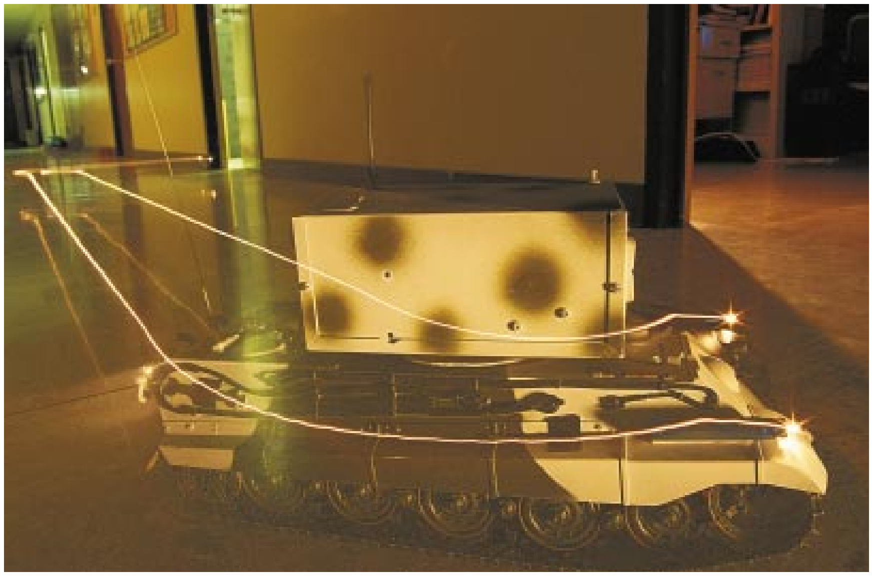
Something Borrowed, Something New

The iron-doped lithium niobate crystals used in the recent demonstrations are not the only surviving aspect of the early experiments more than two decades ago. The argon lasers typically used today are also the same. And angle multiplexing was relied on in the past, as now. What changes, then, have revived holographic data storage?

The most significant advance has been the emergence of a mature optoelectronics industry, which has produced the inexpensive, compact and power-efficient devices needed to build large-scale holographic memories and to interface them with digital computers. For instance, tiny semiconductor lasers that emit red light, originally developed for fiber-optic communications, can be used as light sources either with a cerium- and iron-doped lithium niobate crystal or with Du Pont's photopolymer. Large detector arrays made for television cameras, which take an optical image and convert it to an electronic signal, read the output of the memory. Liquid-crystal display screens originally designed for video projectors serve as the input devices, creating the bright-and-dark patterns that represent pages of data.

Such technological advances made possible the recent memory demonstrations that, in turn, prompted new investigations into the underlying physics. For example, a long-standing problem in holographic memories is cross-talk noise—the partial, spontaneous and unwanted readout of stored data. In practice, cross talk causes faint, ghostlike images of all the pages to be called up when only one is being accessed. Cross-talk noise and its sources are now completely understood, allowing us to calculate and counteract the effect in any recording setup from such parameters as the angle between the signal and reference beams, the angle between the reference beams in a multiplexed recording and the geometric properties of the page of data.

Another by-product of the theoretical work has been the development of



CALIFORNIA INSTITUTE OF TECHNOLOGY; ERIC SANDER (*vehicle*)

VEHICLE STEERED BY HOLOGRAMS navigated itself around the authors' laboratory at the California Institute of Technology. Each compound photograph in this sequence shows what a video camera on the vehicle saw (*main image*), along with another image (*inset*) that was transmitted to the little machine from a holographic memory. To navigate, the vehicle (*shown above*) oriented itself until its camera image matched the one from its memory. Lights in the other, smaller inset indicate the extent to which two image sequences are in synchrony. In this series, the vehicle initially recognized and approached a bicycle. It was then prompted by the image it would see after a left turn, which it found after a bit of searching.

new multiplexing methods and the refinement of existing ones. These can replace or supplement angle multiplexing, giving the system designer more options. In one alternative, pursued separately at Pennsylvania State University and at Caltech, successive pages are recorded with reference beams of different wavelengths. Reference beams that are coded with a different pattern for each page have also been demonstrated at the University of California in San Diego and, independently, at the Optical Institute in Orsay, France.

Increasing the Volume

Better multiplexing techniques are certainly welcome, but a fundamental means of increasing capacity will be needed if holographic memories are to make inroads against compact discs. Holographic memories have been shown to be significantly faster at present than are compact-disc systems, but speed alone is rarely enough for a new technology to supplant an entrenched one. What is generally needed is another basic advantage, such as greater storage capacity.

One way to increase storage in a holographic memory would be to tile a two-dimensional surface with sugar-cube-like memory crystals, a technique called spatial multiplexing. As expected, the capacity of such a system is proportional to the number of cubes. Data are stored in each of the cubes in the usual way, as angle-multiplexed holograms.

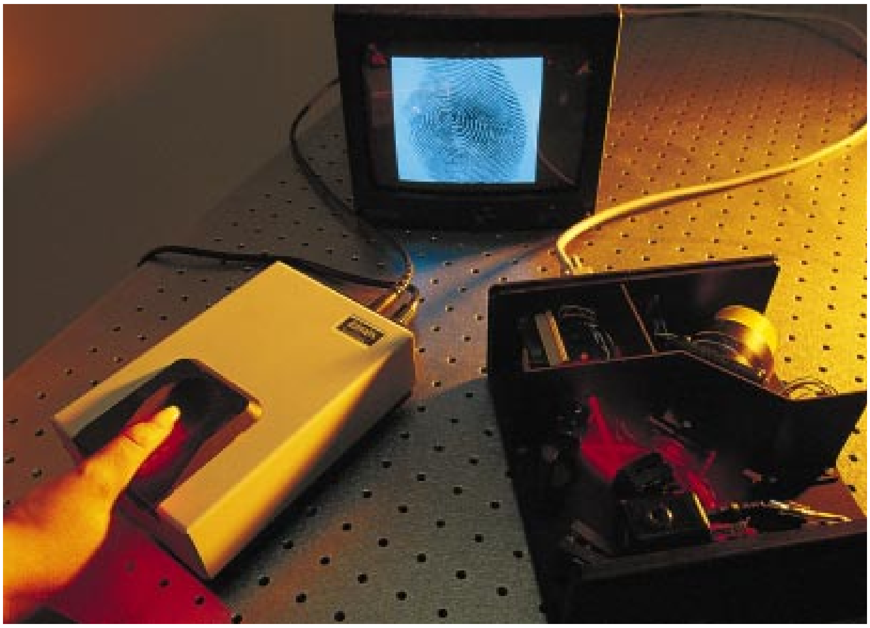
The challenging part of this kind of system is the optical assembly, which must be capable of addressing any one of the cubes individually. One such assembly is the three-dimensional disk, which has many similarities to a conventional CD. The disk-shaped recording material is placed on a rotating stage; a laser-based reading and writing device, or head, is mounted above it. The rotation of the disk and radial scanning of the head make it possible to illuminate any spot on the disk. Psaltis proposed the idea in 1992; Pu built a system based on it earlier this year at Caltech.

As in any holographic medium, data are stored throughout the volume of the recording layer of the 3-D disk. The head has a detector array for reading out an entire page of data and a beam deflector for angle multiplexing. A spatial-light modulator, which imprints the page of data onto the signal beam (such as the LCD screen used in current demonstrations), could also be incorporated into the head.

Even though a 3-D disk stores information in three dimensions, the number of bits that could theoretically be stored per square micron of disk surface can be computed for the purpose of comparing this areal density to that of a conventional CD. Such a comparison is reasonable because a 3-D disk can be as thin as a CD. It turns out that for thicknesses less than two millimeters, the areal density of the holographic disk is approximately proportional to the thickness of the recording medium. In his demonstration at Caltech, Pu achieved a surface density of 10 bits per square micron in a disk made with a polymer film 100 microns thick (the maximum available for this particular material). This density is about 10 times that of a conventional CD.

We can increase the surface density, moreover, by simply increasing the thickness of the holographic layer. Density of 100 bits per square micron would be possible with a material one millimeter thick. Such a 3-D disk would be nearly identical in size and weight to a conventional CD, but it would store 100 times more information.

Among the companies pursuing this basic technology is Holoplex, a small start-up that we co-founded in Pasadena, Calif. The company has built a high-speed memory system capable of storing up to 1,000 fingerprints, for use as a kind of selective lock to restrict access to buildings or rooms. Although the capacity of this system is approximately half that of a CD, its entire contents can be read out within one second. Holoplex is now working on another product that would be capable of



ERIC SANDER

HOLOGRAPHIC LOCK stores up to 1,000 fingerprints. To gain entry to a room, a user places a finger on a glass plate. The fingerprint must match one of those in the memory, which are stored as holograms. The fast memory minimizes the delay while the system searches for a match. This type of device is being developed by the Japanese company Hamamatsu. It uses the holographic memory shown here from Holoplex, a Pasadena, Calif., start-up company co-founded by the authors.

storing up to a trillion bits, or almost 200 times what can be put on a CD.

Memory by Association

Before such a "super CD" becomes a commercial reality, holographic memories may be used in specialized, high-speed systems. Some might exploit the associative nature of holographic storage, a feature first expounded on in 1969 by Dennis Gabor, who was awarded the 1971 Nobel Prize for Physics for the invention of holography.

Given a hologram, either one of the two beams that interfered to create it can be used to reconstruct the other. What this means, in a holographic memory, is that it is possible not only to orient a reference beam into the crystal at a certain angle to select an individual holographic page but also to accomplish the reverse. Illuminating a crystal with one of the stored images gives rise to an approximation of the associated reference beam, reproduced as a plane wave emanating from the crystal at the appropriate angle.

A lens can focus this wave to a small spot whose lateral position is determined by the angle and therefore reveals the identity of the input image. If the crystal is illuminated with a hologram that is not among the stored patterns, multiple reference beams—and therefore multiple focused spots, are the result. The brightness of each spot is proportional to the degree of similarity between the input image and each of the stored patterns. In other words, the array of spots is an encoding of the input image, in terms of its similarity with the stored database of images.

Earlier this year at Caltech, Pu, Robert Denkewalter and Psaltis used a holographic memory in this mode to drive a small car through the corridors and laboratories of the electrical engineering building there. We stored selected images of the hallways and rooms in a holographic memory connected to a digital computer on a laboratory bench and communicated them to the car via a radio link. A television camera mounted on the car provided the visual input. As the car maneuvered, the computer compared images from the camera with those in the holographic memory [*see illustration on preceding two pages*]. Once it spied a familiar scene, it guided the vehicle along one of several prescribed paths, each defined as a sequence of images recalled from the memory. Some 1,000 images were stored in the memory, but only 53 were needed, it was found, to navigate through several rooms in the building.

We are now designing a different vehicle, which we hope to equip with a large enough memory to travel autonomously anywhere on the campus. Even with so much capacity, the parallelism of the holographic memory would permit stored information to be called up rapidly enough to let the vehicle follow roads and avoid obstacles. Indeed, navigation may be one of the specialized applications that generates the impetus needed to bring the technology into widespread use.

Such acceptance may be years away. But as the need to store vast amounts of data increases, so, too, will the expediency of storing the information in three dimensions rather than two.

The Authors

DEMETRI PSALTIS and FAI MOK began working together at the California Institute of Technology. Psaltis is professor of electrical engineering and executive officer of Computation and Neural Systems at Caltech. His research interests are typically in areas that combine optics and information sciences. Psaltis has worked extensively on optical computers and did pioneering work in establishing the analogy between holography and adaptive neural networks. In 1989 he was awarded the International Commission for Optics Prize. He received his Ph.D. at Carnegie Mellon University. Mok is president of Holoplex, a company he co-founded with Psaltis in 1993. He received his Ph.D. in 1989 for work on binary signal processing supervised by Psaltis. He has been focusing on volume holographic information storage and processing since 1988. He and his wife, Suk, consider their daughters, Jiann and Jasmine, their proudest accomplishments.

Further Reading

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THREE-DIMENSIONAL HOLOGRAPHIC DISKS. Hsin-Yu Sidney Li and Demetri Psaltis in *Applied Optics,* Vol. 33, No. 17, pages 3764–3774; June 10, 1994.

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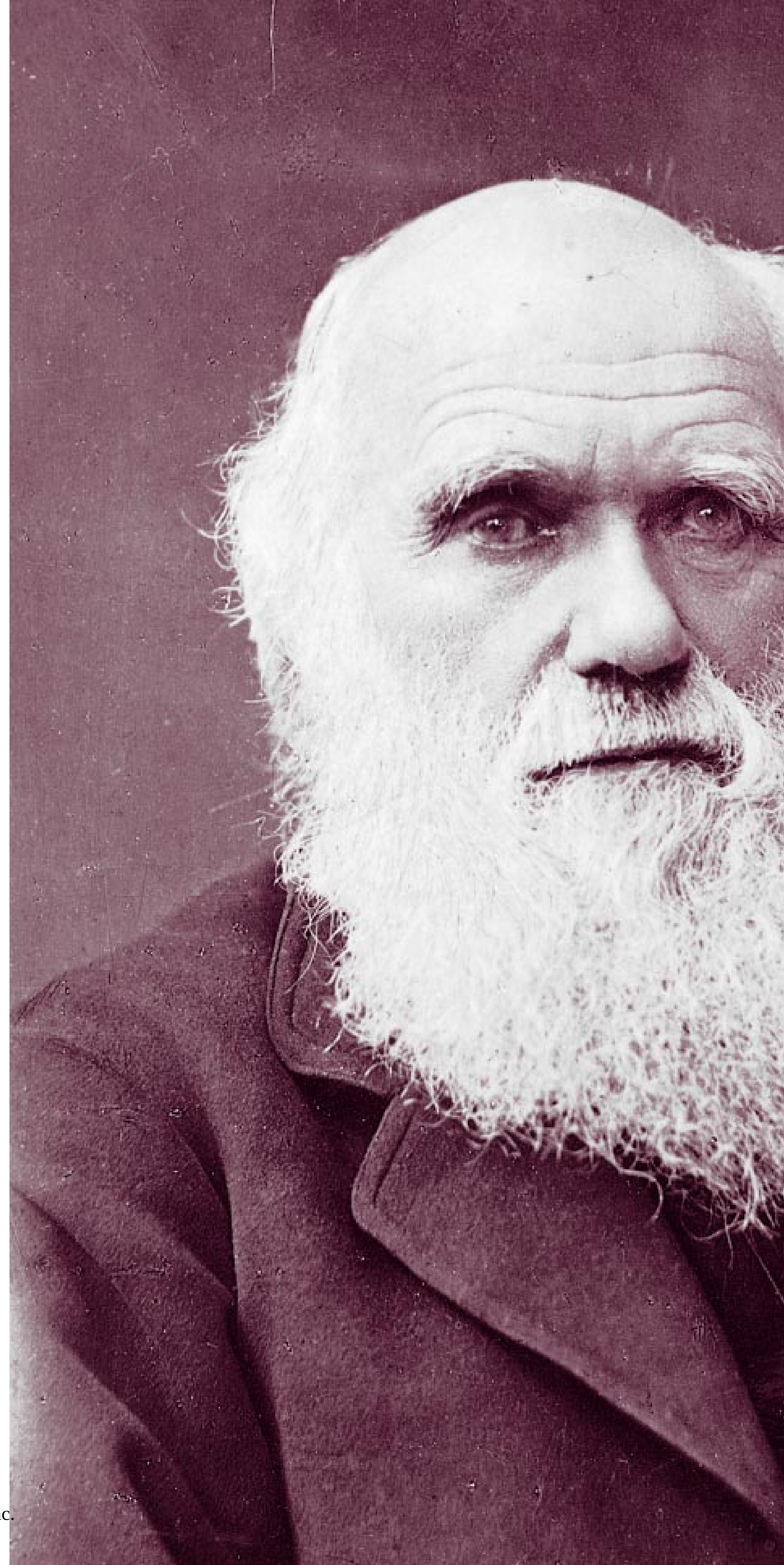
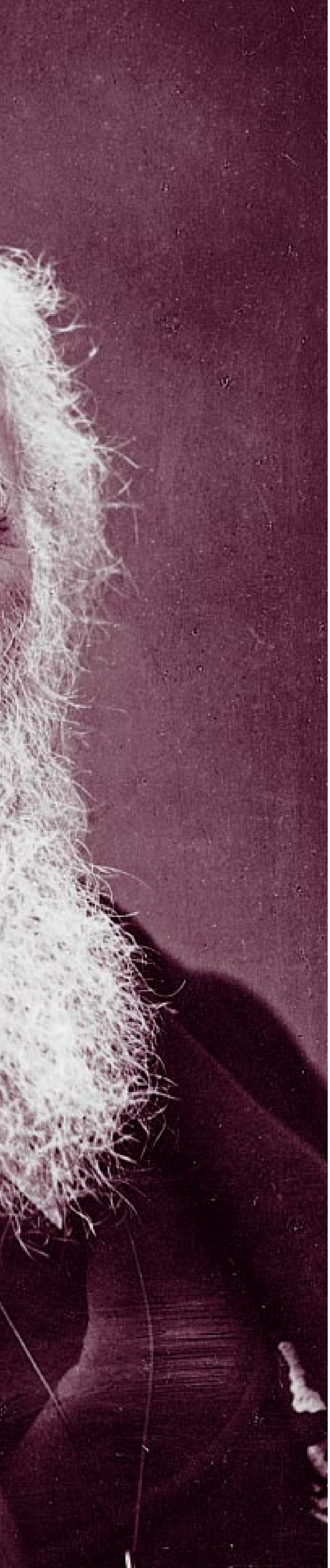
Charles Darwin: The Last Portrait

This newly rediscovered photograph appears to be the last ever made of the great evolutionist

by Richard Milner

"I AM VERY SORRY TO BE DISOBLIGING ABOUT THE PHOTOGRAPHERS," WROTE CHARLES DARWIN, "BUT I CANNOT ENDURE THE THOUGHT OF SITTING AGAIN."





The Huntington Library

Despite the reclusive naturalist's lifelong efforts to avoid public lectures, dinner parties and photography sessions, a few early lensmen managed to capture Charles Darwin's image. This newly rediscovered portrait—recently acquired by the Huntington Library in San Marino, Calif.—is the work of Herbert Rose Barraud (1845–1896), a London photographer of Victorian celebrities. Unpublished for more than a century, it was made in 1881, the year before Darwin died, and was probably the evolutionist's last.

Over the past 20 years, Gene Kritsky, an entomologist at the College of Mount St. Joseph in Cincinnati, has gathered some 53 photographs of Darwin, including a stereoscopic view [see "Darwin in 3-D," "Science and the Citizen," SCIENTIFIC AMERICAN, August 1985]. When the Huntington Library's new portrait turned up among a donor's massive contribution of Darwiniana, historian of science Ralph Colp, Jr., asked Kritsky if he could identify it. From references in his own collection, Kritsky not only came up with the name of the photographer and the date of the sitting but also opined that it was Darwin's final portrait.

Darwin's visitors often came away deeply impressed with the biologist's face, which seemed to express his character completely. One author who met him described Darwin's "quiet contemplative look" that was "both penetrative and meditative." His gaze had "the keenness and sensitiveness of the man whom nothing escaped…whose eyes seemed to pierce beneath the surface of things." Another pilgrim to Down House in Kent saw in the aging scientist "a Socrates come to life…with the high-domed brow of the true philosopher." Francis Darwin recalled that his father "did not realise that he would be recognised from his photographs, and I remember his being uneasy at being recognised by a stranger at the Crystal Palace Aquarium."

In 1869 a German translator asked Darwin to pose for a joint photograph with Alfred Russel Wallace, his friendly rival and co-discoverer of evolution by natural selection. Darwin declined to travel from his country home to a London studio for what would have been a historic double portrait. Sitting for a photograph, he wrote, "is what I hate doing & wastes a whole day owing to my weak health; and to sit with another person would cause still more trouble & delay." Even the staunchest Darwinians, however, admit that their hero disliked sharing credit for "his" theory. Last year Wallace's descendant, John Wallace, was asked whether his family resented Darwin for having so completely overshadowed his junior partner. "Grandfather didn't mind," Wallace replied good-naturedly. "Why should we?"

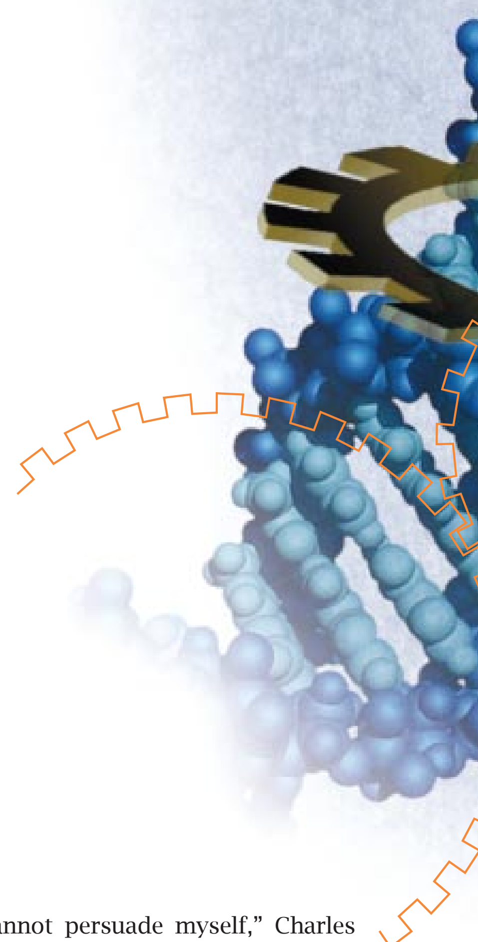
RICHARD MILNER is the author of The Encyclopedia of Evolution: Humanity's Search for Its Origins *(Henry Holt, 1993) and* Charles Darwin: Evolution of a Naturalist *(Facts on File, 1994).*

"PENETRATIVE AND MEDITATIVE, HIS GAZE HAD THE KEENNESS AND SENSITIVENESS OF THE MAN WHOM NOTHING ESCAPED…WHOSE EYES SEEMED TO PIERCE BENEATH THE SURFACE OF THINGS."

God's Utility Function

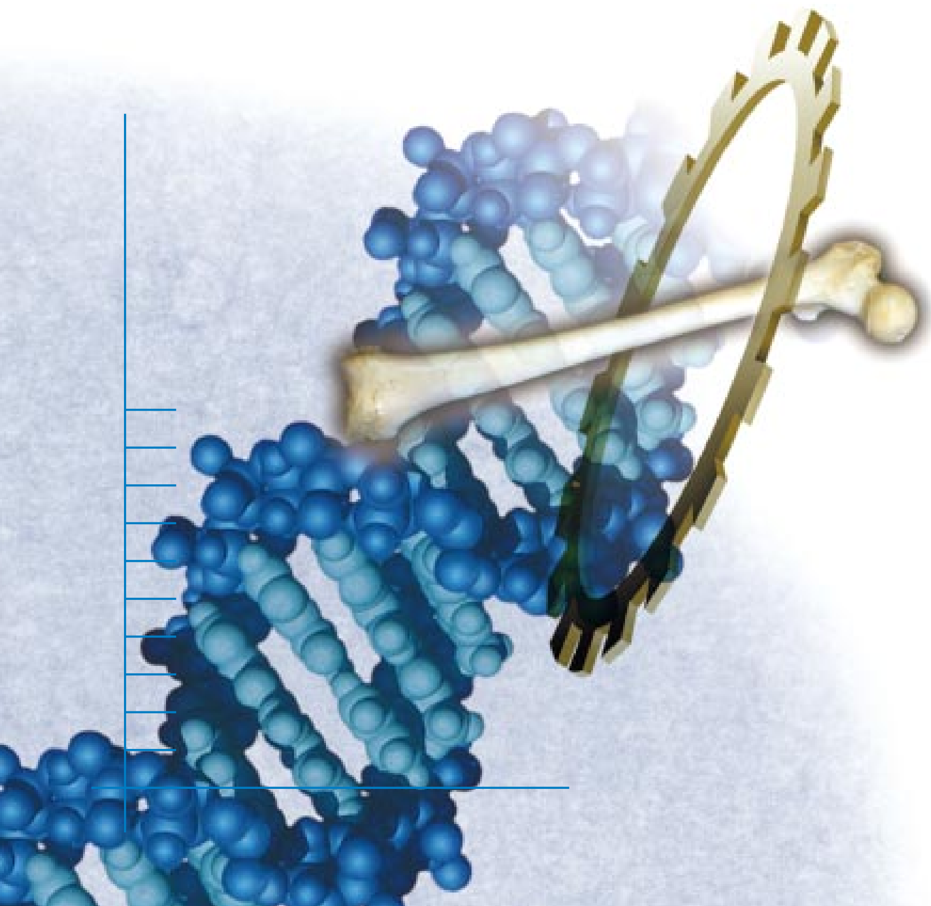
Humans have always wondered about the meaning of life. According to the author, life has no higher purpose than to perpetuate the survival of DNA

by Richard Dawkins



In his many books on evolution and natural selection, Richard Dawkins examines the topics not from the perspective of individual organisms (as Charles Darwin did) but instead from what he has termed "the gene's-eye view." The genes in living creatures today are, he claims, the "selfish" ones that ensured their own survival by enabling their hosts—what Dawkins calls "survival machines"—to live long enough to reproduce. Dawkins argues that the complexity of life can be explained by the extraordinary contest among genes for survival, rather than by any grand purpose in the universe.

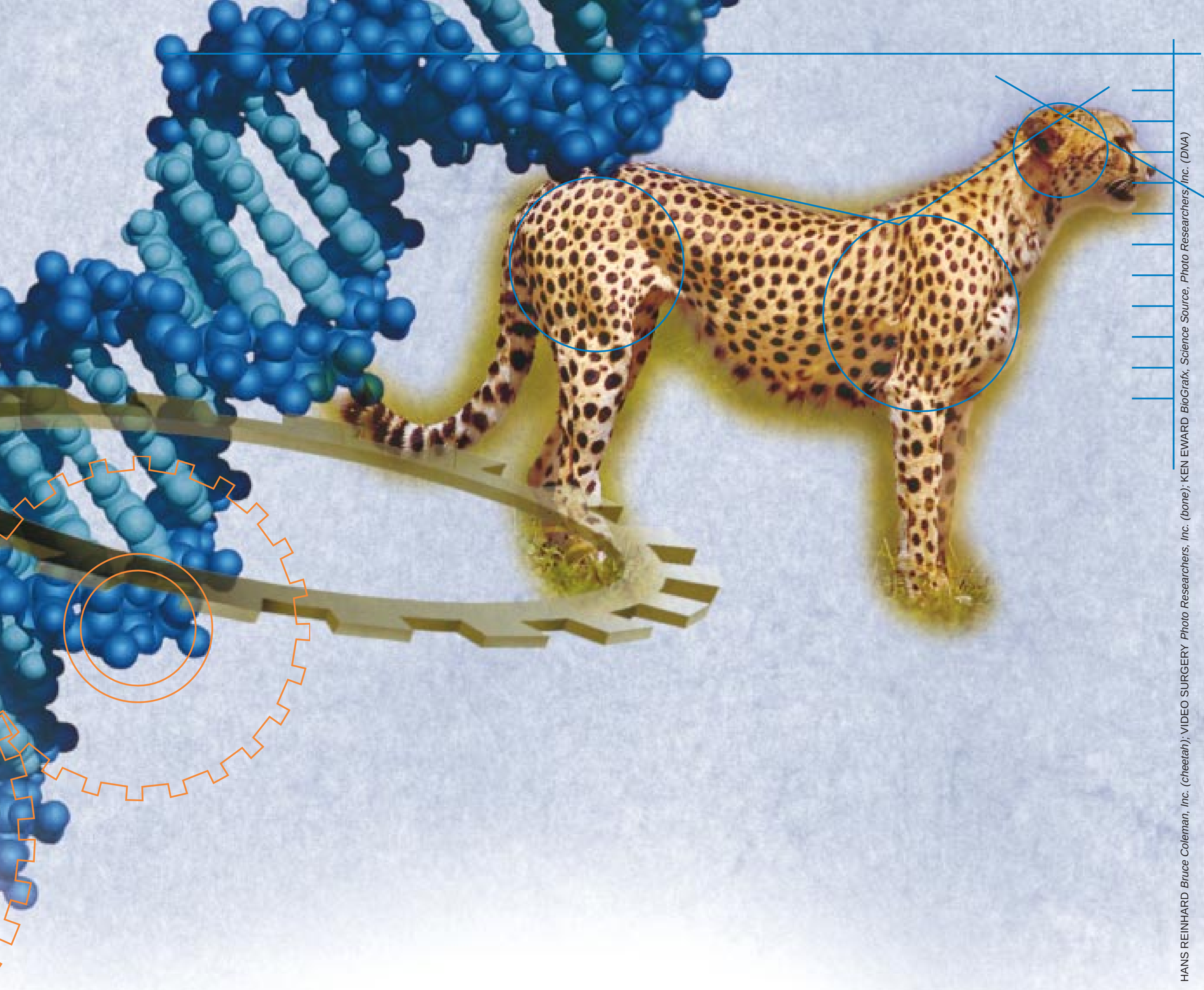
In his recently published book, River Out of Eden: A Darwinian View of Life, *Dawkins explains how the struggle of genes to replicate might account for some of the central mysteries of life, including "How did life begin?" and "Why are we here?" The article that follows is adapted from a chapter of* River Out of Eden *(BasicBooks, 1995).*



DIGITAL COMPOSITION BY TOM DRAPER

I cannot persuade myself," Charles Darwin wrote, "that a beneficent and omnipotent God would have designedly created the Ichneumonidae with the express intention of their feeding within the living bodies of Caterpillars." The macabre habits of the Ichneumonidae are shared by other groups of wasps, such as the digger wasps studied by the French naturalist Jean Henri Fabre.

Fabre reported that before laying her egg in a caterpillar (or grasshopper or bee), a female digger wasp carefully guides her sting into each ganglion of the prey's central nervous system so as to paralyze the animal but not kill it. This way, the meat stays fresh for the growing larva. It is not known whether the paralysis acts as a general anesthetic or if it is like curare in just freezing the victim's ability to move. If the latter, the prey might be aware of being eaten alive from inside but unable to move a muscle to do anything about it. This sounds savagely cruel, but, as we shall see, Nature is not cruel, only pitilessly



“SURVIVAL MACHINES,” as the author describes living creatures, are engineered by natural selection to propagate DNA. The cheetah constitutes one of the most dramatic examples.

HANS REINHARD *Bruce Coleman, Inc. (cheetah)*; VIDEO SURGERY *Photo Researchers, Inc. (bone)*; KEN EWARD *BioGrafx, Science Source, Photo Researchers, Inc. (DNA)*

indifferent. This lesson is one of the hardest for humans to learn. We cannot accept that things might be neither good nor evil, neither cruel nor kind, but simply callous: indifferent to all suffering, lacking all purpose.

We humans have purpose on the brain. We find it difficult to look at anything without wondering what it is “for,” what the motive for it or the purpose behind it might be. The desire to see purpose everywhere is a natural one in an animal that lives surrounded by machines, works of art, tools and other designed artifacts—an animal, moreover, whose waking thoughts are dominated by its own goals and aims.

Although a car, a tin opener, a screwdriver and a pitchfork all legitimately warrant the “What is it for?” question, the mere fact that it is possible to frame a question does not make it legitimate or sensible to do so. There are many things about which you can ask “What is its temperature?” or “What color is it?” but you may not ask the temperature question or the color question of, say, jealousy or prayer. Similarly, you are right to ask “Why?” of a bicycle’s mudguards or the Kariba Dam, but at the very least you have no right to assume that the question deserves an answer when posed about a boulder, a misfortune, Mount Everest or the universe. Questions can be simply inappropriate, however heartfelt their framing.

Somewhere between windscreen wipers and tin openers on the one hand, and rocks and the universe on the other, lie living creatures. Living bodies and their organs are objects that, unlike rocks, seem to have purpose written all over them. Notoriously, of course, the apparent purposefulness of living bodies has dominated the reasoning of theologians from Thomas Aquinas to William Paley. For example, Paley, the 18th-century English theologian, asserted that if an object as comparatively simple as a watch requires a watchmaker, then far more complicated living creatures must certainly have been divinely designed. Modern “scientific” creationists also support this “argument from design.”

The true process that has endowed wings, eyes, beaks, nesting instincts and everything else about life with the strong illusion of purposeful design is now well understood. It is Darwinian natural selection. Darwin realized that the organisms alive today exist because their ancestors had traits allowing them and their progeny to flourish, whereas less fit individuals perished with few or no offspring. Our understanding of evolution has come astonishingly recently, in the past century and a half. Before Darwin, even educated people who had abandoned the “Why” question for rocks, streams and eclipses still implic-

PAT GREANY *USDA*

SCOTT NIELSEN *Bruce Coleman, Inc.*

itly accepted the legitimacy of the "Why" question where living creatures were concerned. Now only the scientifically illiterate do. But "only" conceals the unpalatable truth that we are still talking about an absolute majority of the world's population.

Engineering a Cheetah

Darwin assumed that natural selection favored those individuals best fitted to survive and reproduce. This statement is equivalent to saying that natural selection favors those genes that replicate through many generations. Although the two formulations are comparable, the "gene's-eye view" has several advantages that become clear when we consider two technical concepts: reverse engineering and utility function.

Reverse engineering is a technique of reasoning that works like this: you are an engineer, confronted with an artifact you have found and do not understand. You make the working assumption that it was designed for some purpose. You dissect and analyze the object with a view to working out what problem it would be good at solving: "If I had wanted to make a machine to do so and so, would I have made it like this? Or is the object better explained as a machine designed to do such and such?"

The slide rule, talisman until recently of the honorable profession of engineer, is as obsolete in the electronic age as any Bronze Age relic. An archaeologist of the future, finding a slide rule and wondering about it, might note that it is handy for drawing straight lines or for buttering bread. But a mere straightedge or butter knife would not have needed a sliding member in the middle. Moreover, the precise logarithmic scales are too meticulously disposed to be accidental. It would dawn on the archaeologist that, in an age before electronic calculators, this pattern would constitute an ingenious trick for rapid multiplication and division. The mystery of the slide rule would be solved by reverse engineering, using the assumption of intelligent, economical design.

We humans have purpose on the brain. We find it difficult to look at anything without wondering what it is "for"—what the "motive" for it or the purpose behind it might be.

"Utility function" is a technical term not of engineers but of economists. It means "that which is maximized." Economic planners and social engineers are rather like architects and physical engineers in that they strive to optimize something. Utilitarians strive for "the greatest happiness of the greatest number." Others avowedly increase their own happiness at the expense of the common welfare. If you reverse-engineer the behavior of one country's government, you may conclude that what is being optimized is employment and universal welfare. For another country, the utility function may turn out to be the continued power of the president, the wealth of a particular ruling family, the size of the sultan's harem, the stability of the Middle East or the maintenance of the price of oil. The point is that more than one utility function can be imagined. It is not always obvious what individuals, firms or governments are striving to achieve.

Let us return to living bodies and try to extract their utility function. There could be many, but it will eventually turn out that they all reduce to one. A good way to dramatize our task is to imagine that living creatures were made by a Divine Engineer and try to work

GREGORY G. DIMIJIAN *Photo Researchers, Inc.*

NORBERT WU

DAVID MADISON *Bruce Coleman, Inc.*

DIVERSITY OF LIFE reflects the innovative techniques that DNA exploits to maximize its survival. For example, a cheetah's leg muscles enable it to chase gazelles; gazelles, however, are well equipped to outrun cheetahs. In this life-and-death struggle, both animals strive to guarantee their survival and that of their DNA. Parasitic wasps seek to maximize survival of their DNA by preying on caterpillars: a female wasp lays an egg in a caterpillar paralyzed by her sting; after hatching, the wasp larva eats the caterpillar alive. Physical characteristics used in mating rituals are as specialized as those for hunting. Many birds, such as the Himalayan pheasant, and fish, including the Oriental sweetlips, display a kaleidoscope of color to attract mates and ensure reproduction of DNA. Plants, too, compete with others for an opportunity to reproduce. Tropical rain forests stretch toward the sky as each tree seeks more sunlight and a better chance of spreading seedlings.

out, by reverse engineering, what the Engineer was trying to maximize: God's Utility Function.

Cheetahs give every indication of being superbly designed for something, and it should be easy enough to reverse-engineer them and work out their utility function. They appear to be well designed to kill gazelles. The teeth, claws, eyes, nose, leg muscles, backbone and brain of a cheetah are all precisely what we would expect if God's purpose in designing cheetahs was to maximize deaths among gazelles. Conversely, if we reverse-engineer a gazelle, we shall find equally impressive evidence of design for precisely the opposite end: the survival of gazelles and starvation among cheetahs. It is as though cheetahs were designed by one deity, gazelles by a rival deity. Alternatively, if there is only one Creator who made the tiger and the lamb, the cheetah and the gazelle, what is He playing at? Is He a sadist who enjoys spectator blood sports? Is He trying to avoid overpopulation in the mammals of Africa? Is He maneuvering to boost David Attenborough's television ratings? These are all intelligible utility functions that might have turned out to be true. In fact, of course, they are all completely wrong.

The true utility function of life, that which is being maximized in the natural world, is DNA survival. But DNA is not floating free; it is locked up in living bodies, and it has to make the most of the levers of power at its disposal. Genetic sequences that find themselves in cheetah bodies maximize their survival by causing those bodies to kill gazelles. Sequences that find themselves in gazelle bodies increase their chance of survival by promoting opposite ends. But the same utility function—the survival of DNA—explains the "purpose" of both the cheetah and the gazelle.

Nothing can stop the spread of DNA that has no beneficial effect other than making males beautiful to females.

This principle, once recognized, explains a variety of phenomena that are otherwise puzzling—among them the energetically costly and often laughable struggles of male animals to attract females, including their investment in "beauty." Mating rituals often resemble the (now thankfully unfashionable) Miss World pageant but with males parading the catwalk. This analogy is seen most clearly in the "leks" of such birds as grouse and ruffs. A lek is a patch of ground used by male birds for displaying themselves in front of females. Females visit the lek and watch the swaggering demonstrations of a number of males before singling one out and copulating with him. The males of lekking species often have bizarre ornamentation that they show off with equally remarkable bowing or bobbing movements and strange noises. The words "bizarre" and "remarkable," of course, reflect subjective value judgments. Presumably, lekking male black grouse, with their puffed-up dances accompanied by cork-popping noises, do not seem strange to the females of their own species, and this is all that matters. In some cases, female birds' idea of beauty happens to coincide with ours, and the result is a peacock or a bird of paradise.

The Function of Beauty

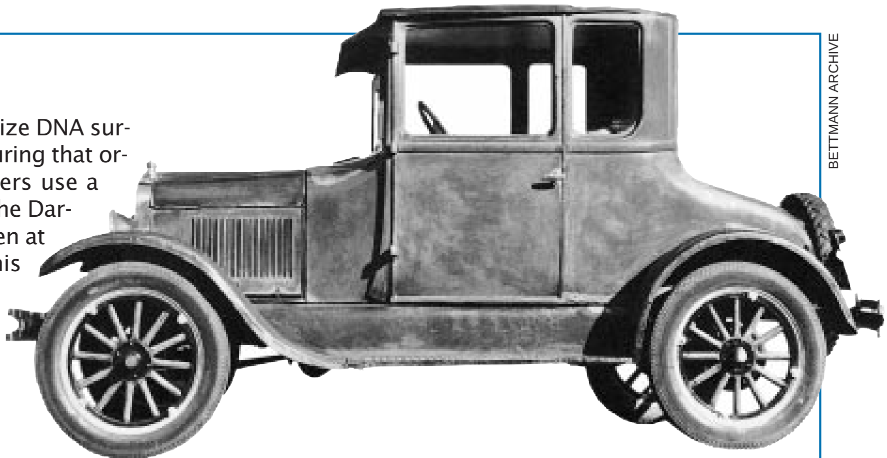
Nightingale songs, pheasant tails, firefly flashes and the rainbow scales of tropical reef fish are all maximizing aesthetic beauty, but it is not, or is only incidentally, beauty for human delectation. If we enjoy the spectacle, it is a bonus, a by-product. Genes that make males attractive to females automatically find themselves passed down to subsequent generations. There is only one utility function that makes sense of these beauties: the quantity that is being diligently optimized in every cranny of the living world is, in every case, the survival of the DNA responsible for the feature you are trying to explain.

This force also accounts for mysterious excesses. For example, peacocks are burdened with finery so heavy and cumbersome that it would gravely hamper their efforts to do useful work—if they felt inclined to do useful work, which, on the whole, they don't. Male songbirds use dangerous amounts of time and energy singing. This certainly imperils them, not only because it attracts predators but also because it drains energy and uses time that could be spent replenishing that energy. A student of wren biology claimed that one of his wild males sang itself literal-

The Great Leveler

One way multicellular organisms maximize DNA survival is by wasting little energy on ensuring that organs survive indefinitely. Automobile makers use a similar approach when constructing cars. The Darwinian psychologist Nicholas Humphrey, then at the University of Cambridge, developed this particular analogy. Humphrey, in the book *Consciousness Regained: Chapters in the Development of Mind,* supposed that Henry Ford, the patron saint of manufacturing efficiency, once

> ...commissioned a survey of the car scrapyards of America to find out if there were parts of the Model T Ford which never failed. His inspectors came back with reports of almost every kind of failure: axles, brakes, pistons—all were liable to go wrong. But they drew attention to one notable exception, the *kingpins* of the scrapped cars invariably had years of life left in them. With ruthless logic Ford concluded that the kingpins on the Model T were too good for their job and ordered that in future they should be made to an inferior specification.

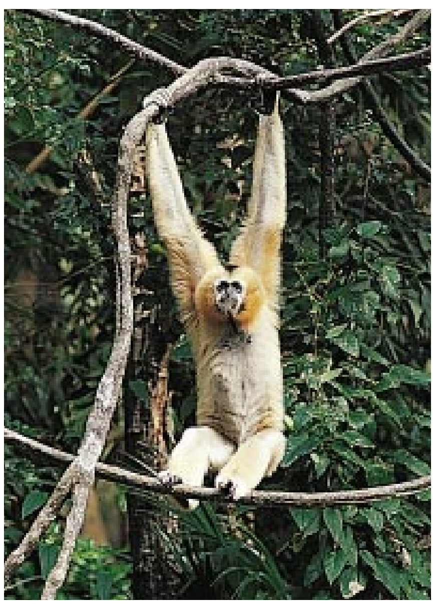


BETTMANN ARCHIVE

MODEL T was not made to run forever, so it would have been foolish to waste money on indestructible parts.

You may, like me, be a little vague about what kingpins are, but it doesn't matter. They are something that a motor car needs, and Ford's alleged ruthlessness was, indeed, entirely logical. The alternative would have been to improve all the other bits of the car to bring them up to the standard of the kingpins. But then it would not have been a Model T he was manufacturing but a Rolls-Royce, and that was not the object of the exercise. A Rolls-Royce is a respectable car to manufacture, and so is a Model T—but for a different price. The trick is to make sure that the whole car is built either to Rolls-Royce specifications or to those for the Model T. If you make a hybrid car with some components of Model T quality and some components of Rolls-Royce quality, you are getting the worst of both worlds, for the car will be thrown away when the weakest of its components wears out, and the money spent on high-quality components that never have time to wear out is simply wasted.

Ford's lesson applies even more strongly to living bodies than to cars because the components of a car can, within limits, be replaced by spares. Monkeys and gibbons make their living in the treetops, and there is always a risk of falling and breaking bones. Let's say we commissioned a survey of gibbon corpses to count the frequency of breakage in each major bone of the body. Suppose it turned out that every bone breaks at some time or another with one exception: the fibula (the calf bone that runs parallel to the shinbone) has never ever been observed to break in any gibbon. Henry Ford's unhesitating prescription would be to redesign the fibula to an inferior specification, and this is exactly what natural selection does, too. Mutant individuals with an inferior fibula, whose growth rules called for diverting precious calcium away from the fibula, could use the material saved to thicken other bones in the body and so reach the ideal of making every bone equally likely to break. Or these individuals could use the calcium saved to make more milk and so rear more young. Bone can safely be shaved off the fibula, at least up to the point where it becomes as likely to break as the next most durable bone. The alternative—the "Rolls-Royce solution" of bringing all the other components up to the standard of the fibula—is harder to achieve.



E. R. DEGGINGER *Animals, Animals*

GIBBON, too, was designed—by natural selection—with no indestructible parts.

Natural selection favors a leveling out of quality in both the downward and upward directions until a proper balance is struck over all parts of the body. Seen from the perspective of natural selection, aging and death from old age are the grim consequences of such a balancing act. We are descended from a long line of young ancestors whose genes ensured vitality in the reproductive years but made no provision for vigor in later years. A healthy youth is crucial to ensure DNA survival. But a healthy old age may be a luxury analogous to the superior kingpins of the Model T. *—R.D.*

ly to death. Any utility function that had the long-term welfare of the species at heart, or even the individual survival of a particular male, would cut down on the amount of singing, the amount of displaying, the amount of fighting among males.

Yet when natural selection is also considered from the perspective of genes instead of just the survival and reproduction of individuals, such behavior can be easily explained. Because what is really being maximized in singing wrens is DNA survival, nothing can stop the spread of DNA that has no beneficial effect other than making males beautiful to females. If some genes give males qualities that females of the species happen to find desirable, those genes, willy-nilly, will survive, even though the genes might occasionally put some individuals at risk.

Humans have a rather endearing tendency to assume that "welfare" means group welfare, that "good" means the good of society, the well-being of the species or even of the ecosystem. God's Utility Function, as derived from a contemplation of the nuts and bolts of natural selection, turns out to be sadly at odds with such utopian visions. To be sure, there are occasions when genes may maximize their selfish welfare by programming unselfish cooperation or even self-sacrifice by the organism. But group welfare is always a fortuitous consequence, not a primary drive.

The realization that genes are selfish also explains excesses in the plant kingdom. Why are forest trees so tall? Simply to overtop rival trees. A "sensible" utility function would see to it that they were all short. Then they would get exactly the same amount of sunlight with far less expenditure on thick trunks and massive supporting buttresses. But if they all were short, natural selection could not help favoring a variant individual that grew a little taller. The ante having been upped, others would have to follow suit. Nothing can stop the whole game from escalating until all trees are ludicrously and wastefully tall. But it is ludicrous and wasteful only from the point of view of a rational economic planner thinking in terms of maximizing efficiency rather than survival of DNA.

Homely analogies abound. At a cocktail party, everybody talks themselves hoarse. The reason is that everybody else is shouting at the top of their voices. If only everyone could agree to whisper, they would hear one another exactly as well, with less voice strain and less expenditure of energy. But agreements like that do not work unless they are policed. Somebody always spoils it by selfishly talking a bit louder, and, one by one, everybody has to follow suit. A stable equilibrium is reached only when everybody is shouting as loudly as they physically can, and this is much louder than they need from a "rational" point of view. Time and again, cooperative restraint is thwarted by its own internal instability. God's Utility Function seldom turns out to be the greatest good for the greatest number. God's Utility Function betrays its origins in an uncoordinated scramble for selfish gain.

So long as DNA is passed on, it does not matter who or what gets hurt in the process. Genes don't care about suffering, because they don't care about anything.

A Universe of Indifference

To return to our pessimistic beginning, maximization of DNA survival is not a recipe for happiness. So long as DNA is passed on, it does not matter who or what gets hurt in the process. Genes don't care about suffering, because they don't care about anything.

It is better for the genes of Darwin's wasp that the caterpillar should be alive, and therefore fresh, when it is eaten, no matter what the cost in suffering. If Nature were kind, She would at least make the minor concession of anesthetizing caterpillars before they were eaten alive from within. But Nature is neither kind nor unkind. She is neither against suffering nor for it. Nature is not interested in suffering one way or the other unless it affects the survival of DNA. It is easy to imagine a gene that, say, tranquilizes gazelles when they are about to suffer a killing bite. Would such a gene be favored by natural selection? Not unless the act of tranquilizing a gazelle improved that gene's chances of being propagated into future generations. It is hard to see why this should be so, and we may therefore guess that gazelles suffer horrible pain and fear when they are pursued to the death—as many of them eventually are.

The total amount of suffering per year in the natural world is beyond all decent contemplation. During the minute that it takes me to compose this sentence, thousands of animals are being eaten alive, many others are running for their lives, whimpering with fear, others are being slowly devoured from within by rasping parasites, thousands of all kinds are dying of starvation, thirst and disease. It must be so. If there is ever a time of plenty, this very fact will automatically lead to an increase in population until the natural state of starvation and misery is restored.

In a universe of electrons and selfish genes, blind physical forces and genetic replication, some people are going to get hurt, other people are going to get lucky, and you won't find any rhyme or reason in it, nor any justice. The universe that we observe has precisely the properties we should expect if there is, at bottom, no design, no purpose, no evil and no good, nothing but pitiless indifference. As that unhappy poet A. E. Housman put it:

For nature, heartless, witless nature
Will neither care nor know

DNA neither cares nor knows. DNA just is. And we dance to its music.

The Author

RICHARD DAWKINS, an Englishman, was born in Kenya in 1941. Educated at the University of Oxford, he completed his doctorate in zoology under the Nobel Prize–winning ethologist Niko Tinbergen. After two years on the faculty of the University of California, Berkeley, Dawkins returned to Oxford, where he is now a reader in zoology and a fellow of New College. Dawkins is well known for his books *The Selfish Gene* and *The Blind Watchmaker.* His next book, *Climbing Mount Improbable,* will be published by W. W. Norton in the spring of 1996. Dawkins will soon take up the newly endowed Charles Simonyi Chair of Public Understanding of Science at Oxford.

Further Reading

THE EXTENDED PHENOTYPE: THE LONG REACH OF THE GENE. Richard Dawkins. Oxford University Press, 1989.

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The Discovery of X-rays

One hundred years ago this month, Wilhelm Conrad Röntgen cast the first x-ray images by chance

by Graham Farmelo

The maid had to be dispatched several times to call him from his laboratory. When Wilhelm Conrad Röntgen, the head of the physics department at the University of Würzburg, finally joined his wife at the dinner table, he was distracted, eating little and saying less. No sooner had they finished their meal than he returned to his work. It was November 8, 1895. For several months, Röntgen had been investigating the behavior of cathode rays, later identified by other scientists as electrons.

He knew that these rays, copiously produced in a special evacuated tube charged with high-voltage electricity, penetrated only a few centimeters of air. And so he was astonished on that Friday evening before dinner to see a flickering image so far away from the tube that it could not have been caused by the cathode rays, but it appeared only when they were present.

Röntgen pursued the matter intensively that night, failing to hear an elderly laboratory assistant knock at the door, enter and leave. For days after, he ate and slept in his laboratory. (So preoccupied was he with this puzzle that he ignored a cardinal rule of experimentation—he did not begin to take notes until nearly a week later.) Only by repeating the experiment many times did Röntgen come to believe that a new type of ray had cast the image he saw. Because he did not know the nature of these rays, he called them x-rays—"x" for unknown.

He told no one but his closest friend, Würzburg zoologist Theodor H. Boveri, about the rays. "I have discovered something interesting," he said, "but I do not know whether or not my observations are correct." First to witness his experiments was his wife, Bertha, whom he invited into his laboratory on the Sunday before Christmas. There he made a portrait exposing the bones in her left hand—the first permanent x-ray photograph of a part of the human body [*see top left illustration in box on page 88*].

The week after Christmas, Röntgen published a short paper, and by the first week of the new year, newspapers all over the world began reporting his discovery. Never before had a scientific breakthrough caused such excitement in the popular press. Any number of truly remarkable inventions emerged during the late 19th century, but the public was particularly fascinated by Röntgen's find; it provided a way to probe the human body without cutting it open.

The diagnostic potential of x-rays was grasped almost immediately. Within a month, surgeons in Europe and the U.S. were using them in a variety of ways. Perhaps the most bizarre early application was an attempt, described by the College of Physicians and Surgeons in New York City, "to reflect anatomic diagrams directly into the brains of their students, making a much more enduring impression than the ordinary methods of learning anatomic details." Some 20 years would pass before scientists determined the true nature of x-rays. All the same, Röntgen's initial announcement proved to be one of the most celebrated in the history of physics—despite the several scientists at the time who argued that it owed more to luck than to skill.

Cathode Rays

Although he eventually attained celebrity as a physicist, Röntgen had originally planned to become an engineer. He was born in 1845 into a well-to-do mercantile family in the small town of Lennep in northwestern Germany and spent most of his childhood in the Netherlands. At age 20, he moved to Zurich and three years later graduated with a bachelor's degree in engineering from the Federal Institute of Technology. Although Röntgen had not taken any experimental physics courses as an undergraduate, he decided to pursue graduate work in the field, persuaded in part by his mentor, August E. E. Kundt, professor of physics at the institute.

After receiving his Ph.D. in 1869, Röntgen held a series of teaching positions at sundry German universities. In collaboration with Kundt, he made careful studies of the behavior of matter and was, for example, the first to demonstrate (using a homemade thermometer) that it is easier to heat humid air than dry air. Other aspects of his work lent strong support to the unified theory of electricity and magnetism put forward in the 1870s by Scottish mathematical physicist James Clerk Maxwell.

Röntgen was 43 years old when he became professor of physics and director of the physical institute at the university in Würzburg, a small, prosperous Bavarian city. On the second floor of the institute, he and his wife shared ample accommodations, including a study connected to one of two private laboratories. This appointment must have given him considerable pleasure; 18 years earlier the university had not allowed him to pursue a position as a professor there, because he could not produce an *Abitur,* a certificate testifying that he had completed high school.

Röntgen devoted a good deal of time to winning laboratory space, additional staff and other resources for the fledgling physics department at Würzburg. By dint of his efforts, he sought to make it among the best in Germany. His colleagues knew him to be a particularly ambitious, meticulous worker, who was extraordinarily knowledgeable about the latest developments in all areas of physics. Although he was sociable, during his entire working life he hardly exchanged a professional word with another physicist.

In June 1894 he began studying cathode rays, then an extremely popular research topic. German physicist Eugen Goldstein of the University of Berlin had named these rays 18 years earlier. Goldstein and several others established that cathode rays were negatively charged and that they traveled considerably slower than the speed of light. But one central puzzle remained: whereas most British physicists believed that these rays were particles, their German counterparts thought them to be disturbances in some all-pervasive ether.

We shall probably never know Röntgen's motivation in turning his attention to cathode rays. His notebooks indicate that he was checking results obtained by two experimenters at the University of Bonn—the recently deceased Heinrich R. Hertz, the discoverer of radio waves, and his assistant, Philipp E. A. Lenard. Röntgen's work was interrupted in the fall, when he was elected rector of the university, its highest office. Some scientists become addicted to the manifold pleasures of administration, but not Röntgen. By the autumn of the following year, he had returned to his laboratory.

Discovery Day

Today a visitor to room 119A of the Technical College in Würzburg can quickly tell that it is a special part of the building [*see illustration on page 91*]. It was in this high-ceilinged space, six meters square, overlooking the botanical gardens and leafy Pleicher Ring road (now called the Röntgen Ring), that Röntgen made the discovery that was to astonish the world. Although this one-room museum does not contain the actual apparatus he used, it breathes history. It is no wonder that the college staff reverentially lower their voices when they usher visitors into the shrine.

The night of November 8, 1895, together with its seven-week aftermath of secrecy, is a rich source of fascination and speculation. Röntgen himself did much to fuel this interest, no doubt unintentionally, by his characteristic reticence and inscrutability, and also because he never gave a definitive account of what actually happened. The description here is, therefore, a version of the events, compiled from Röntgen's reported comments and scant writings.

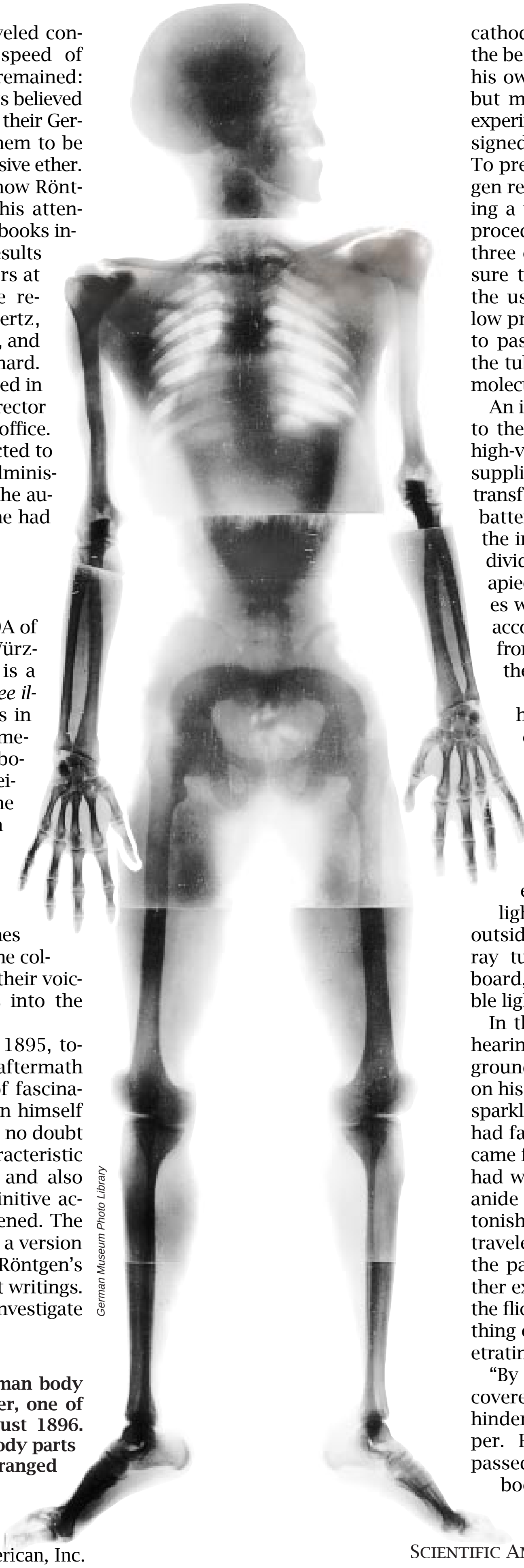
The equipment he used to investigate cathode rays was at that time among the best available. He preferred to build his own apparatus whenever possible, but most of the equipment for these experiments had been supplied and designed by leading instrument makers. To prepare his cathode-ray tube, Röntgen removed gas and vapor from it using a vacuum pump. In this standard procedure, the tube was pumped for three or four days to reduce the pressure to below about a thousandth of the usual atmospheric pressure. This low pressure enabled the cathode rays to pass as freely as possible through the tube, colliding only rarely with gas molecules.

An induction coil, similar in principle to the transformer that generates the high-voltage sparks in a car's engine, supplied the electric current. Röntgen's transformer took a 20-volt supply from batteries housed in the basement of the institute and converted it into individual pulses of about 35,000 volts apiece. Every second about eight pulses were generated, each one audibly accompanied by a loud crack coming from the electrical discharge between the ends of the secondary coil.

Röntgen was working alone, as he normally did. He knew well that cathode rays caused a barium platinocyanide–coated screen to fluoresce with a characteristic green color. But he probably found this glow difficult to discern because he was partially color blind. So he darkened the room and blocked all light coming from the gaslit street outside. He also covered the cathode-ray tube with pieces of black cardboard, pasted together so that no visible light could escape from the tube.

In the pitch-black of the laboratory, hearing the coil snapping in the background, Röntgen happened to notice on his worktable a small piece of paper sparkling as though a single ray of light had fallen on it. This light, he realized, came from the letter "A" that a student had written on the sheet in platinocyanide solution. He must have been astonished: cathode rays could not have traveled the distance from his tube to the paper to reveal its markings. Further experiments indicated that indeed the flickering light was caused by something emitted from the tube more penetrating than cathode rays.

"By accident," Röntgen said, he discovered that this emanation went unhindered through a piece of black paper. He then demonstrated that it passed through a playing card. A thick book, he noted, cast a sharp shad-



German Museum Photo Library

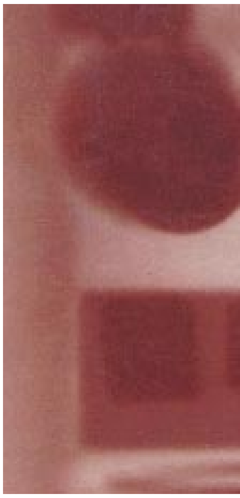
FIRST X-RAY IMAGE of a human body was made by Ludwig Zehnder, one of Röntgen's assistants, in August 1896. The photographs are of the body parts of several people. Exposures ranged from five to 15 minutes.

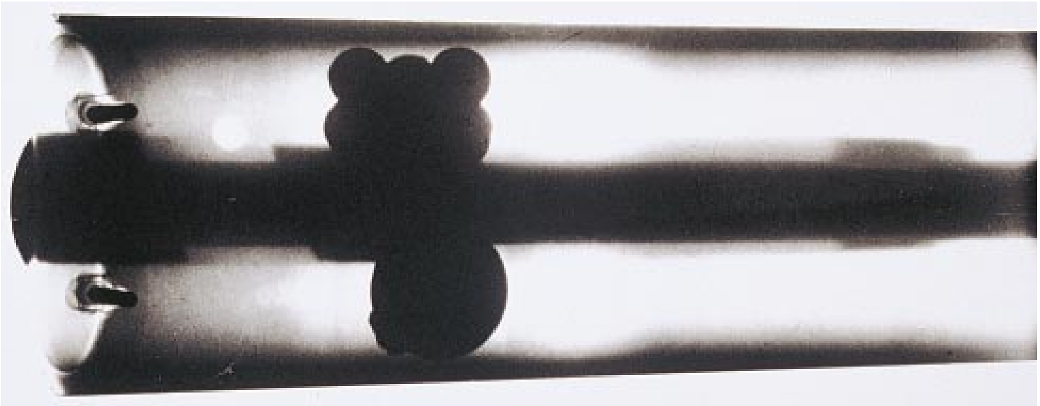
Lasting Uses for X-ray Imaging

Röntgen pioneered three key applications of x-ray imaging during his initial investigations. First, he took an x-ray photograph of a closed wooden box of weights that clearly displayed its contents, presaging the security application familiar to every airline passenger (*top right*). He also took an x-ray image of his hunting rifle that showed an internal flaw (*bottom left*). X-rays are now commonly used in manufacturing to reveal hidden structural defects in a variety of objects. In addition, Röntgen made a permanent x-ray of his wife's left hand—the first such photograph taken of a part of the human body (*top left*).

German Museum Photo Library

First x-ray of a part of the human body





Röntgen's hunting rifle

ow on the screen, giving a clear indication that he was observing rays of some kind, moving in straight lines. When he examined the extent to which the rays penetrated metals, he had perhaps the biggest surprise of all. As he put a small piece of lead in the path of the rays, he saw not only the object's dark shadow, but a fainter shadow in the shape of his thumb and finger as well. That shadow in turn enclosed another set outlining the bones of his hand.

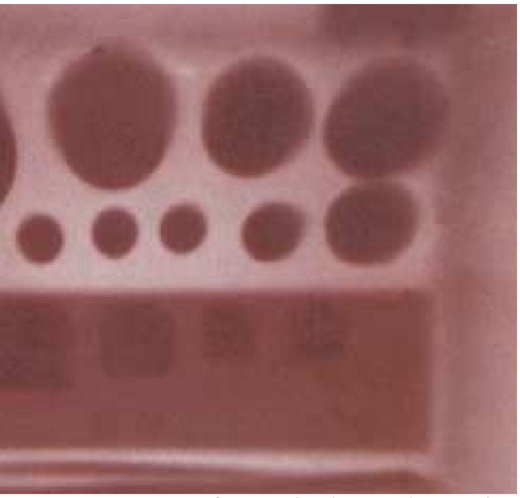
Röntgen elucidated the properties of x-rays in a classic piece of experimentation. Using a magnet to deflect a beam of cathode rays so that it struck the side of the vacuum tube in different areas, he convinced himself—in a matter of minutes—that the x-rays were emitted from the point at which the cathode rays hit the interior wall of the tube and not from any other point in the circuit. He also showed that magnetic forces did not affect x-rays, confirming that they had no electrical charge.

Röntgen next determined that x-rays, like cathode rays, could darken a photographic plate. By placing objects between the source of the rays and the plate, he took permanent x-ray photographs, exploiting the differing abilities of materials to transmit the rays. In taking these photographs, he pioneered three key areas of x-ray imaging. First, a photograph of his closed wooden box of weights clearly revealed its contents, thus presaging the security application found at every airport check-in.

Second, an x-ray image of his hunting rifle revealed a flaw inside the metal of the gun: it was the first time a hidden structural flaw had been exposed without destroying the object. Finally, and most startling of all, he took a permanent x-ray photograph of his wife's left hand, revealing the bones and the rings that she was wearing. To produce this image, Bertha held her hand still against the plate for about 15 minutes, which gave her a dose of x-rays that dangerously exceeded the limits set in modern health and safety standards. Such are the hazards that pioneers unwittingly face.

Röntgen carefully compared the properties of x-rays with those of visible light. Although both are electrically neutral and can cast sharp shadows, he found that in other ways, the x-rays appeared to differ from light. He was unable to reflect them, nor could he refract them (he could not change their direction by making them traverse from one medium to another, for example, by passing them through a glass prism). In addition, he found no evidence that they could be diffracted (the rays did not bend around obstacles in their path).

The similarities between x-rays and light nonetheless led Röntgen to propose that they were in some way related. According to the theory put forward by Maxwell in 1873, light is an electromagnetic wave propagating in the ether, having electrical and magnetic signals



X-ray of a wooden box and optical photograph of the same box (below)

Photographs in box (except as noted) and portrait at right from *100 Jahre Röntgenstrahlen: 1895–1995*, exhibition catalogue from the University of Würzburg, 1995

vibrating perpendicular to the wave's direction of motion. Röntgen tentatively suggested that the x-rays were vibrations in the ether in the same direction in which the rays were traveling. This speculation—which turned out to be wrong—concluded his paper, *On a New Kind of Rays, a Preliminary Communication*, a masterpiece of experimental physics and concise reporting for which the University of Würzburg receives requests to this day.

Three days after Christmas in 1895, he gave the 10-page, handwritten manuscript to the secretary of the Würzburger Physical Medical Society with the unusual request that it be published quickly. On New Year's Day, after posting copies of his manuscript and photographs to several leading European physicists, he remarked to his wife: "Now there will be the devil to pay."

The Immediate Aftermath

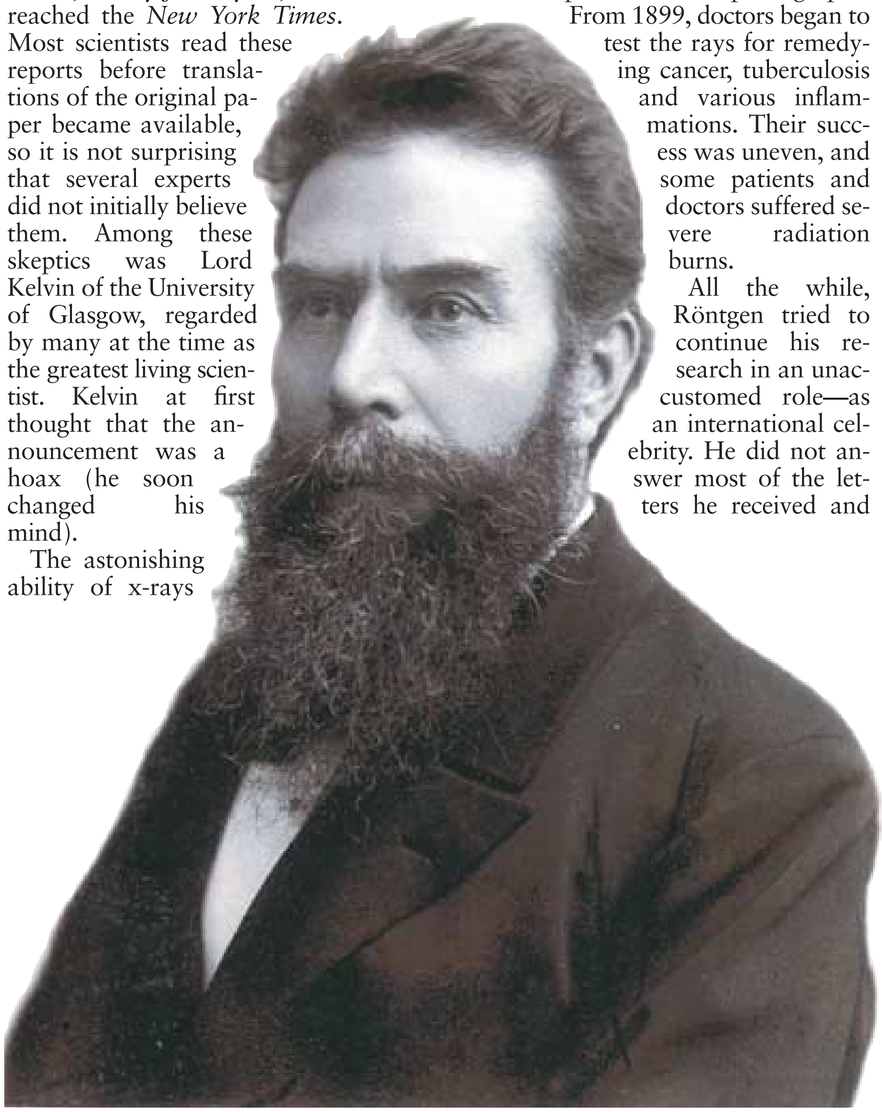
"In a few days I was disgusted with the business. I could not recognize my own work in the reports any more," Röntgen wrote to a former assistant about a month after the news of his discovery broke. He was angry and upset by the initial newspaper stories, which seized on his remarkable photographs as though they represented by far the most important aspect of his experiments. Röntgen himself was far more interested in discovering both the true nature and the properties of x-rays.

The first newspaper account appeared on Sunday, January 5, in the Vienna *Presse*, and by January 16, word had reached the *New York Times*. Most scientists read these reports before translations of the original paper became available, so it is not surprising that several experts did not initially believe them. Among these skeptics was Lord Kelvin of the University of Glasgow, regarded by many at the time as the greatest living scientist. Kelvin at first thought that the announcement was a hoax (he soon changed his mind).

The astonishing ability of x-rays to penetrate matter gave rise to many cartoons that betrayed popular misunderstandings about the new rays. In addition, the discovery stimulated a good deal of quackery. A London firm advertised its "x-ray-proof underclothing," and French enthusiasts made attempts at "photographing the soul." In Iowa, a farmer reported that he had used the new rays to transform a 13-cent piece of metal into gold worth $153.

Engineers and photographers were on the whole even quicker than doctors to grasp the potential of x-ray devices. As the American journal *Electrical Engineer* commented in March 1896, "It is safe to say that there is probably no one possessed of a vacuum tube and an induction coil, who has not undertaken to repeat Professor Röntgen's experiments." By the end of the year hundreds of crude x-ray machines were in operation. The first attempts at radiography were haphazard because its practitioners could only guess at the exposures needed to produce clear photographs. From 1899, doctors began to test the rays for remedying cancer, tuberculosis and various inflammations. Their success was uneven, and some patients and doctors suffered severe radiation burns.

All the while, Röntgen tried to continue his research in an unaccustomed role—as an international celebrity. He did not answer most of the letters he received and



WILHELM CONRAD RÖNTGEN was a meticulous and solitary experimenter who scarcely spoke a professional word to another physicist. His unexpected discovery of x-rays caused a great sensation in the world's press and brought him attention and celebrity that he quickly came to shun.

refused all but two lecture invitations. One acceptance came in response to a summons from the Imperial Court in Berlin. He was asked to demonstrate his discovery on January 13 to the emperor, Wilhelm II, whom Röntgen admired for his politics and interest in science. After the successful demonstration, the emperor awarded Röntgen the Prussian Order of the Crown (Second Class) and promptly commissioned three other scientists to investigate the military potential of the discovery. Röntgen knew of this work but neither helped nor hindered it.

He gave a second lecture for the faculty and students at Würzburg, high-ranking members of the military and local officials. Speaking quietly, in a pronounced Dutch accent, Röntgen presented his results and delighted his audience by preparing in front of them an x-ray photograph of his friend's hand. This friend and colleague, E. Albert von Kölliker, who was one of the founders of histology, called for three cheers and proposed that the rays should thereafter be called Röntgen rays. Against Röntgen's wishes, this name was soon adopted in all German-speaking countries, where it is still used today.

The First Nobel

Despite the unwelcome distractions of fame, Röntgen completed two more papers on x-rays, one in March 1896 and the other a year later. In these short papers, written in the same concise style as the first, he reported on the effects of exposing various materials to x-rays. For the rest of his life, he wrote nothing more about them, although he continued to investigate their properties.

Shortly after the discovery of x-rays, Alfred Nobel drew up his last will and testament, in which he endowed the prizes that bear his name. In 1901 the first Nobel Prize for Physics was awarded to Röntgen. The appointing committee voted overwhelmingly in his favor, despite exceptional competition. Eight of the other 11 nominees later won a prize of their own.

He received his insignia from the Swedish crown prince and delivered an eloquent speech of thanks at the banquet afterward but left the next day, shyly declining to give his Nobel Lecture. Although he had recently accepted a post at the University of Munich, where he remained for the rest of his academic career, he gave all the prize money to the physics department at Würzburg to provide financial support to students (interest from these funds is still used for this purpose).

Within a few months of Röntgen's discovery, there emerged several competing theories about the nature of x-rays. Two theories were especially popular. In one, the rays were described as impulses (short bursts) of electromagnetic energy, emitted when cathode rays suddenly struck matter and stopped. In the other, x-rays were envisioned simply as another type of electromagnetic wave, like visible light but with a much shorter wavelength. It was not until 1912 that important evidence in favor of the latter theory emerged from an experiment done in Munich.

Max T. F. von Laue of the Institute for Theoretical Physics brilliantly suggested that if the wave theory were correct, beams of x-rays should be diffracted by crystals, which were widely (and correctly) believed to consist of regularly spaced atoms. Von Laue passed this idea on to two students, Walter Friedrich and Paul Knipping, who quickly produced some startling patterns indicating that their x-ray beam had indeed been diffracted by crystals of zinc sulfide.

Contrary to popular belief, Friedrich and Knipping's results did not deal a swift and mortal blow to the rival theory. A few months after their results were announced, Hendrik A. Lorentz of the University of Leiden showed, using a virtuoso theoretical argument, that they could also be explained by the impulse theory. No single experiment could refute the impulse theory, and the consensus in favor of the wave theory emerged only gradually.

Science historian Arne Hessenbruch of the University of Cambridge has recently contributed important insights

Courtesy of the Science Museum, London

HOMEMADE MACHINE is believed to be the oldest surviving device for producing x-ray images. The English doctor John Reynolds and his son, Russell, began building it shortly after they read of Röntgen's discovery in the *London Standard* on January 7, 1896. The induction coil (*on top, left of center*) received electric power from seven quart-size chromic-acid batteries (*on floor, at back*). The Reynolds team wound the coil by hand, which was no small task—the secondary coil comprised more than 13 miles of wire. The high-voltage supply from the coil was then supplied to the x-ray tube, which was fixed to the mahogany stand.

into the factors that led to this consensus. He has pointed out that the influential and burgeoning community of medical radiologists had begun as early as 1907 to refer routinely to x-rays as electromagnetic waves and that workers in this field almost always espoused the wave theory. Their arguably premature acceptance of the wave theory contributed heavily to marginalizing the impulse theory.

And the wave theory had consistently given a simple explanation of the observations Röntgen made in his Würzburg laboratory. When his beam of negatively charged cathode rays (electrons) struck the side of the vacuum tube, they slowed down rapidly and lost most or all of their energy of motion. In common with all charged particles, when an electron accelerates or decelerates, it emits electromagnetic radiation. It was this radiation, in the form of deeply penetrating x-rays, that Röntgen had detected.

GRAHAM FARMELO

ROOM 119A of the Technical College in Würzburg, now a one-room museum, is where Röntgen discovered x-rays in the early evening of Friday, November 8, 1895. It is perhaps surprising that the discovery had not been made before: hundreds of physicists were doing experiments similar to Röntgen's own work at the time.

Until his death from intestinal cancer in 1923, Röntgen continued to use his fame to advance the cause of physics in Germany. It was partly through his influence with Emperor Wilhelm II that the German Museum of the history of technology was built in Munich rather than in the originally favored site of Berlin. Röntgen's most recent biographer, journalist Angelika Schedel, has found substantial evidence suggesting that Röntgen enjoyed his political work far more than is generally believed.

Although he is usually portrayed as unapproachable and introspective, Schedel points out that Röntgen probably gained this reputation because of his prolonged absences from the university while he was devotedly nursing his wife, who died in 1919 of an attack of renal colic. Heartbroken, he retired the following year.

What is perhaps most surprising about the discovery of x-rays is that it was not made sooner. Many other scientists were equipped to make the necessary observations, and the effects of x-rays had certainly been seen, if not recognized, long before 1895. Some 15 years earlier William Crookes of the University of London made note that photographic plates stored near his cathode-ray tubes were often foggy, and he even returned some of them to the manufacturer, complaining that they were unsatisfactory.

Several scientists claimed to have discovered x-rays before Röntgen, and many others dismissed his work as mere luck. The most bitter among the malcontents was Lenard, Hertz's assistant, who believed that Röntgen should have acknowledged his work. Shortly before Röntgen's breakthrough, Lenard had designed a specially modified cathode-ray tube, one of which Röntgen had obtained from him. Although Röntgen had not used Lenard's equipment when he made his discovery, Lenard ungraciously remarked that "if Röntgen was the midwife to the discovery of x-rays, I was the mother." To these and to many other slighting comments, Röntgen made no reply.

There is no doubt that Röntgen was extremely well placed to make the discovery. He possessed state-of-the-art apparatus and brought to it prodigious experimental skill and tremendous knowledge. So was he lucky? The answer must be yes, if luck can be ascribed to what happens when extraordinary preparation seizes an equally extraordinary opportunity.

The Author

GRAHAM FARMELO is currently head of programs at the Science Museum in London. He joined the museum in 1990, after a sabbatical at Northeastern University, where he is now an adjunct professor of physics. From 1977 to 1990, he was a lecturer in physics at the Open University. His research interests have included scattering of subnuclear particles and, more recently, chaos in quantum systems and in classical scattering. He enjoys literature, theater, film, music and cooking.

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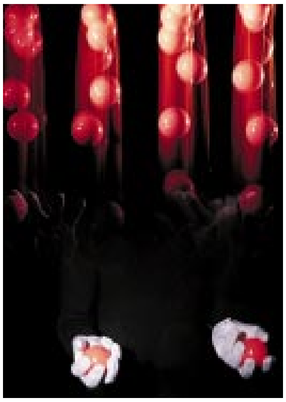


The Science of Juggling

Studying the ability to toss and catch balls and rings provides insight into human coordination, robotics and mathematics

by Peter J. Beek and Arthur Lewbel

To complete a delivery of munitions, a 148-pound man must traverse a high, creaking bridge that can support only 150 pounds. The problem is, he has three, one-pound cannonballs and time for only one trip across. The solution to this old riddle is that the man juggled the cannonballs while crossing. In reality, juggling would not have helped, for catching a tossed cannonball would exert a force on the bridge that would exceed the weight limit. The courier would in fact end up at the bottom of the gorge.

Though not practical in this case, juggling definitely has uses beyond hobby and entertainment. It is complex enough to have interesting properties and simple enough to allow the modeling of these properties. Thus, it provides a context in which to examine other, more complex fields. Three in particular have benefited.

One is the study of human movement and the coordination of the limbs. Another is robotics and the construction of juggling machines, which provides a good test bed for developing and applying principles of real-time mechanical control. The third is mathematics; juggling patterns have surprising numerical properties.

Juggling is an ancient tradition—the earliest known depiction is Egyptian, in the 15th Beni Hassan tomb of an unknown prince from the Middle Kingdom period of about 1994 to 1781 B.C.; however, the first scientific study we know of did not appear until 1903. At that time, Edgar James Swift published an article in the *American Journal of Psychology* documenting the rate at which some students learned to toss two balls in one hand. By the 1940s, early computers were being used to calculate the trajectories of thrown objects, and the International Jugglers Association was founded. The 1950s and 1960s saw a few scattered applications, mostly successors to Swift's work, which used juggling as a task to compare general methods of learning sensorimotor skills.

Finally, in the 1970s, juggling began to be studied on its own merits, as evidenced by events at the Massachusetts Institute of Technology. There, Claude E. Shannon created his juggling machines and formulated his juggling theorem, which set forth the relation between the position of the balls and the action of the hands. Seymour A. Papert and other researchers at Project MAC (which later became M.I.T.'s Artificial Intelligence Laboratory) investigated how people master the art of juggling, and the M.I.T. juggling club, one of the oldest organizations devoted to amateur juggling still in existence, was established. The 1980s witnessed the rise of the mathematics of juggling, as several workers developed a special kind of notation to summarize juggling patterns [*see box on page 94*].

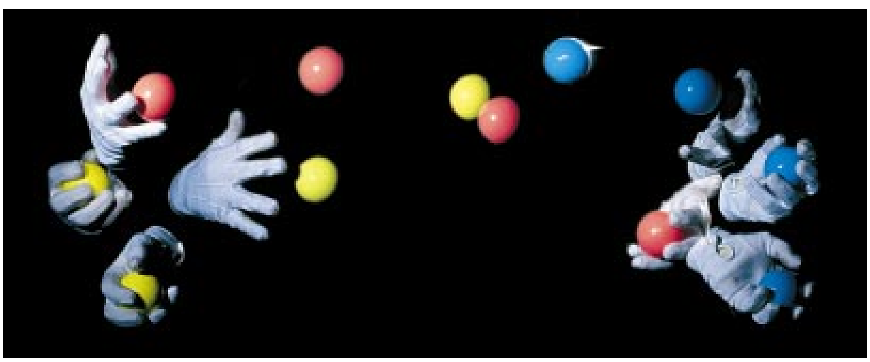
With three balls, most neophytes attempt to juggle in the shower pattern (around in a circle), although the cascade pattern—in which the hands alternate throwing balls to each other, resulting in a figure eight—is far easier. It often takes just hours or days to learn to juggle three balls. But learning times can be weeks or months for four balls, months or years for five, as practitioners refine their sense of touch and toss.

The world record for the greatest number of objects juggled (where each object is thrown and caught at least once, known as a flash) is 12 rings, 11 balls or eight clubs. The types of juggled objects, or props, affect the number because they vary in correct orientation, in the difficulty of holding and throwing them and in the margin of error to avoid collisions.

Limits on the Learning Curve

The obvious physical constraints that affect mastery and limit the number of objects juggled arise from gravity—more specifically, Newtonian mechanics. Each ball must be thrown sufficiently high to allow the juggler time to deal with the other balls. The time that a ball spends in flight is proportional to the square root of the height of the throw. The need for either speed or height increases rapidly with the number of objects juggled.

Then there is human imperfection, leading to errors of both space and time. Juggling low leaves little room to avoid collisions and hence requires catching and throwing quickly, which can cause mistakes. Throwing higher provides more time to either avoid or correct mistakes but also amplifies any error. For throws of only a few meters, a devi-



EXPERT JUGGLING relies more on the sense of touch and less on sight than does novice juggling. Hence, a professional can manage to juggle common patterns blindfolded for several minutes, from a simple exchange of balls (*opposite page*) to the four-ball fountain (*top left corner*) and the three-ball cascade (*above*).

Photographs by Ken Regan *Camera 5*; props courtesy of Dubé Juggling Equipment

EARLIEST DEPICTION OF JUGGLING known shows skillful Egyptian women on the 15th Beni Hassan tomb of an unknown prince from the Middle Kingdom period of about 1994 to 1781 B.C.

Redrawings from *Bildatlas zum Sport im Alten Ägypten*, by Wolfgang Decker

ation of just two or three degrees in the toss can cause an error in the landing location of 30 centimeters or more.

The temporal constraints on juggling are elegantly summarized by Shannon's theorem. It defines relations that must exist among the times that the hands are empty or full and the time each ball spends in the air. In other words, increasing the number of balls leaves less room to vary the speed of the juggle. If one were to juggle many balls to a certain height, the theorem indicates that even the smallest variation in tossing speed would destroy the pattern.

How jugglers coordinate their limbs to move rhythmically and at the same frequency within these constraints has become a primary focus in the study of human movement. Researchers have borrowed concepts from the mathematical theory of coupled oscillators [see "Coupled Oscillators and Biological Synchronization," by Steven H. Strogatz and Ian Stewart; SCIENTIFIC AMERICAN, December 1993].

The key phenomenon in coupled oscillation is synchronization: the tendency of two limbs to move at the same frequency. The particular type of coordination displayed by juggling hands depends on the juggling pattern. In the cascade, for instance, the crossing of the balls between the hands demands that one hand catches at the same rate that the other hand throws. The hands also take turns: one hand catches a ball after the other has thrown one.

The fountain pattern, in contrast, can be stably performed in two ways: by throwing (and catching) the balls simultaneously with both hands (in sync) or by throwing a ball with one hand and catching one with the other at the same time (out of sync). Theoretically, one can perform the fountain with different frequencies for the two hands, but that coordination is difficult because of the tendency of the limbs to synchronize.

Defining the physical and temporal constraints is one aspect of juggling analysis. A realistic model must also incorporate at least three other complicating factors. First, the oscillation of a juggling hand is not uniform, because the hand is filled with a ball during part of its trajectory and empty during the remaining part. Second, the movements of both hands are affected by the phys-

The Mathematics of Juggling

One useful method that many jugglers rely on to summarize patterns is site-swap notation, an idea invented independently around 1985 by Paul Klimek of the University of California at Santa Cruz, Bruce Tiemann of the California Institute of Technology and Michael Day of the University of Cambridge. Site swaps are a compact notation representing the order in which props are thrown and caught in each cycle of the juggle, assuming throws happen on beats that are equally spaced in time.

To see how it works, consider the basic three-ball cascade. The first ball is tossed at time periods 0, 3, 6 . . . , the second at times 1, 4, 7 . . . , and the third ball at times 2, 5, 8 . . . . Site-swap notation uses the time between tosses to characterize the pattern. In the cascade, the time between throws of any ball is three beats, so its site swap is 33333 . . . , or just 3 for short. The notation for the three-ball shower (first ball 0, 5, 6, 11, 12 . . . , second ball 1, 2, 7, 8, 13 . . . , third ball 3, 4, 9, 10, 15 . . . .) consists of two digits, 51, where the 5 refers to the duration of the high toss and the 1 to the time needed to pass the ball from one hand to the other on the lower part of the arc. Other three-ball site swaps are 441, 45141, 531 and 504 (a 0 represents a rest, where no catch or toss is made).

The easiest way to unpack a site swap to discover how the balls are actually tossed is to draw a diagram of semicircles on a numbered time line. The even-numbered points on the line correspond to throws from the right hand, the odd-numbered points to throws from the left.

As an example, consider the pattern 531. Write the numbers 5, 3 and 1 a few times in a row, each digit under the next point in the number line starting at point 0 [*see top illustration at right*]. The number below point 0 is 5, so starting there, draw a semicircle five units in diameter to point 5, representing a throw that is high enough to spend five time units (beats) in the air. The number below point 5 is a 1, so draw a semicircle of diameter 1 from point 5 to 6. Point 6 has a 5 under it, so the next semicircle is from point 6 to 11. You have now traced out the path in time of the first ball, which happens to be the same as the first ball in the three-ball shower pattern 51 described above. Repeat the process starting at times 1 and 2, respectively, to trace out the path of the remaining two balls. The result is that the first and third balls both move in shower patterns but in opposite directions, and the second ball weaves between the two showers in a cascade rhythm. Leaving out this middle ball results in the neat and simple two-ball site swap 501.

Not all sequences of numbers can be translated into legitimate juggling patterns. For example, the sequence 21 leads to both balls landing simultaneously in the same hand (although more complicated variants of site-swap notation permit more than one ball to be caught or thrown at the same time, a feat jugglers call multiplexing).

Site-swap notation has led to the invention of some patterns that are gaining popularity because they look good in performances, such as 441, or because they are helpful in mastering other routines, such as the four-ball pattern 5551 as a prelude to learning to cascade five balls. Several computer programs exist that can animate arbitrary site swaps and identify legitimate ones. Such software enables jugglers to see what a pattern looks like before attempting it or allows them simply to gaze at humanly impossible tricks.

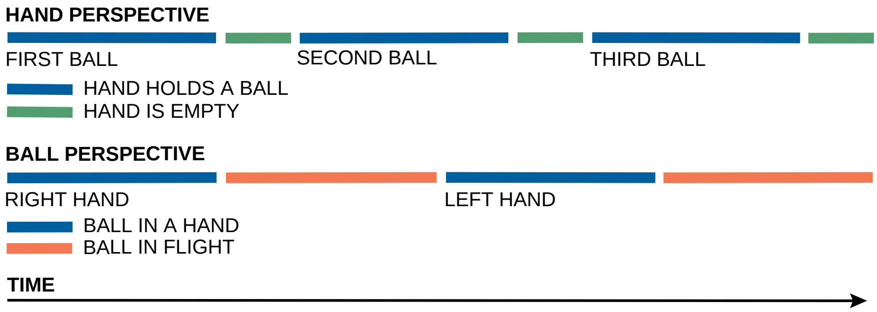
The strings of numbers that result in legitimate patterns have unexpected mathematical properties. For instance, the number of balls needed for a particular pattern equals the numerical average of the numbers in the site-swap sequence. Thus, the pattern 45141 requires $(4+5+1+4+1)/5$, or three balls. The number of legitimate site swaps that are n digits long using b (or fewer) balls is exactly b raised to the n power. Despite its simplicity, the formula was surprisingly difficult to prove.

ical demands of accurate throwing and catching. Third, the timing between the hands is based on a combination of vision, feel and memory.

These three factors render juggling patterns intrinsically variable: however solid a run, no two throws and no two catches are exactly the same. Analyzing this changeability provides useful clues about the general strategy of jugglers to produce a solid pattern that minimizes breakdown.

Variables associated with throwing (angle of release, release velocity, location of throws, height of throws) are those most tightly controlled: jugglers attempt to throw the balls as consistently as possible, the timing of which must obey Shannon's theorem. Given a height, a crucial measure of the rate of juggling is the so-called dwell ratio. It is defined as the fraction of time that a hand holds on to a ball between two catches (or throws). In general, if the dwell ratio is large, the probability of collisions in the air will be small. That is because the hand cradles the ball for a relatively long time and hence has the opportunity to throw accurately. If the dwell ratio is small, the number of balls in the air averaged over time is large, which is favorable for making corrections, because the hands have more time to reposition themselves.

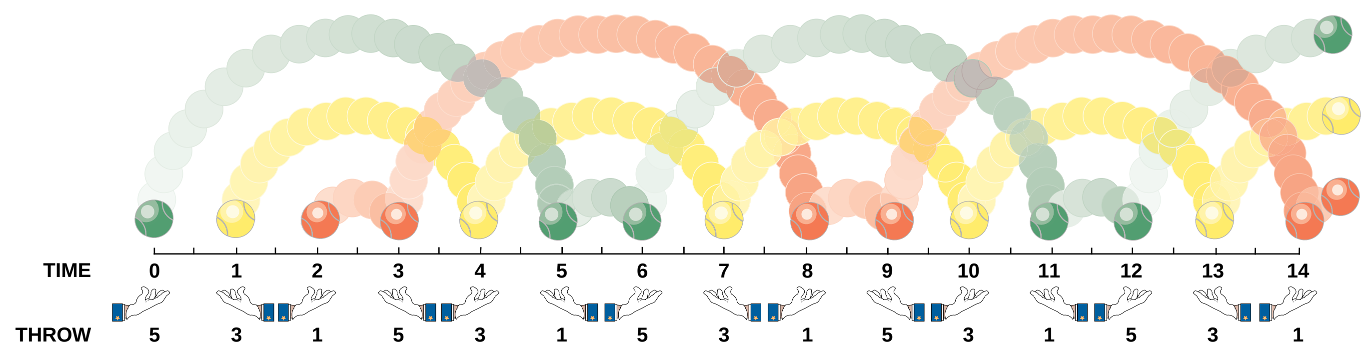
Novice jugglers will opt for larger dwell ratios to emphasize accurate tosses. More proficient jugglers tend toward smaller values, especially when juggling three balls, because of a greater flexibility to shift the pattern. Measurements by one of us (Beek) demonstrate that the ratio attained in cascade juggling changes roughly between 0.5 and 0.8, with ratios close to $^3/_4$, $^2/_3$ and $^5/_8$ most commonly observed. That is, in a three-ball cascade, the balls may spend up to twice as much time in the air as they



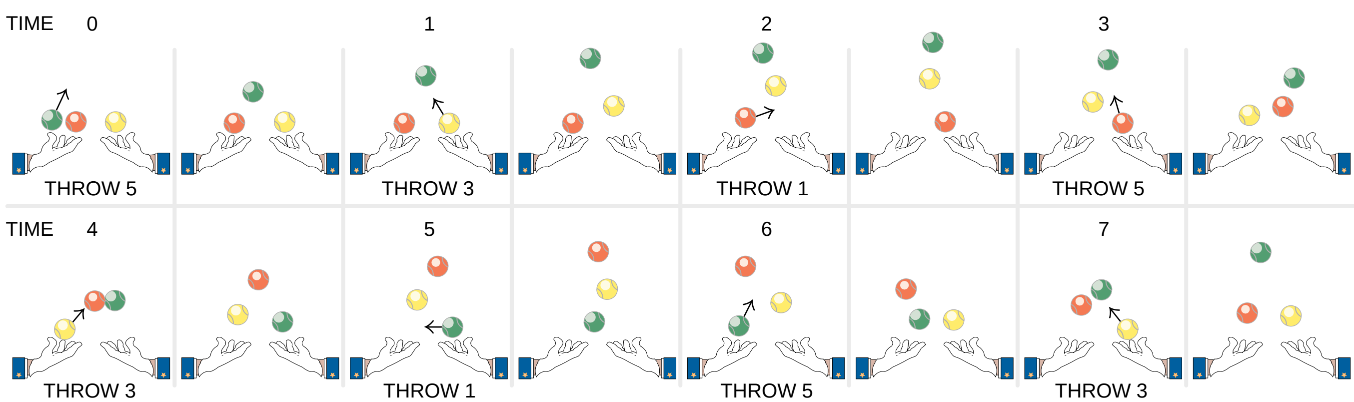
CAREY BALLARD

JUGGLING THEOREM proposed by Claude E. Shannon of the Massachusetts Institute of Technology is schematically represented for the three-ball cascade. The exact equation is $(F+D)H=(V+D)N$, where F is the time a ball spends in the air, D is the time a ball spends in a hand, V is the time a hand is vacant, N is the number of balls juggled, and H is the number of hands. The theorem is proved by following one complete cycle of the juggle from the point of view of the hand and of the ball and then equating the two.

Site-swap theory does not come close to describing completely all possible juggling feats, because it is concerned only with the order in which balls are thrown and caught. It ignores all other aspects of juggling, such as the location and style of throws and catches. Many of the most popular juggling tricks to learn, such as throwing balls from under the leg or behind the back, are done as part of a regular cascade and so have the same site-swap notation.



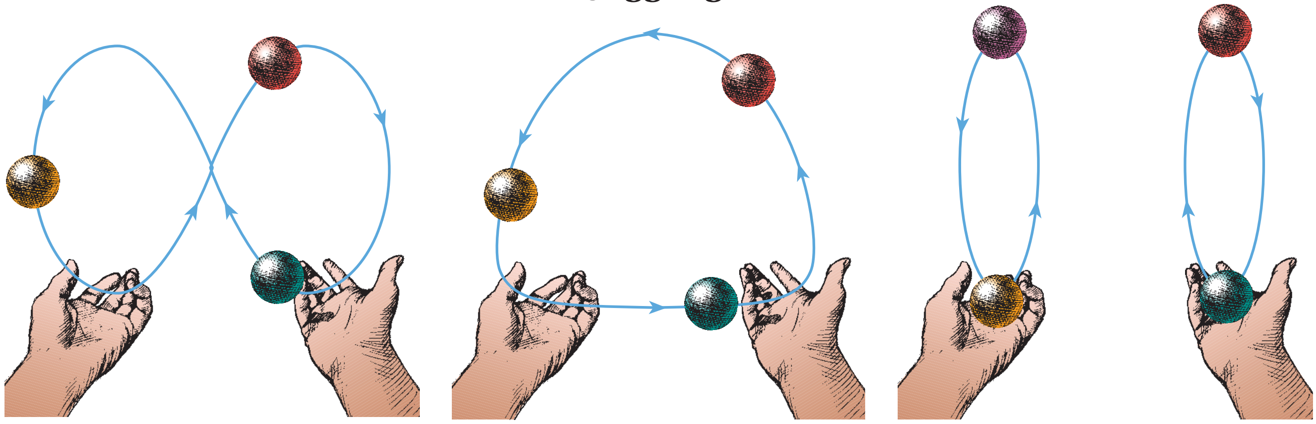
Unpacking the site swap 531



The 531 in action

JOHNNY JOHNSON

Common Juggling Patterns



THREE-BALL CASCADE — THREE-BALL SHOWER — FOUR-BALL FOUNTAIN (“IN SYNC”)

KARL GUDE

do in the hands. Such a range suggests jugglers strike a balance between the conflicting demands of stability and flexibility, correcting for external perturbations and errors. Moreover, the tendency toward dwell ratios that are simple fractions subtly illustrates a human tendency to seek rhythmic solutions to physical tasks.

Juggling more than three balls leaves less room to vary the ratio, because the balls have to be thrown higher and, hence, more accurately. This fact greatly limits what jugglers can do. Juggling three objects allows ample opportunity for modification, adaptation, tricks and gimmicks. At the other extreme, there are few ways to juggle nine objects.

Keep Your Eye Off the Ball

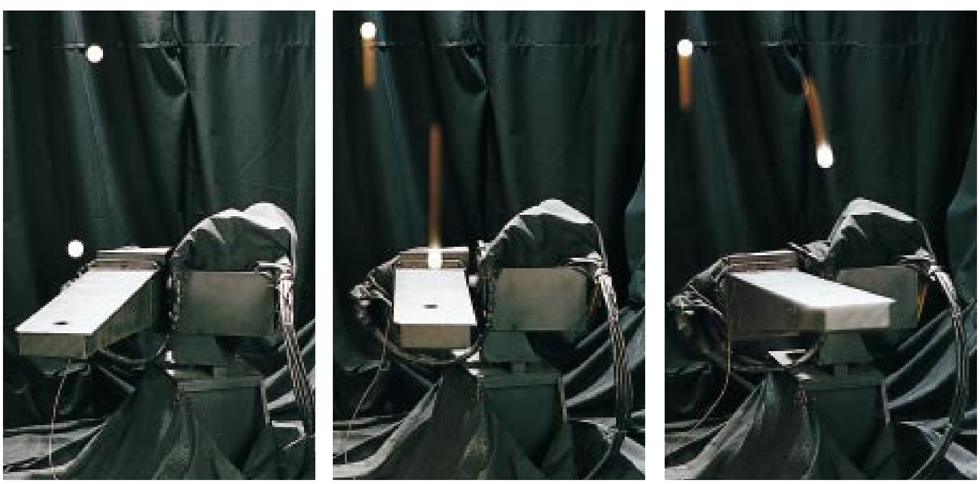
Modeling the movement patterns of juggling as such, however, says little about the necessary hand-eye coordination. Jugglers must have information about the motions of both the hands and the balls. There are few contexts in which the coaching advice to “Keep your eye on the ball” makes as little sense as it does in juggling. Attention must shift from one ball to the next, so that a juggler sees only a part of each ball’s flight.

Which part is most informative and visually attended to? “Look at the highest point” and “Throw the next ball when the previous one reaches the top” are common teaching instructions. As a graduate student at M.I.T. in 1974, Howard A. Austin investigated how large a region around the zenith had to be seen by practitioners of intermediate skill for them to be able to sustain juggling. He placed between the hands and the eyes of the juggler a fanlike screen that had a wedge-shaped notch cut out of it. Successful catches of a ball occurred even when as little as one inch of the top of the ball flight was visible. That roughly corresponds to a viewing time of 50 milliseconds, implying that briefly glimpsing the zeniths of the ball flights was sufficient to maintain a juggle.

In 1994 Tony A. M. van Santvoord of the Free University in Amsterdam examined the connection between hand movements and ball viewing in more detail. He had intermediate-level jugglers perform a three-ball cascade while wearing liquid-crystal glasses, which opened and closed at preset intervals and thus permitted only intermittent sightings of the balls. From the relation between the motion of the balls in the air and the rhythm defined by the glasses, one could deduce the location of the balls when the glasses were open, the preferences for any segments of the flight paths during viewing and the degree of coordination between the hand movements and visual information.

On some occasions, subjects modified their juggling to match the frequency of the opening and closing of the glasses. In that case, the balls became visible immediately after reaching their zeniths. The experiments also suggest that seeing the balls becomes less important after training. In general, novice and intermediate jugglers rely predominantly on their eyes. Expert performers depend more on the sensations coming from the contact between the hands and the balls. Indeed, in his 1890 *The Principles of Psychology,* William James observed that the juggler Jean-Eugène Robert-Houdin could practice juggling four balls while reading a book. Many skilled jugglers can perform blindfolded for several minutes.

A plausible hypothesis is that viewing the moving ball



DAVID KOETHER

ROBOTIC ARM can bat two balls in a fountain pattern indefinitely. A camera records the flights of the balls, and a special juggling algorithm, which can correct for errors and change the cadence of the juggle, controls the robot’s motion. Daniel E. Koditschek and Alfred A. Rizzi of the University of Michigan built the apparatus.

gradually calibrates the sense of touch in the course of learning. An expert immediately detects a slight deviation in the desired angle of release or in the energy imparted to the ball, whereas a novice has to see the effect of mistakes in the flight trajectories. As a consequence, the corrections made by an expert are often handled with little disturbance to the integrity of the pattern. Fixes made by less proficient jugglers, in contrast, often disrupt the overall stability of the performance.

Robots That Juggle

Insights into human juggling have led researchers to try to duplicate the feat with robots. Such machines would serve as a basis for more sophisticated automatons. Indeed, juggling has many of the same aspects as ordinary life, such as driving an automobile on a busy street, catching a fly ball on a windy day or walking about in a cluttered room. All these tasks require accurately anticipating events about to unfold so as to organize current actions.

Shannon pioneered juggling robotics, constructing a bounce-juggling machine in the 1970s from an Erector set. In it, small steel balls are bounced off a tightly stretched drum, making a satisfying "thunk" with each hit. Bounce juggling is easier to accomplish than is toss juggling because the balls are grabbed at the top of their trajectories, when they are moving the slowest.

In Shannon's machine, the arms are fixed relative to each other. The unit moves in a simple rocking motion, each side making a catch when it rocks down and a toss when it rocks up. Throwing errors are corrected by having short, grooved tracks in place of hands. Caught near the zenith of their flight, balls land in the track; the downswing of the arm rolls the ball to the back of the track, thus imparting sufficient energy to the ball for making a throw. Shannon's original construction handled three balls, although Christopher G. Atkeson and Stefan K. Schaal of the Georgia Institute of Technology have since constructed a five-ball machine along the same lines.

Although the bounce-juggling robots are fiendishly clever, a robot that can toss-juggle a three-ball cascade and actively correct mistakes has yet to be built. Some progress, however, has been achieved. Machines that can catch, bat and paddle balls into the air have been crafted. Engineers have also built robots that juggle in two dimensions. In the 1980s Marc D. Donner of the IBM Thomas J. Watson Research Center used a tilted, frictionless plane, similar to an air-hockey table. It was equipped with two throwing mechanisms moving on tracks along the lower edge of the table.

KEN REGAN *Camera 5*

PROFESSIONAL JUGGLER Tony Duncan, whose skilled hands appear in the opening photographs, also handles pins.

In 1989 Martin Bühler of Yale University and Daniel E. Koditschek, now at the University of Michigan, took the work a step further. Instead of a launching device running on a track, they used a single rotating bar padded with a billiard cushion to bat the pucks upward on the plane. To control the bar so as to achieve a periodic juggle, the researchers relied on the help of the so-called mirror algorithm.

This concept essentially combines two ideas. The first is to translate (or "mirror") the continuous trajectory of the puck into an on-line reference trajectory for controlling the motion of the robot (via a carefully chosen nonlinear function). The advantage of this mirror algorithm is that it avoids the need to have perfect information about the state of the puck at impact, which is difficult to obtain in reality. The second idea, to stabilize the vertical motion of the puck, analyzes the energy of the ball to see if it matches the ideal energy from a perfect throw. Thus, the program registers the position of the puck, calculates the reference mirror trajectory, as well as the puck's actual and desired energy, and works out when and how hard the puck must be hit. With an extended version of the mirror algorithm, the robot can also perform a kind of two-dimensional, two-puck, one-hand juggle. It bats the pucks straight up, alternately with the left and the right part of the pivoting bar, in two separate columns.

Watching the mirror algorithm in action is spooky. If you perturb one of the pucks, the robot arm will make some jerky movements that look completely unnatural to human jugglers but result in a magically rapid return to a smooth juggle. The mirror algorithm cleverly controls batting, but it does not extend to the more difficult problem of juggling with controlled catches.

In addition to bouncing and batting, robots have managed a host of other juggling-related activities, including tapping sticks back and forth, hopping, balancing, tossing and catching balls in a funnel-shaped hand and playing a modified form of Ping-Pong. Despite these advances, no robot can juggle in a way that seems even passingly human. But the science of juggling is a relatively new study, and the pace of improvement over the past two decades has been remarkable. It may not be too long before we ask, How did the robot cross the creaking bridge holding three cannonballs?

The Authors

PETER J. BEEK and ARTHUR LEWBEL can juggle three and eight balls, respectively. Beek is a movement scientist at the Faculty of Human Movement at the Free University in Amsterdam. His research interests include rhythmic interlimb coordination, perception-action coupling and motor development. He has written several articles on juggling, tapping and the swinging of pendulums. Lewbel, who received his Ph.D. from the Massachusetts Institute of Technology's Sloan School of Management, is now professor of economics at Brandeis University. He founded the M.I.T. juggling club in 1975 and writes the column "The Academic Juggler" for *Juggler's World* magazine.

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Measuring the Wind with Hot Metal

How well does a bird's nest cut the chill of a winter storm? How strong a breeze does it take to force a leaf-cutter ant to adjust its grip on its spoils? Answers to such questions can be found if you can measure low wind speeds in tight places. Unfortunately, anemometers using hemispherical cups mounted on a vertical shaft are bulky, and many are good only for wind speeds above about five meters per second (11 miles per hour). An approach more suitable for lower wind speeds is thermal anemometry, which determines wind velocity based on the degree to which flowing air cools a heated piece of metal.

Professional thermal anemometers rely on tiny, red-hot wires and can sample air speeds one million times every second. But such systems are expensive, and the wires often break. The more economical method described here relies on two small metal balls and a few dollars' worth of electronics. One of the balls is heated by an electric current flowing through a resistor. The temperature difference between the balls indicates the wind speed to within a few percent, and the device can operate in a space as small as a peanut butter jar.

Aluminum balls $^1/_2$ inch in diameter make the best anemometers. Aluminum conducts heat much better than steel and bronze do, and it is not easily weathered like copper and brass. It can also take a high polish and is a good reflector of both visible and infrared radiation, making the anemometer insensitive to direct sunlight.

The balls will need to be protected. Polished aluminum scratches easily, and the marks will alter the thermal properties of the balls. Although a coat of white enamel will shield them, it will also insulate the balls somewhat, making them respond more sluggishly to changes in wind speed. A better solution is to plate the unpolished balls with gold, which is extremely reflective and surprisingly durable. Plating costs less than you may think; my electroplater charges $1.50 per square inch.

Prepare the balls by drilling $^3/_{32}$-inch-diameter holes in them; go all the way through one ball (the one that will be heated) and about $^3/_8$ inch into the second. Electrically insulate the leads of a 100-ohm, $^1/_4$-watt resistor (1 percent tolerance) with a coat of latex-based enamel. When the leads are dry, insert the resistor into the ball that will be heated, allowing the leads to stick out from either end. Cement the resistor in place using a dab of low-viscosity aluminized epoxy, which provides good thermal contact between the ball and the resistor.

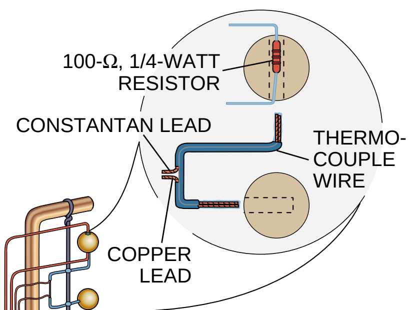
To heat the resistor, use a 7805 integrated circuit, which provides five volts to the resistor. You can power the chip with any direct-current voltage between five and 35 volts. This circuit will deplete a nine-volt alkaline battery in about five hours, so consider using an adapter or large lantern batteries. Also connect a heat sink to the back of the chip; I used a dab of aluminized epoxy.

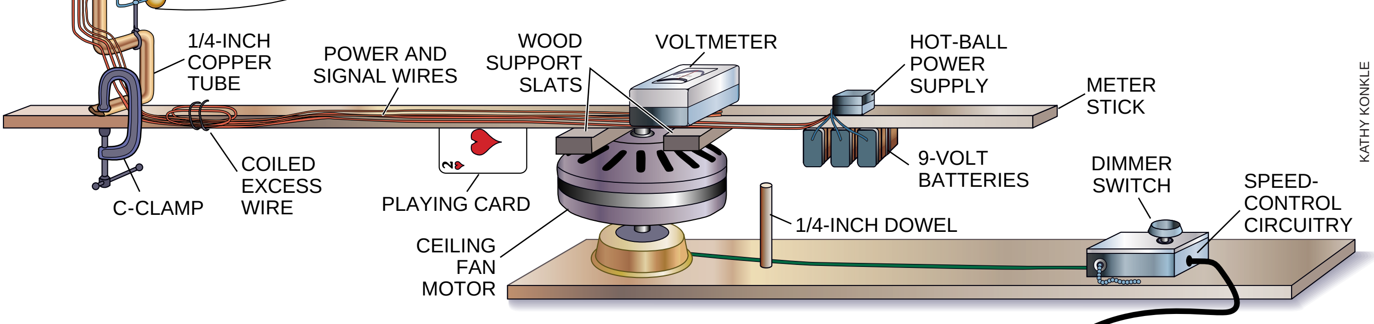
The temperature difference between the balls is measured by a device called a thermocouple, which consists of two wires, made from different metals, joined together. Copper and constantan wires are most commonly used; you will need about four inches' worth. Strip $^3/_8$ inch of insulation off both ends of each wire and twist them together to form two junctions. Electrically insulate the junctions by dipping them in enamel. At the center, cut the copper wire only and solder the two ends to separate copper wires. Insert one junction into each ball and seal with aluminized epoxy.

Bend a 12-inch piece of $^1/_4$-inch-diameter copper pipe tubing into an S-shape and secure some wire across the top opening of the S. Mount the balls a few inches apart on the stiff wire [*see illustration below*]. The voltage signal from the anemometer is boosted with an operational amplifier (type 741) and read with a digital voltmeter. With these components you can detect wind speeds as low as 0.1 meter per second.

To calibrate the anemometer, you will need to measure the output voltage at a number of known wind speeds. One way to do that is to compare the readings against those of a cup anemometer. This approach will be accurate down to only about five meters per second because of the insensitivity of the cup anemometer. You can extrapolate to lower speeds, but such a projection will likely be incorrect because the rate at which the heated ball cools changes in low winds.

A more precise means of calibration





***CALIBRATING AN ANEMOMETER** requires mounting the balls on one end of a meter stick* (far left) *rotated by a ceiling-fan motor. (Illustration is not to scale.)*

is to pass air currents of known speeds over the device—more specifically, to place the instrument on a rotating platform. The platform can be made from a motor cannibalized from an old ceiling fan. Such fans are ideal because they come with a mountable base and speed control, and they rotate at slow, safe rates, no faster than five revolutions per second (other fans spin much too quickly to be safe).

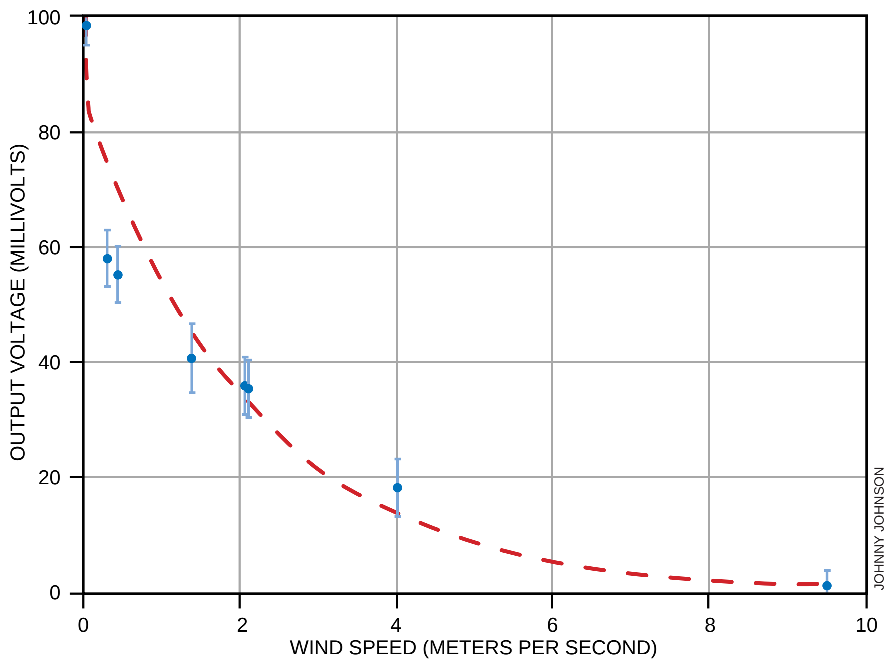
A ceiling fan's controls are, unfortunately, mounted on the wrong side for our purposes, so you will have to rewire the switches to the back of the motor and extend the leads. A mistake here could create a shock hazard, so let a professional electrician do all the rewiring. Also for safety, ask your electrician to mount the motor's speed-control circuitry inside a metal project box and, for finer adjustment, to wire in a dimmer switch as well.

Mount a meter stick on the motor housing [*see illustration on opposite page*]. Clamp the anemometer to one arm of the meter stick and mount all the electronics on the other. I duct-taped my voltmeter just beside the center of the motor and read it as it spun. Although easy at slow speeds, reading the voltmeter this way becomes tough at five revolutions per second. At high speeds, you will need to read the meter with a strobe light.

As the anemometer rotates, its speed (or alternatively, the velocity of the air rushing over it) is the circumference of the circular path times the frequency of the rotation, in cycles per second. That is, the speed equals $2\pi Rf$, where R is the distance from the center of the motor to the anemometer, and f is the frequency. The rotation frequency is easily measured using a bent playing card stapled to the underside of the arm. Mount a short dowel so that the card will strike it every time around; it will produce a sharp sound. Count the number of clicks over some interval. The frequency is the number divided by the measurement time. By selecting both the anemometer's position on the arm and the motor's rotation rate, I could create any wind speed from 0.1 to 22 meters per second.

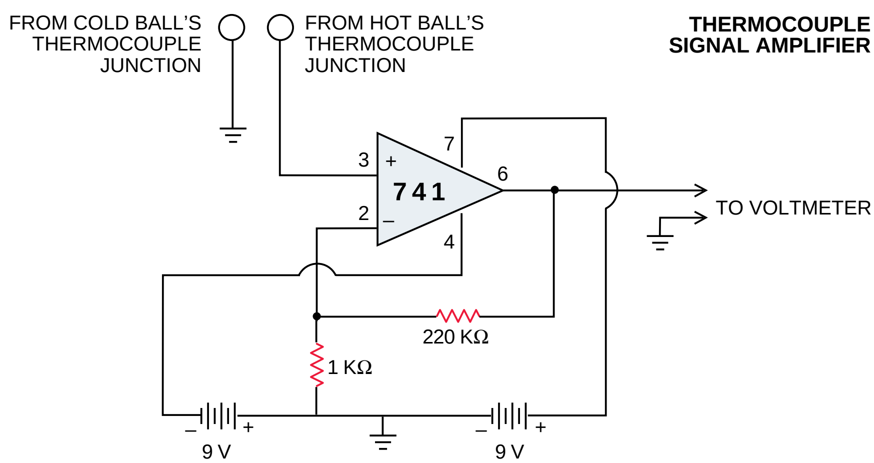
Do all your calibrations in a closed room. Seal the windows and doors; do not walk about during the trials. The device is somewhat sensitive to ambient temperature, so make sure to calibrate it on both a cold morning and a hot afternoon. Thereafter, make certain to record the air temperature whenever you are in the field.

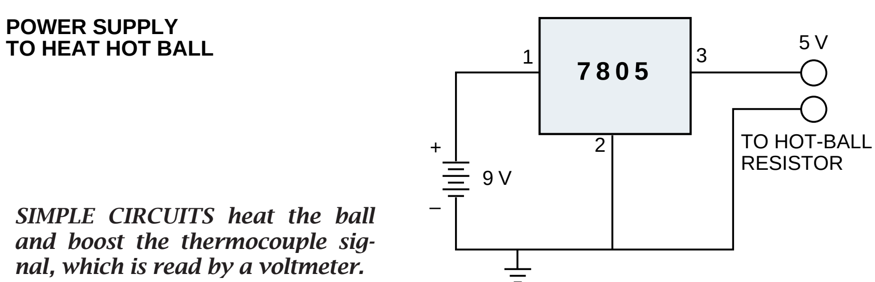
Once the anemometer is calibrated, you can explore the subtle interplay between many animals and their environments or measure air currents anywhere inside a building, cave or large machine. Amateurs who document these "microclimates" stand shoulder to shoulder with professionals. It is an exciting area, ripe for original work from all comers.



CALIBRATION DATA indicate the relation between the output voltage and the wind speed. With more care, it should be possible to reduce the size of the error bars.

Hot-ball anemometry kits are available for $45 from the Society for Amateur Scientists, 4951 D Clairemont Square, Suite 179, San Diego, CA 92117. This offer expires October 1, 1996. Additional construction tips are available for $2 from the above address or may be accessed free on the society's World Wide Web page (http://www.thesphere.com/SAS/) or in Scientific American*'s area on America Online.*

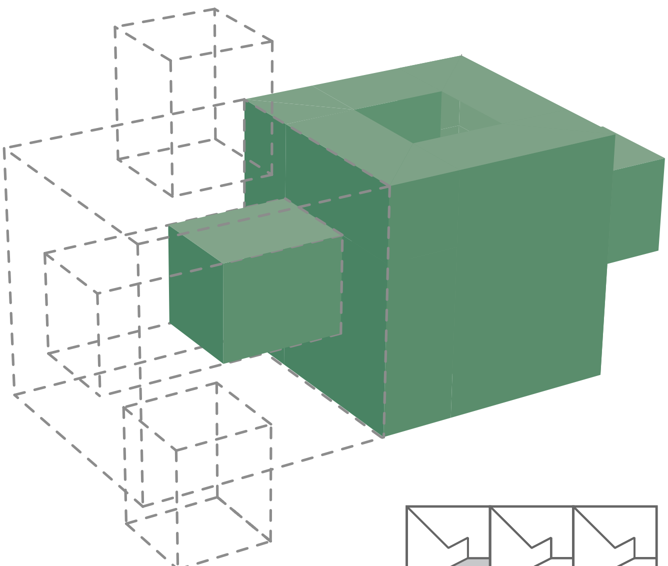


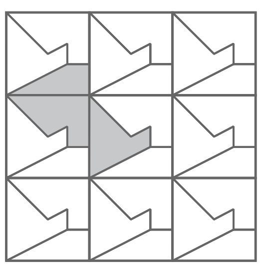


SIMPLE CIRCUITS heat the ball and boost the thermocouple signal, which is read by a voltmeter.

Ways to Tile Space with Knots

Shapes that tile the plane—those that fill it completely and never overlap—are a recurring theme in recreational mathematics. Solids that "tile" three-dimensional space have also attracted a lot of attention. So much so, in fact, that it is hard to believe that any questions about these objects remain. But they do, as was brought home to me by a beautiful article in the *Mathe-*





MICHAEL GOODMAN

TOROIDAL BLOCK can tile space. To form a two-dimensional tiling by way of the pick-and-mix principle, take a plane of squares, subdivide each one, then recombine the pieces differently.

matical Intelligencer this past spring. In it, Colin C. Adams of Williams College described new methods that he has discovered for constructing intricate three-dimensional tiles from copies of a single shape, or prototile.

The simplest three-dimensional tiling uses a cube as its prototile. Stacked cubes, after all, tile space like a checkerboard. This cubic lattice example might seem prosaic, but basic modifications to it can create surprisingly complex tiles, as we will see. These modifications follow the rules of topology, or "rubber-sheet geometry." More formally, topology is the study of those properties of shapes that remain unchanged when the shape is stretched, squashed, bent, twisted or generally deformed in some other continuous manner (no tearing or cutting is allowed). Such deformations are called topological equivalences. A cube, for example, is topologically equivalent to a sphere because you can transform it into a sphere by squashing its corners.

A favorite shape among topologists is the torus, which resembles a doughnut. For our purposes, think of a solid torus, or the dough of the doughnut and not just its sugary surface. What kind of prototile is topologically equivalent to a torus? One possible solution is a cube with a square hole bored through the middle. This shape is equivalent to a torus, but it would not tile space. So break the square peg taken from the cube into two rectangular "lugs" of equal length and place them in the middle of opposite faces [*see top illustration at left*]. This form is still equivalent to a torus: if you made it from modeling clay, you could squash the lugs flat and round the corners to produce a traditional torus.

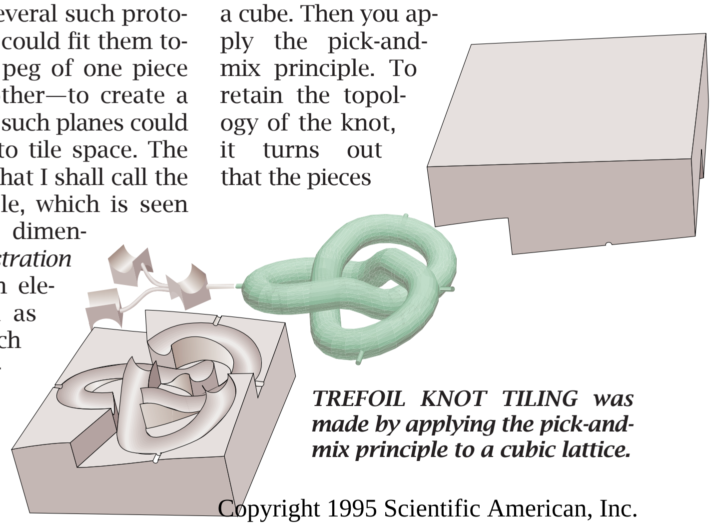
And if you made several such prototiles from wood, you could fit them together—sticking the peg of one piece into the hole of another—to create a one-cube-thick plane; such planes could then be stacked up to tile space. The example illustrates what I shall call the pick-and-mix principle, which is seen most clearly in two dimensions [*see bottom illustration above*]. Start with an elementary tiling, such as squares. Subdivide each tile into several pieces, using the same subdivisions in each tile. Now assemble a new prototile by choosing one copy of each piece—not necessarily from the original square. The result automatically tiles the plane. In our three-dimensional example, we subdivided a cube into three pieces.

The pick-and-mix strategy can produce even more exotic tiles known as cubes-with-holes. To form one, simply bore several tunnels through a cube, always starting at the top face and ending at the bottom face. These tunnels can wind around one another, form knotted loops or generally intertwine in complicated ways. And any cube-with-holes can be modified to create a topologically equivalent prototile: just add lugs to the left and right faces of the cube corresponding to the appropriate half-tunnels. These prototiles will then snap together as did those in the first example.

Moreover, the addition of the lugs does not change the topology of the original cube-with-holes, because you can imagine that each lug has been stretched out from the face to which it is attached. Call this fact the sprouting principle—a shape retains the same topology if it sprouts extra protuberances. There is one important restriction: the protuberances must not develop holes themselves or produce any by attaching to more than one face. To be precise, the protuberances must be topologically equivalent to cubes.

Adams examines many other interesting shapes using another clever technique. I'll illustrate it using a solid torus tied in a simple overhand (or trefoil) knot, but a very similar method works with any knot whatsoever. The basic idea is to think about how you might cast a trefoil knot in bronze using a mold whose pieces fit together to make a cube. Then you apply the pick-and-mix principle. To retain the topology of the knot, it turns out that the pieces

MICHAEL GOODMAN



TREFOIL KNOT TILING was made by applying the pick-and-mix principle to a cubic lattice.

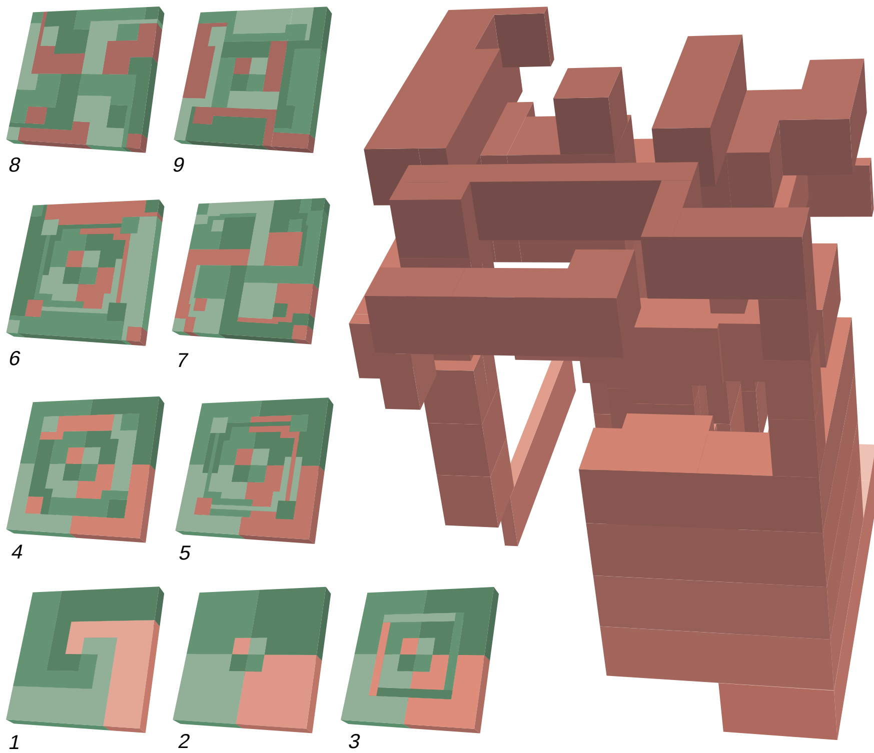
of the mold must be topological cubes.

Two of the pieces in this mold are half-cubes that have indentations along one face; the third is a strange treelike structure. The role of the tree is to fit between the overlapping regions of the knot and convert it into a many-holed torus. With the tree in place, the strands of the knot loop around one another instead of merely intersecting. The tree consists of three squarish patches that are connected by thin tubes so that only one extra piece is needed to complete the mold instead of three. Note that this single piece is topologically equivalent to a cube.

The top and bottom pieces of the mold fit together to form a typical square-sided cube, lacking only an inner region that corresponds to the knot and the tree. The stem of the tree extends to the edge of the cube. Why introduce the extra complexity of the tree? The reason is that you cannot cast a trefoil knot from a two-piece mold if those pieces must be topologically equivalent to cubes (the pieces would need to include loops of some kind to separate the overlapping regions of the knot). The tree makes it possible to cast the knot from cube-equivalent molds.

Having constructed the three-part mold, you can use the pick-and-mix principle to create curious prototiles [*see lower illustration on opposite page*]. Begin with a cubic lattice whose cubes are split into four pieces: a trefoil knot plus its three-piece mold. Imagine space filled with such cubes, arranged in a cubic lattice. Then choose one copy of each piece: the knot from one cube, the top half-cube from the one behind it, the bottom half-cube from the one in front of it and the tree from the one to its left. You must also cut a few grooves and add matching tubes, with semicircular cross sections, as shown, so that the pieces fit together into a single, rather elaborate prototile. Despite its spindly architecture, this prototile is equivalent to the original trefoil knot, according to the sprouting principle: the prototile is formed by adding three protuberances to the trefoil knot, and despite their complex shapes, those protuberances are topologically equivalent to cubes.

This method leads to rather complex shapes, and you could be forgiven for wanting shapes more like an ordinary knotted tube. Adams has an answer for that, too: he starts with a cube and cuts it into congruent knotted pieces. The illustration above shows such a decomposition into four symmetrically related trefoil knots. If you start with a cubic lattice and break each cube into four trefoil knots in the manner shown, then you have tiled space with knots. If any reader finds a simpler solution, I will consider it for "Feedback."



MICHAEL GOODMAN

KNOT* (right) *was formed by stacking the layers* (left) *and attaching the brown pieces. Four of these knots will fit together and make a solid cube.

Feedback

This month's correspondence arose from the July 1994 column, "The Ultimate in Anty-Particles." The topic was Langton's ant, a mathematical entity that lives on the squares of an infinite grid and moves around painting the squares black or white, following some simple rules. One of my sources attributed various results to the wrong people—errors that I slavishly followed: First, Christopher Langton of the Santa Fe Institute introduced the original ant, but the ant I described was due to Greg Turk of the University of North Carolina at Chapel Hill. The highways these ants create were discovered by Langton and named by Jim Propp at the Massachusetts Institute of Technology.

And the result I called the Cohen-Kong Theorem was first proved by Leonid A. Bunimovich of the Georgia Institute of Technology and Serge E. Troubetzkoy of the University of Bielefeld. Bernd Rümmler of the University of Göttingen has now solved one of the big mysteries of myrmecology concerning "generalized ants," also known as turmites, after their inventor, Turk. Bunimovich and Troubetzkoy invented the same idea independently. Turmites follow more complex rules than do ants and paint squares in many colors. Their rules are defined by sequences of 0's and 1's. In computer experiments, some rule-strings, such as 1001 and 1100, repeatedly lead to symmetrical patterns; the problem is to prove that the symmetry recurs infinitely often.

In 1990 Rümmler found the key idea, which involves decorating the square with curves known as Truchet tiles. He originally used the properties of these tiles to explain the symmetrical tracks of the rule-string 1100, but—as he was aware—the same technique applies more generally.

Because of the volume of "Feedback" correspondence, I regret that I cannot reply individually to many letters—but please don't let that stop you from writing in. —*I.S.*

REVIEWS

Truth Abducted

by Robert Sheaffer

CLOSE ENCOUNTERS OF THE FOURTH KIND: ALIEN ABDUCTION, UFOS, AND THE CONFERENCE AT M.I.T., by C.D.B. Bryan. Alfred A. Knopf, 1995 ($25).

In June 1992 a UFO "Abduction Study Conference" was held at the Massachusetts Institute of Technology. David E. Pritchard, the M.I.T. physicist who co-sponsored the event, joked that it signified only its organizers' academic freedom to "make fools of themselves." Nevertheless, the proximity between the name M.I.T. and the term UFO inevitably conferred a certain amount of respectability to the topic. Among the other principal organizers of the conference were Harvard University psychiatrist John E. Mack, historian David M. Jacobs of Temple University and New York City artist Budd D. Hopkins—all authors of prominent books promoting the reality of UFOs. *Close Encounters of the Fourth Kind* marks a further step in bringing discussion of UFOs into the mainstream. The book comes from Knopf, a reputable publisher; its author is C.D.B. Bryan, a writer and novelist, a Yale graduate and a member of the New York literary crowd. He attended the Abduction Study Conference, as did I, although if we met I do not recall it.

The stories told at the conference, by researchers and "abductees" alike, are about as bizarre as anything we have heard. If they are true, then Little Gray Men are shining down rays that freeze human beings in their tracks, float them out through solid walls and beam them up to a craft hovering high overhead. Abductees typically report these experiences to be profoundly meaningful. Perhaps most amazing of all, extraterrestrials are said to be busily extracting human ova to be combined with alien sperm, and vice versa—indeed, the aliens seem positively obsessed with human sexuality.

One might expect that Bryan, a self-described agnostic on the reality of UFOs and a working journalist, would approach such stories with a questioning attitude. Why should these creatures show virtually no interest in studying our cardiovascular, lymphatic or digestive systems but instead concentrate practically all their attention on our genitals? Such aliens sound very much like inventions of our own minds. (A number of abductees indicate that their only sex life takes place on board the flying saucers or in their dreams about aliens.) Might not tales of alien abduction be attributable to universal human motives, such as the pursuit of excitement and meaning? Perhaps some people embrace "alien encounters" for the same reason that others turn to drugs or alcohol, fetishistic sex, dangerous sports or charismatic religions.

Early on, however, it becomes clear that Bryan is no neutral reporter. He is clearly sympathetic to Mack's claim that the emotional intensity of abductees when they are hypnotically regressed suggests the reality of the phenomenon: "They will literally *scream* with terror and their whole body shakes.... There is *no other condition* I know of that can elicit, bring forth, that kind of emotional expression." Nevertheless, a recent *Frontline* television documentary, "Divided Memories," which aired on PBS, showed a woman doing exactly that while being "regressed" by her therapist to a time when the patient claims that as an ovum, she had gotten stuck inside her mother's Fallopian tube. But Bryan declines to question Mack's statement.

Mack boasts of his ability to spot insincere reports: "I've spent 40 years in psychiatry; I did forensic psychiatry. It's my job when somebody's putting me on, or lying, or has some ulterior motive, or distorting." Yet when investigative writer Donna Bassett went to him with a concocted tale of extraterrestrial abuse, Mack not only found nothing amiss but to this day says he is unsure whether she really could have made up such a story. His suspicion was not even raised by her claim to have encountered, in a childhood abduction during the Cuban missile crisis, President John F. Kennedy and Soviet Premier Nikita S. Khrushchev on board the alien craft. Throughout *Close Encounters of the Fourth Kind,* Bryan seems to be in awe of Mack, Hopkins and Jacobs, disinclined to challenge or contradict them in any way.

Bryan's claim to journalistic objectivity is further undermined by the inclusion of large amounts of UFO material from sympathetic sources. Timeworn tales are trotted out more or less exactly as they appear in mass-market UFO books of the 1970s and 1980s. In a few instances, such as for the Roswell "saucer crash" story, Bryan does follow up sensational claims with later findings that call them into question. But he credulously repeats other wild assertions, such as the MJ-12 "crashed saucer panel" papers and the Manhattan high-rise "abduction" of Linda [Cortile] Napolitano, that are widely disbelieved even among UFO proponents. Moreover, many of the older UFO cases Bryan relates are now quite convincingly answered in the skeptical literature. If Bryan is aware of any objections to these cases, he keeps them to himself.

For reasons that are never made clear, Bryan inflicts on the reader more than 140 pages of narrative from a pair of imaginative abductees referred to as Carol and Alice. Their bizarre, rambling tales of repeated alien pursuit and molestation, presented with scarcely a hint of incredulity, quickly become tedious. Uncritical statements such as "I [Bryan] am thinking that Alice's 'half an arch' might be the forty-five-degree-angle-tilted spacecraft" are suggestive of a genre of UFO books that is unworthy of serious attention. The discerning reader is surely less interested in "What did the beings do next?" than in "Can any of this be substantiated?"

Like certain other writers, however, Bryan argues that "true" and "false" are concepts far too crude to be applied to incidents as profound as UFO abduction narratives. He suggests that they might perhaps be instead "simultaneous *other realities"* or

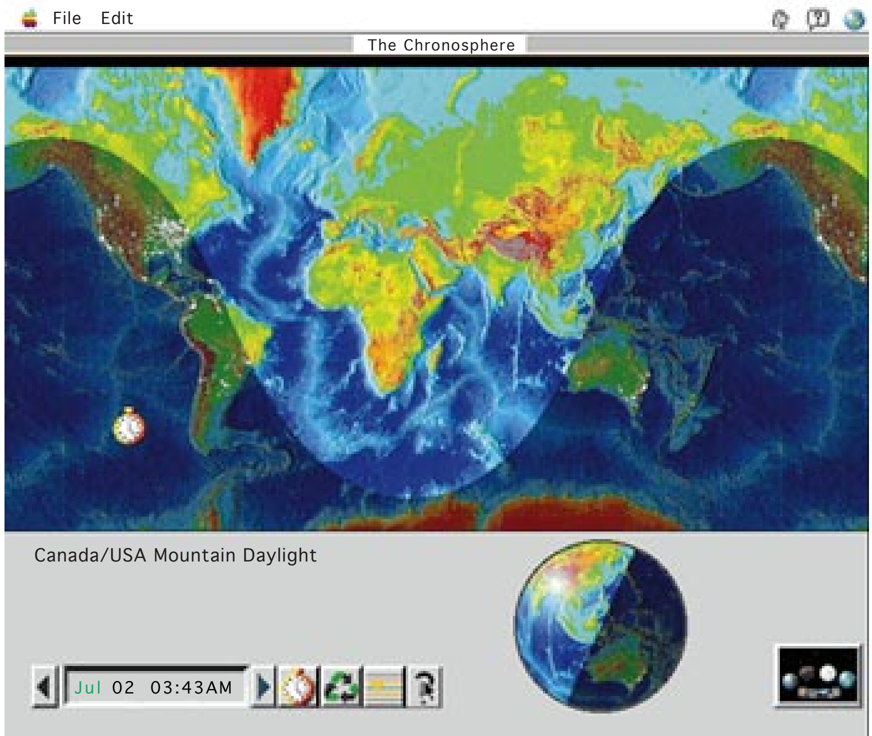
DOUGLAS A. CHAFFEE From *Amazing Stories* some other strange phenomena that he explains with quotes from deep thinkers who say things such as " 'The psychoid nature of the unus mundus is a blurred-reality genre.' " As a nonscientist, Bryan seems perhaps not to realize how the appearance of great complexity can be mimicked by noise.

Even as a document of the M.I.T. conference, *Close Encounters of the Fourth Kind* is seriously flawed, because Bryan selectively edited out numerous contributors and papers, without telling us that he has done so. Indeed, in several places the text implies continuity where one or more papers have been skipped. Some of the papers on which Bryan did not see fit to report have titles such as "Methodological Problems in Abduction Work to Date" and "Sampling Bias in Close Encounter Investigations." Were they skipped out of fear of boring the reader or fear of complicating a tidy picture?

Attendance at the Abduction Study Conference was by invitation only. It was contingent on signing an agreement stating that the conference is "emphatically closed to the press" and stipulating "I agree not to discuss with any reporter or in any public forum or publication any of the following: material in the abstracts book for this meeting, what transpired at this meeting, or who said what at this meeting." That Bryan, in preparing his book, not only was not hindered by his confidentiality agreement but was freely given interviews and a great deal of assistance by Pritchard, Hopkins, Mack and Jacobs implies that his book represents an authorized version. Had Bryan espoused an unwelcome view of the conference, he would not have been at liberty to publish it. Surely such a disclaimer belongs in the book; not surprisingly, it is not there.

To get an uncensored view of the M.I.T. conference, see the published proceedings, *Alien Discussions,* edited by Andrea Pritchard (North Cambridge Press, P.O. Box 241, Cambridge, MA 01240; 683 pages, $55). No contributors were "written out" of the proceedings, and its rich illustrations depicting all manner of implausible beings and events will delight those who relish the bizarre. Most of the papers have follow-up discussions, with many of the participants displaying a kind of logic seldom seen outside Lewis Carroll. The "state of the art" of American UFOlogy is laid bare in the proceedings, its warts plainly visible to all.

ROBERT SHEAFFER is a writer and regular columnist for The Skeptical Inquirer. *He works in the computer industry in Silicon Valley.*



Screen from *Small Blue Planet: The Real Picture World Atlas 2.0*

Atlas in the Round

by Mark Monmonier

SMALL BLUE PLANET: THE REAL PICTURE WORLD ATLAS 2.0. Now What Software, 1995 ($59.95, hybrid Macintosh/Windows). **SMALL BLUE PLANET: THE CITIES BELOW: THE AERIAL ATLAS OF AMERICA.** Now What Software, 1995 ($49.95, hybrid Macintosh/Windows). **PC GLOBE: MAPS 'N' FACTS.** Broderbund, 1995 ($34.95, hybrid Macintosh/Windows).

Anyone who has ever flipped through giant paper atlases can appreciate the commodious convenience of a CD-ROM. And anyone who has struggled to master older mapping applications will welcome the lively graphic interfaces of recent multimedia atlases. Although their flaws and limitations might support the pontificating pronouncement that "we're not there yet," current releases succeed nicely in redefining what "there" might be like. One thing is clear: the atlas is no longer just a bound collection of ossified cartographic views.

Perhaps the biggest surprise raised by the CD-ROM atlases reviewed here is that they are priced more like mass-market print atlases than like specialized and flagrantly expensive mapmaking software. In compensation, however, one has to put up with the gee-whiz features that parents and educators apparently think make geography bearable, if not interesting. So *Maps 'n' Facts* offers flags and instrumental renditions of national anthems, and *The Real Picture World Atlas* includes a talking phrase book demonstrating how citizens of various countries enunciate "Good morning," "How are you?" and nine other pleasantries. This "Human Chorus" and its 69 languages is good fun, but a far more useful audio enhancement would be a point-and-speak module offering locally correct pronunciations of perplexing place names. Anyone ever forced to utter Reykjavik or Ulaanbaatar in embarrassed ignorance knows what I mean.

All three products are based for the most part on preexisting geographic data gathered by the United Nations, the National Aeronautics and Space Administration, the National Oceanic and Atmospheric Administration, the Central Intelligence Agency and the U.S. Geological Survey. The CD-ROM developers therefore must not only engage users with glitzy options but also edit and informatively integrate public-domain data. Authoring an electronic atlas involves shrewd, clever packaging as much as it does geographic scholarship.

The Real Picture World Atlas demonstrates the importance of first impressions by welcoming users with a master menu showing four spinning globes and a gallery icon. Clicking on the leftmost globe opens the "Chronosphere," an interactive picture of the worldwide pattern of light and darkness for any season, day, hour and minute. Moving forward or backward in time, the viewer can relate a rectangular map of world time zones to the rotating globe's instantaneous circle of illumination. Although the Chronosphere is both informative and engaging, the developer's choice of a Mercator world map reflects a traditional, dysfunctional bias all too common in geographic educational materials. Seasonality and illumination have little to do with navigation (the classical province of Mercator projections), and a plain-chart projection would not only show comparable distances from the equator but also allow the map to include the North and South Poles.

The other three globes offer complementary views of the planet. One icon leads to a collection of Advanced Very High Resolution Radiometer mosaics, similar to color-infrared satellite images. The user can zoom in for a more detailed view as well as scroll from place to place. Another icon summons the NOAA Global Relief Map, a vivid world portrait based on estimated elevations at the intersections of meridians and parallels spaced five minutes, or one twelfth of a degree, apart. The fourth globe opens a world political map, which the user can also view on the relief and mosaic maps through a circular, movable "Looking Glass," a tool that would be a masterpiece of cartographic integration were the maps more detailed and their place names not so jagged.

Now What Software's companion U.S. atlas, *The Cities Below,* integrates mosaics of *Landsat* color-infrared imagery with U.S. Geological Survey topographic line maps and offers comparatively detailed views of selected metropolitan regions (at a scale of 1:100,000). Although its geographic detail is markedly better than that of *The Real Picture World Atlas,* the low resolution of the typical monitor imposes a severe impediment on this (and any other) electronic atlas.

The Cities Below also offers snappy zooming and scrolling, making it something of a cartographic video game. A gray nationwide relief map studded with city icons invites the viewer to explore 39 cities, which are chosen as much for tourism and regional balance as for population. (Were Jack Kemp in the White House, Buffalo, N.Y., would surely displace less populous Little Rock, Ark.) Clicking on a city icon yields a choice of one to 20 small-scale color-infrared images, on which users can zoom in two steps to a more detailed but faintly fuzzy picture, similar to a 1970s color composite satellite image.

Although Syracuse, the medium-size city where I live, was not included in *The Cities Below,* I was pleased to see that the imagery for Baltimore included (just barely) the western suburb where I grew up. But the vague details of my old neighborhood, where my father still lives, were vexing: although the topographic map in the Looking Glass revealed streets hidden by trees, I had really wanted to see Dad's house. Perhaps I am jaded, having seen far better images available for over a decade. Nevertheless, I do not envy atlas authors, forced by the huge size of geographic data files to choose among spatial resolution, color (rather than monochrome) imagery, wider metropolitan areas or more cities.

Maps 'n' Facts offers a broader variety of views, including political, physical feature and statistical maps at world and regional scales, a "Quick Look" mode for point-and-click retrieval of Trivial Pursuit–style facts about countries and places and an interactive tool for estimating great-circle distances between points. Also noteworthy are electronic bookmarks, which afford a rapid return to specific maps and charts, and 24 "group maps," which point out political and economic affiliations such as NATO, the Arab League and even former countries such as the U.S.S.R.

Despite its flags, anthems and other playful options, *Maps 'n' Facts* functions as a serious reference tool for compiling small-scale locator maps. Although the developers wisely sacrificed precise coastlines and national boundaries to conserve memory and boost speed, the level of detail is satisfactory for cartography students, professional mapmakers and journalists, who can export a map into Aldus Freehand or other illustration programs to tailor and redesign it. The disk encourages mapmaking by including "Custom Tools" for adding labels, zooming in and out and adding cities; it also incorporates options for either printing maps directly or exporting them to another application.

My greatest disappointment centered on the statistical maps in *Maps 'n' Facts.* A rich database invites users to explore numerical maps providing 216 reasonably current economic and demographic indices for the whole world or for any of 15 regions. But because the developers ignored a few well-established cartographic principles, many of these maps are uninformative, if not misleading. For instance, the CD-ROM uses choropleth maps (maps in which colored symbols represent ranges of values) to portray count data, but count data are more appropriately represented by graduated circles, so that big means lots and small means little. When a choropleth map shows raw counts, rather than rates or densities, dark symbols representing larger amounts can inaccurately suggest high densities or concentrations. Elsewhere, choropleth maps portray densities, percentage rates and other intensity data by means of symbols varying largely in hue, so that instead of applying the simple rule "dark is more, light is less," conscientious viewers must constantly refer back to the map's key.

A third failing is the disk's two, only marginally informative classification methods: users can either divide a variable's range into equally broad intervals or assign an equal number of countries to each numerical category. More informative strategies would include two-category maps based on the U.S. or world averages (above- and below-average GNP per capita, for instance), multicategory maps with homogeneous groups of countries separated by "natural breaks" and multicategory maps whose break points are specifically set by the user. An even more appropriate and hands-on solution would be an interactive two-category map having a single break that the user could move back and forth, watching to see at what point each country switches categories; a one-dimensional scatterplot that shows the total distribution of data values for the various countries could serve as the map key.

All these ideas, and more, are out there, waiting to be exploited in the cartographic literature. Why, then, do software developers do little more with statistical maps than parrot their equally lax competitors? I suspect there are two closely related explanations. Widespread cartographic ignorance among consumers lets the developers get away with it. And then there is the deeper and sadder problem. Elementary and secondary educators—who strongly influence the marketability of these products—have yet to recognize maps and mapping as objects of critical thinking.

MARK MONMONIER is professor of geography at Syracuse University and author of How to Lie with Maps.

Science Faction

by James S. Trefil

THE BOURBAKI GAMBIT, by Carl Djerassi. University of Georgia Press, 1994 ($19.95). **GOOD BENITO,** by Alan Lightman. Pantheon Books, 1994 ($21).

Science and technology have played an important role—some would say *the* important role—in shaping Western culture. Yet if you look at our literature and arts, you would be hard-pressed to find evidence for this fact. By and large, the accomplishments of science have remained invisible in the world of the humanities. The one notable exception is found in the area where fiction and science overlap. Starting with the magnificent yarns woven by Jules Verne and H. G. Wells, science fiction has long been established as a genre in which it is acceptable for authors to toss in a few technical terms and maybe even a scientific explanation or two. Hidden among the space operas and bug-eyed alien monsters are occasional excursions into Newtonian physics, relativity theory and (among modern authors) molecular biology.

Science fiction has functioned as more than entertainment. For many scientists of my generation, growing up in a society that values the fruits of science while harboring ambivalent attitudes toward scientists themselves, science fiction provided a much needed personal validation. It told us that being smart and interested in science was okay, a message we received from few other sources. The late Isaac Asimov suggested that science fiction might play an important educational role by serving as a diagnostic tool for identifying those youngsters who have an interest in scientific careers. The intersection between science and fiction may help spur those youngsters on to become scientists and may provide a way to increase overall scientific literacy.

The works under review here represent two very different approaches to exploring that intersection. Carl Djerassi is a Stanford University biochemist best known for his synthesis of the first oral contraceptive. In the preface to *The Bourbaki Gambit,* he is quite clear about his goal. He is attempting to found a new genre, which he calls “science-in-fiction” (to distinguish it from science fiction). His aim is to produce a novel that gives an accurate and plausible insight into the workings of science.

The title of the book refers to Nicolas Bourbaki, the fictitious name used earlier in this century by a real group of mainly French mathematicians to publish their collective work on fundamental problems. (The conflict between the pursuit of science as impersonal truth and the need for personal recognition is one of Djerassi’s central themes.) *The Bourbaki Gambit* falls into the genre of “caper stories”—those in which an unlikely group of confederates come together to pull off an even more unlikely task. In this case, the group consists of prominent scientists at or near the age of retirement who feel that they have been mistreated by their respective institutions. Their scheme is to collaborate on a series of brilliant research papers published under an assumed name, then announce their true identity, to the consternation of the colleagues who put them out to pasture.

As luck would have it, one member of the group makes a revolutionary discovery, the polymerase chain reaction, or PCR. (It is an apt choice of findings: in reality, PCR, a means of duplicating strands of genetic material, was one of those important ideas in science that required a single insight rather than years of work.) Ultimately, the magnitude of the discovery becomes obvious, and the researchers must decide how to make their final announcement. A large part of *The Bourbaki Gambit* is devoted to explorations of the workings of the scientific community. Interspersed with these are several good explanations of the science that underlies the story. Using the time-honored technique of having a character explain something to a nonexpert, Djerassi incorporates several pages of discussion of PCR into the text. This section offers as good an explanation of this subject as you will find anywhere.

If Djerassi is trying to develop science-in-fiction, theoretical astrophysicist Alan Lightman’s *Good Benito* can be thought of as “fiction-about-a-scientist.” Using the technique of isolated flashes of insight that worked so well in his first novel, *Einstein’s Dreams,* Lightman paints a portrait of the childhood and early adulthood of a man who happens to be a theoretical physicist. I say “happens to be” because *Good Benito* is a character portrait, and the fact that the protagonist is a scientist is almost a side issue.

Nevertheless, *Good Benito* can be examined as a piece of science education—an approach that might not have been in Lightman’s mind when he wrote the book but one to which he probably would not object. Lightman’s spare style does not lend itself to lectures, so there is little about the content of science in the book. Instead we find a brilliant exposition of why people become scientists. Here is his protagonist working on his thesis problem:

> He could write down an equation on his white pad of paper and ten thousand stars would appear, careening through space. Or he could add a mathematical symbol and the stars would bounce off the walls of a great cosmic vessel. If he paused to eat tuna fish, the stars suddenly froze—ten thousand suns held in suspended animation—until he swallowed his last bite and returned to his calculations.

In the end, what Lightman gives us is an insight into another human soul—

exactly what a good novelist is supposed to do.

So what are we to make of these two recent attempts to meld science with fiction? Perhaps my reaction to *The Bourbaki Gambit* illustrates a more general truth about this kind of literature. The opening chapters of the book moved quickly; the dialogue fairly sizzled. When I got to the discussions of the mechanics of the scientific community, however, I found my attention flagging. I just could not stay focused on the arguments about teaching versus research, individual versus collective credit and the like, even though I have participated in many such arguments at faculty clubs. I did not have this problem in *Good Benito,* because in the few cases where the daily life of scientists came front and center, it did so in captivatingly weird situations.

Musing on my reaction, I came to a somewhat unnerving conclusion. The fact of the matter is, we scientists are simply not all that interesting. If I may generalize wildly, we are usually dull people with interesting ideas—as distinguished from artists (interesting people with dull ideas) and dancers and athletes (dull people with dull ideas and magnificent physical skills). The more a story focuses on what scientists actually do, I fear, the less interesting it will be.

You have only to look at modern movies and books to find confirmation of that point. When was the last time you saw a realistic portrayal of a scientist in a popular work? Instead of watching the hero or heroine staring at a computer screen for hours on end, we find paleontologists being chased around the landscape by dinosaurs (*Jurassic Park*) or virologists being chased around the sky in a stolen army helicopter (*Outbreak*). Be honest—when have any of you scientists had a professional experience that comes remotely close?

I wish my colleagues well in their attempts to put a more human face on our profession and perhaps slip in a little contribution to the reader's knowledge in the process. God knows the problem of scientific literacy is big enough that those laboring in the vineyards need help from anyone willing to lend a hand. Speaking for myself, though, I think I will stick with nonfiction science until intrepid pioneers like Djerassi and Lightman have blazed a trail into more speculative domains.

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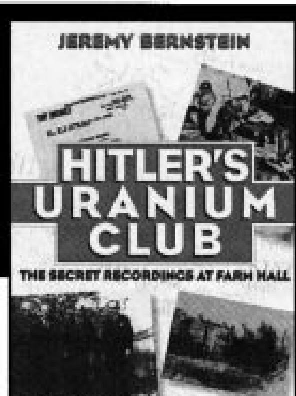
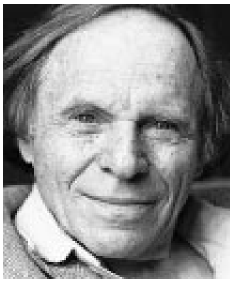


WONDERS

by Philip Morrison



DONNA COVNEY

On Neutrino Astronomy

"Nothing is too wonderful to be true." Carved in stone on a lintel of the physics building at the University of California at Los Angeles, that lively phrase is there ascribed to the nonpareil Michael Faraday. A sharp-eyed searcher lately pursued it to its source, the fifth volume of Faraday's published lab diaries, entry 10,040, dated March 19, 1849, where it continues: "...if it be consistent with the laws of nature, and in such things as these, experiment is the best test of such consistency." This quote inspires both the title of my new column and the themes I will explore here each month.

In the *Scientific American* of August 1962, I published an early piece on neutrino astronomy. The discipline had then no experimental results at all. What has happened since is almost—not quite—too wonderful to be true, and I admit that in this column I haven't mentioned even the half of it!

Most astronomy is the study of photons, the generic name for the stable quanta in any wave band of the electromagnetic field, the simplest of the structureless "elementary" particles. Neutrinos, too, are stable and without known structure, but they dance to another field of force, once called the weak field. Optical astronomers seek thin mountain air. But neutrino astronomers burrow deep to observe, down into the hard rock or the watery depths of the polar ice cap. Such geologic shields are transparent to neutrinos yet filter out the cosmic-ray particles whose many interactions add noise. Observations from these subterranean perches reveal the universe from the neutrino's perspective, a surprising place in which stars are translucent and the familiar world of light may fade into insignificance.

The photon is held to have no rest mass, a supposition bolstered by experimental data to an extremely high precision. Photons therefore cannot decay as they stream through space, unbound and tireless, at ultimate speed. As you read, this page is lighted by visible photons in abundance, all born anew out of the electrons within a hot lamp filament or within the phosphors in a fluorescent bulb. The photons bounce lossily again and again from floor and walls for a tenth of a microsecond. All the energy the photons held swiftly passes to modify or to warm atoms, but the lost photons are constantly replenished by new ones from the lamp. When any photon disappears, its energy, momentum and spin remain like the grin of the vanished cat, always passed on to some other particles.

Photons were first clearly recognized in 1905 by the young Albert Einstein, building on Max Planck's grand idea of the quantum of energy. Neutrinos entered our maps of nature only between the world wars. Recognition of them took two decades, led by the experimenters, but was sealed in the 1930s by two celebrated theorists. In an informal letter written in 1930, Wolfgang Pauli postulated the existence of the neutrino as a "desperate proposal" to end an enigma in the physics of natural radioactivity; in 1934 Enrico Fermi turned that superb insight into an audacious quantitative theory of the "little neutral one," the Italian name Fermi chose for the particle.

Electrons are ejected from certain unstable nuclei in decay processes dubbed beta decays. Electrical charge was obviously conserved in the decays, but energy and spin remained unbalanced, even after long searches for some oversight of accounting. For a time, Niels Bohr proposed to abandon the strict conservation of energy in quantum physics to solve the problem. At last, it became clear in the lab and on paper that a low-mass, uncharged, unseen particle escaped in every decay event, embezzling the missing quantities.

Lacking any bonds to matter, neutrinos are fine messengers from space. Like photons, they traverse the cosmos stably in straight lines and at near light speed. But they act very unlike photons in other ways. Gamma rays are examples of photons that we regard as quite penetrating, for they easily pierce several centimeters of solid lead. But an energy-matched beam of neutrinos could penetrate a layer of lead *light-years* thick before the rare atomic collisions drained energy away.

Between the wars, a couple of grams of radium was judged a luxurious source of decay neutrinos. By the 1950s a high-power nuclear reactor emitted as many neutrinos as does 100 tons of radium. The old detectors held only an ounce or two of target gas. They were supplanted by a ton of water as target; a fluorescent layer nearby was closely watched by hundreds of photomultiplier video tubes, able to pick up even the few light quanta made in the rare neutrino collision in the water. Nuclear reactions are a stringently fair lottery; corner the tickets by arraying plenty of target atoms and floods of neutrinos, and you can be sure a few collision events will show up. Frederick Reines and Clyde L. Cowan, Jr., set up to audit the Fermi energy ledger: Was the energy really out there with the fugitive neutrino?

It was, and in 1956 the two men caught one out of every billion billion passing neutrinos that flowed through their detectors from the reactor at the Savannah River site in South Carolina. In their experiment, a neutrino was swallowed up by a proton in the water. In place of those two particles, a moving neutron and a positron appeared, signaled by patterns of visible photons as the products slowed down.

The particle count was balanced under the rules that govern neutrinos: an electron may replace a neutrino, and an antielectron an antineutrino. The missing energy is only the normal kinetic energy of the neutrinos in motion, although they are loath indeed ever to give it back. Now energy was visibly in balance; it could be followed to the specific collision that ended the journey of one of the idiosyncratic new particles.

Some years back, neutrino astronomy enjoyed amazing good fortune for 10 seconds. Two big detectors, each many kilotons of closely watched water, were waiting patiently. One is buried in the Japanese Alps, one in a salt mine under our Lake Erie shore. At the same moment one February night in 1987, both of them recorded a 100-fold spike in the neutrino counting rate, a peak never seen before or after. A few hours later a supernova appeared to human eyes in the southern sky, in the Large Magellanic Cloud, the closest visible supernova in three centuries. The worldwide coincidence makes it hard to doubt that the earth was bathed for a short time in a flow of neutrinos carrying more energy than that of all sunlight on the earth, although their source was the collapsing core of a massive, young star 160,000 light-years away.

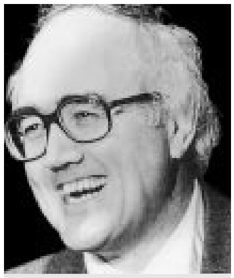
The theorists had forecast it amazingly well. A dozen or two neutrinos were caught from the million million million that crossed both house-size detectors, flowing up through the solid earth from the south. (Of course, you yourself, like all the rest of us, were pierced through and through by trillions of the supernova neutrinos: no damage.) The neutrino flash from that single star collapse was, for a second, more powerful than the steady optical light of all the stars in all the galaxies we can see!

An inferno at the supernova's dense imploding core, only a few miles across, became several thousand times hotter than the center of the sun. From it a tide of neutrinos poured out, able to leave the star, though not without interactions in that enormously thick envelope. The high temperature made neutrinos by heat alone, two at a time, neutrino and antineutrino together. Myriad fierce encounters between hot photons or between electron pairs within the core made neutrinos only rarely, but, once made, the neutrinos promptly left for the cold world outside, taking with them more than 99 percent of all the energy released in the star's collapse.

So much is well supported. One more wonder may also be true. There are strong signs that the cosmos we inhabit is filled with unseen matter, whose gravitational pull is the only evidence we have. We do not know what it is. Surely the simplest conjecture is worth tentative trial against the unknown. This missing matter, 10 or more times as copious as all the ordinary matter that comprises stars and galaxies, may be thermal neutrino pairs. The hot, early cosmos could have made them, although like photons they will cool in the universal expansion.

The rest mass of neutrinos is not known from experiment or theory. If they have any, they can cool only so far. Some part of their energy cannot be taken away, allowing them to be the missing mass of the cosmos, as once before they were the missing energy for the "radioactive ladies and gentlemen" Pauli had saluted in his letter of 1930. The mass of any neutrino (we now know of three kinds of neutrinos, not just the beta-decay ones) is a major open question; watch for news.

Neutrinos may be what the cosmos is made of. Our own kind of complex atomic matter, all those electrons and quark-built nuclei and the photons that build stars, planets and life, may be only a small impurity by weight in a wonderful universe of neutrino pairs.



MILLERSVILLE UNIVERSITY

CONNECTIONS

by James Burke

The Silk Road

This is the first of my monthly columns for *Scientific American.* It is entitled "Connections" (a name I have also used for books and two television series) because I aim to look at the way the great web of change connects events, discoveries, inventions, personalities, politics, the arts and 1,000 other components that can be involved in the act of innovation. Reductionism simply does not begin to describe this complex, serendipitous process, in which even apparently trivial elements have the most important effects. Take, for instance, the case of shot silk.

In the mid-17th century, one of the few mills in northern Europe producing high-quality products such as shot silk—a fine, iridescent and expensive weave—was in Spitalfields in London. So in 1668 a Dutch draper called Antonie Thonisoon went there to see the latest English designs. He was astounded to come across drawings of silk fibers magnified to a much greater extent than was possible by means of the draper's glass he normally used to examine cloth.

Fired by this amazing discovery, he returned to his hometown of Delft, changed his name to the more aristocratic van Leeuwenhoek, took up lens grinding (the 17th-century equivalent of computer chip design) and began to mingle with the local scientific elite. On Christmas Day, 1676, the result of his new interest burst upon an astonished Royal Society of London in the form of a long letter containing illustrations of what Leeuwenhoek had seen through one of his 500-power lenses.

What shook everybody was his claim that the minute objects were alive, because he had seen them moving. With this first sight of rotifers and their waving cilia, protozoan cells rupturing, hair emerging from its roots, wriggling spermatozoa and organisms—30 million of which Leeuwenhoek estimated would fit on a grain of sand—a new world opened to science.

For one German passing through Holland, the microscopic organisms also served as proof of the "Great Chain of Being" theory. This theory held that all life-forms, from the simplest slime all the way up to humankind, had been designed by God into a series of successively more complex species that differed from one to the next only by infinitely small graduations. The German in question, Gottfried W. Leibniz, had a vested interest in things microscopically small, having recently developed an infinitesimal calculus with which to work out the rates of acceleration of planetary bodies. Leibniz saw Leeuwenhoek's organisms during a visit to Delft in 1678 and asserted that they showed the differences between species might be so tiny "that it is impossible for the senses and imagination to fix the exact point where one begins or ends."

Leibniz's philosophy, which was based on the existence of such infinitesimally small, fundamental elements of existence, or "monads," turned out to be exactly the universal substrate for which the 18th century was looking. Jean-Jacques Rousseau's call for a return to the life of the noble savage and the general disenchantment with the social effects of the industrial revolution had spurred the search for a way to reunite human beings with nature. In Jena, the hotbed of this new Romantic view of life, Friedrich Schelling's *Naturphilosophie* brought together recent scientific discoveries (of opposite magnetic poles, positive and negative electric charge, and chemical acids and bases) into a unified theory of nature as a product of the dynamic resolution of mutually conflicting forces.

It was in 1820, while attempting to apply this "conflict" view to electricity and magnetism, that a Dane called Hans Christian Ørsted forced more electricity into a wire than he thought it would take. The wire became incandescent, convincing him that electricity and light were related, so he extended his investigations and discovered that current would affect a magnetized needle at a distance.

Twenty-one years later this electromagnetic principle brought Samuel F. B. Morse to develop the telegraph. In 1842 Morse helped Sam Colt, the inventor of the revolver and Morse's neighbor in

New York City's Washington Square, by providing him with the electromagnetic means to detonate one of Colt's new underwater mines, so as to demonstrate their power to President John Tyler by blowing up a ship on the Potomac. Colt's other aim was to impress the Russians, who were also interested in his invention. But Colt was unwilling to explain exactly how he detonated the mines, so the Russian contract went instead to a Swede called Alfred B. Nobel, whose mines needed no electrical signals to trigger them. When a ship's hull hit Nobel's mine, it distorted a lead casing, breaking a glass tube inside, releasing its sulfuric acid contents onto a mixture of potassium and sugar, causing a flame that ignited gunpowder.

At the time of the Crimean War, the Russians sowed these new Nobel mines in the port of Sevastopol, forcing the Allied supply fleet to ride at anchor outside the harbor. The ships were left disastrously vulnerable to the great hurricane of November 14, 1854. In the course of the storm, the fleet was devastated, and with it the winter supplies for the army ashore. The deprivations that winter were so dreadful that Florence Nightingale's subsequent investigations would bring down the British government and inspire Jean-Henri Dunant to found the Red Cross.

But it was the loss of the warship *Henri IV,* pride of the French navy, that had the biggest effect. The sinking caused a sensation in France. The next day Emperor Napoleon III called for the establishment of weather forecasting services throughout the country. By 1860 daily telegraphic weather reports were being published all over Europe. One leading figure in the new science was a young American naval officer named Matthew Maury, who for nine years collated reports from all over the U.S. and amassed the equivalent of a million days' observations, from which he was able to prove that storms were all either circular or oblong.

By the 1930s the U.S. Weather Bureau had been going for more than 60 years, and nobody had yet attempted to analyze all the data it had collected. So a young physics teacher by the name of John W. Mauchly, who as a student had worked summers at the Weather Bureau, decided to attempt the task. The problem with analyzing the massive data set was the time it would take to do so by conventional methods.

Then Mauchly discovered that researchers studying cosmic rays were counting their particles using a vacuum valve, because it could be turned on and off by particle strikes very rapidly, up to 100,000 times a second. Mauchly realized that vacuum valves might automate the business of calculation by acting as data storage devices.

Before he could do much about the idea, World War II broke out. Mauchly was conscripted and soon found another mathematical problem that was also taking too long to solve. This was the matter of calculating artillery tables, used to instruct a gunner how to aim and fire his piece under all conditions. Early in the war, at the U.S. Army Ballistic Research Laboratories in Aberdeen, Md., dozens of female mathematicians were each taking up to 30 days, working around the clock, to complete one artillery table for one gun. A single shell trajectory (that took into account all the possible variables affecting its flight) required 750 multiplications, and a typical table for one gun involved 3,000 trajectories. By 1942 the laboratory was being asked to calculate new tables at the rate of six a week, bringing the situation close to crisis.

Mauchly put forward his vacuum valve counting idea, and the army accepted it. The process basically involved switching on or off vacuum tubes, arranged in sets of 10, and using the total of each set's on/off state as a number. Mauchly's machine was operative by 1946, too late for the war effort but not too late to calculate how to cause an atomic explosion. Known as ENIAC (Electronic Numerical Integrator and Computer), the machine was effectively the world's first electronic computer, so named after the term commonly used for the female mathematicians at Aberdeen.

ENIAC was fed data by means of punched cards, adapted by inventor Herman Hollerith for use in the 1890 U.S. census. That approach had been suggested to him by his brother-in-law in the textile industry, who knew about an automatic weaving system involving sprung hooks pressed against a paper card with holes in it. Where there was a hole, a hook would pass through and pick up a thread. Hollerith replaced the hooks with electrified wires and made each wire represent a piece of census data; where a wire passed through a hole, it would make electrical contact and cause a dial to move forward by one number. The system greatly sped up the census, counting 62,947,714 Americans in one twentieth the time taken (for a much smaller population) by the previous census.

The weaving technique Hollerith modified had been used to automate the production of cloth made of a material too expensive to make mistakes with: shot silk.

Doing Business on the Net

Like the leaves of autumn, those resolutely noncommercial days on the Internet when ads were anathema are dwindling fast. Nowadays the Internet's World Wide Web has so much commercial promise that it has spun off an association called the HTML Writers' Guild (http://www.mindspring.com). You can hire one of its members literate in Hypertext Mark-up Language (HTML is the language of the Web) to create dramatic "home pages," sites on the Web where a growing number of businesses advertise their wares. "We're there for the same reason we have banks in malls," one Citibank executive explained. "It's where people congregate."

Web ads are quickly evolving into arresting combinations of sound, text and vivid, point-and-click picture links called image maps. Computer science students who were once stern critics of business on the Net now eye the ads appreciatively, so long as they are not "in your face"—inserted where people have no choice but to look at them. Besides, commercials may one day pay for Net services, much as they now underwrite programs on radio and television. And the ads are convenient: click on the icon, read about the product and order, all in one step.

Many companies are poised to put not only advertisements but entire catalogues on the Web as routinely as they now list their services in the Yellow Pages. After all, if e-mail could hatch a generation of letter writers by eliminating the bother of envelopes and stamps, surely commerce should blossom when paper catalogues fall, and we all start buying straight from the screen.

For business to thrive, though, people will need a secure way to pay and be paid on the leaky Net, where messages containing credit-card numbers can be intercepted as they travel from machine to machine. And all those prospective shoppers, entrepreneurs and micromerchants will want not only secure payment mechanisms but also a choice—cash, check or charge—before they hit the convenient, brightly colored order links. Inspired by a vision of untold millions buying and selling on the Net, companies and banks (among them Chase Manhattan, Citibank, CyberCash, DigiCash, Mondex and Microsoft) have joined what is being called the Gold Rush of 1995, as they race to become the Great Central Biller in the Sky.

No victors have yet emerged, but early leaders are probably going to provide security in the form of public-key (PK) cryptography, ingenious algorithms that use pairs of unique numerical "keys" for encoding and decoding messages. If you use PK software for an online shopping trip, you will have your own pair of keys, one public and one as private as the identification number you use to get cash from an automated teller machine. When you order, your program will automatically encrypt the information with your private key. When the company uses your public key to decode the order, it will know without question that the message was generated by you—the match is the digital signature that authenticates the transaction. Companies in turn will encrypt messages to you with your public key; the messages will be secure, for only you can decrypt and read them, using your private key. Netscape and other new Web browsers—software that lets you travel to linked Internet resources without typing complicated addresses—are known as encrypting browsers; they are ready to help you shop securely on the Net. Some will even come with built-in PK signatures.

Whether the cryptographically cloaked digits of e-money will bestow privacy in addition to security is another, far more contentious matter. When people start using e-wallets instead of cash to rent a video or lend a friend $20, fertile new areas for infringing on privacy will bloom. Electronic dossiers can be compiled by automated systems that track spending habits. Many people will not want the details of their daily lives collected and stored in, say, consumer preference data banks, joining the folders that already document their health and credit ratings.

Only a few of the emerging electronic payment systems address privacy issues. The untraceable digital cash closest to hand is probably Chaumian cash, named in honor of David Chaum, founder of DigiCash and of the cryptographic protocols that underlie his anonymous digital-money technology. Chaum's patented e-cash is an adaptation of PK cryptography that includes one-way privacy for the payer. The bank can verify that the money is genuine but is blinded from identifying the source. This means you will be able to prove you have made a payment when you need to, but the bank cannot flick a switch to retrieve the records of your travel and entertainment preferences and add them to its data-mining operations.

The terminology of electronic commerce reflects the clash of cultures that has come about as the youthful language of the Net meets the austere discourse of banking. The jaunty "e-" prefix has attached itself firmly to Nettish talk of the e-wallets and e-purses that we will soon be using to make our e-payments. But bankers resist this linguistic cheeriness. They substitute "digital" for "electronic" whenever possible and never shorten it to "d-" when they speak of the digital time stamps and digital signatures they will soon offer us to authenticate our digital payments. And cryptography (known affectionately as crypto on the Net) is still a four-syllable word at the bank, where it is against nature for managers to be linguistically fond of any action that commits them to untraceable communications and exchanges.

We will know the new, hybrid field of electronic commerce is truly on its way when banking ads on the Web offer "strong crypto" and even, as a backup, steganography (the science of hiding the existence of messages in, say, microdots or sound files) for telephone chats with loan officers. On the Net, of course, this service is already known as stego.

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