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The puzzle of consciousness.

Galileo *spacecraft at Jupiter.*

Understanding cystic fibrosis.

Breast-feeding *strengthens newborns' immune systems.*

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DEPARTMENTS

Letter from the Editor

Year's end is the season of gift-giving for much of the world—and especially for many of the world's children. Some parents among you may be softly hyperventilating at the thought of the miles of ribbon and acres of wrapping paper (not to mention the credit-straining goods they enfold) in your near future. In the hubbub, it is easy to overlook the things of more lasting significance we confer in very different biological and intellectual packages.

Not all these gifts are welcome, nor given wittingly. When parents pass along the genes for a fatal disorder, the results are tragic. Six years ago investigators found the mutant gene responsible for cystic fibrosis; since then, much has been learned about its effects. The dream is to cure the ailment with gene therapy, to rehabilitate the cells whose malfunction gives rise to the disease. In the long run, it is conceivable that germ-line gene therapies could correct the defect in a heritable way, eliminating the disease not only from one individual but from an entire bloodline.

Frustratingly, gene therapy is simple in theory but hard in practice. The latest dispatches from the pilot clinical trials for cystic fibrosis indicate that the current approaches still lack sufficient effectiveness. Few researchers doubt that, eventually, gene therapy will succeed, and cystic fibrosis patients will be among the beneficiaries. Meanwhile parents can confront the specter of cystic fibrosis directly in other ways, including genetic testing. In "Cystic Fibrosis," beginning on page 52, Michael J. Welsh and Alan E. Smith discuss the prospects and alternatives posed by the latest discoveries.

The Wet-Nurse, ***by Alfred Roll, courtesy of the Musée des Beaux-Arts, Lille. Giraudon/ Art Resource.***

Not all of a parent's biological legacy is genetic. Research on the benefits of breast-feeding has shown that human milk helps the newborn rebuff invading germs while his or her immune system matures. "Safe as mother's milk" thus appears to be an understatement. Physician Jack Newman summarizes these antimicrobial properties in our cover story, starting on page 76. (But the symbiosis between mother and child may not always be so nurturing. See also page 25 of "Science and the Citizen" for a report on findings that suggest fetuses and their moms engage in a selfish prenatal contest for nutrients.)

Culture and learning may be the most important part of what we give children to shape their minds. In that spirit, Philip and Phylis Morrison present the 1995 winners of the Scientific American Young Readers Book Awards as a handy guide to the cream of recent offerings for science-minded children (and their parents). These blessings, at least, can be had for a price. Start your wrapping early.

JOHN RENNIE, *Editor in Chief*

LETTERS TO THE EDITORS

Global Research

The solution to the prejudice against scientists in developing countries, described by W. Wayt Gibbs in "Lost Science in the Third World" [SCIENTIFIC AMERICAN, August], lies with these researchers turning their backs on publishing in Western journals and writing in their native languages and journals. Such scientific efforts, if worthwhile, will eventually attract mainstream attention.

SURENDRA KELWALA
Livonia, Mich.

Discrimination can also take a form not mentioned in "Lost Science in the Third World." American scientists working at the Organization of Tropical Studies in Costa Rica generally avoid the scientific journal of the very country where they do their fieldwork, despite the journal's international standards, excellent distribution in tropical research centers and inclusion in *Current Contents.* They would rather publish in newer, less stringent "tropical" journals published in the U.S. and England.

JULIÁN MONGE-NÁJERA
Editor, *Revista de Biología Tropical*
University of Costa Rica

I read with great interest Gibbs's news story about the "Information Have-Nots" ["Science and the Citizen," SCIENTIFIC AMERICAN, May] and his more extensive follow-up article in August. I am constantly throwing out journals; this seems like a tragic waste. Is there some central location that collects and distributes to needy areas?

KENNETH R. KELLNER
University of Florida

"Lost Science in the Third World" makes points based on anecdotal evidence, but these ideas are not well supported by statistical data. To use "percent of total articles published per nation" without regard to the size of a nation is all but meaningless. For example, when adjusted for population, Iceland (given in the table as 0.029 percent) in fact produces as much per capita as the U.S. (30.817 percent).

PAUL W. ROSENBERGER
Manhattan Beach, Calif.

Gibbs replies:

My aim was to illustrate which nations are represented most in mainstream scientific literature and which are largely invisible, despite having large research communities, when viewed through this lens. I thus compared the scientific production of nations, not their scientific productivity. A comparison of productivity, taking into account not only population but also research spending and the number of active scientists in each country, would also be interesting. Insufficient data are available for such an analysis, however.

For those who would like to donate material to scientists in developing countries, the International Network for the Availability of Science Publications (INASP) provides guidelines on how to select books and journals to donate and will try to locate the program nearest you. Contact the INASP at P.O. Box 2564, London W5 1ZD, U.K. You can also e-mail them at inasp@gn.apc.org or fax them at (44) 181-810-9795.

Neighbors, Beware!

Inspired by your July cover story, "The Trebuchet," by Paul E. Chevedden, Les Eigenbrod, Vernard Foley and Werner Soedel, my son Ernie and I built a model in our garage out of two-by-fours. Our trebuchet has a five-foot lever with the fulcrum one foot from the end. The weight is a 50-pound bucket of concrete. It can throw a baseball or a water balloon 100 feet.

DOUG ESSER
Bothell, Wash.

Creating Science

"Darwin Denied" ["Science and the Citizen," SCIENTIFIC AMERICAN, July], Tim Beardsley's excellent review of the attempts to place "creation science" in public schools, fails to note that the guise of "intelligent design" is being replaced by the "initial complexity model." Thus do "scientific creationists" hope to deflect the charge that because intelligent design implies the existence of a Creator, the notion is religious. If creationists have their way, the initial complexity model will be taught with the "initial primitiveness model," their new name for the theory of evolution.

JOHN C. FRANDSEN
Chair, Committee on Science
and Public Policy
Alabama Academy of Science

Up Close, Too Personal

The profile of Stephen Jay Gould by John Horgan ["Escaping in a Cloud of Ink," "Science and the Citizen," SCIENTIFIC AMERICAN, August] is a thoroughly unpleasant piece of work. Obviously irritated by Gould's ground rule of not wanting to talk about personal matters, Horgan forces personal items into the whole article. In addition, a snide tone replaces an analysis of the quality of the science. There is no discussion of how Gould's theory squares with the available evidence; instead we are treated to some pop psychiatry about Darwin and daddy. Perhaps it is a good idea to try some other approach to profiles of scientists than as a God-in-a-lab-coat. But what we have here is a mugging.

EDWARD R. TUFTE
Yale University

National Anthem

Peter M. Narins seemed mystified in his article "Frog Communication" [SCIENTIFIC AMERICAN, August] when 10 coqui frogs failed to call out after he exported them from Puerto Rico to Germany for the purpose of measuring their calls. As any Puerto Rican will confirm, no coqui will sing once removed from its native home—a distinction that has made the coqui the national symbol of Puerto Rico.

STEVEN HUDDLESTON
San Juan, Puerto Rico

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

DECEMBER 1945

Looking upon atomic energy as an addition to the world's supply of fuel, the Gas Turbine Coordinating Committee of the American Society of Mechanical Engineers has issued a report saying, 'It is felt that atomic power certainly will not replace present fuels but will supplement them, as oil supplements coal.' The committee looks forward to the possibility of power-plant units 'above 200,000 kilowatts, using both present fuel and atomic power to achieve the greatest efficiency.' "

"For future reference: Those concerned with the development of aviation—both commercial and private—should give serious consideration to the development of more sightly airports."

"A full-size, compact bedroom has been constructed to show how plastics in home furnishings can be at once functional and attractive. Both the decoration and illumination of the room come from its walls, a curved sheet of Plexiglas which has been engraved and painted with a design. Hidden fluorescent lamps edge-light the wall, causing it to glow radiantly. The chair is a drum formed from sheets of acrylic resin. A flat strip of acrylic acts as a curtain rod for multi-striped polyvinyl chloride curtains. More important than the ease of installation is that these pieces can be wiped clean with a damp cloth."

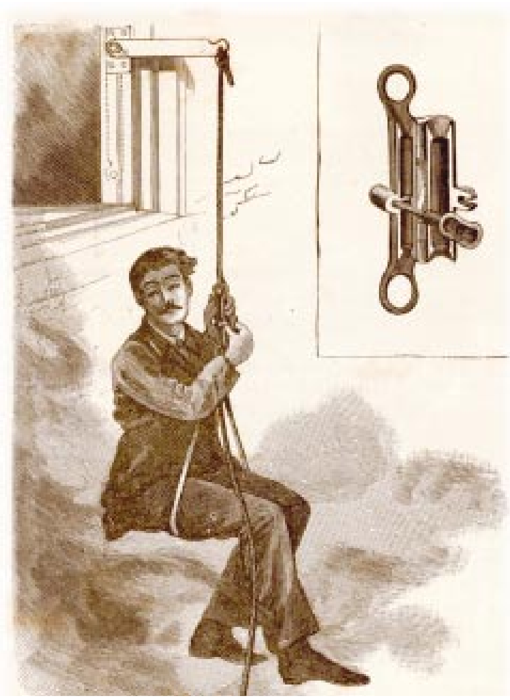
DECEMBER 1895

Practical synthesis of carbon and hydrogen on a small scale in the laboratory has represented one of the triumphs of chemistry. The commercial production of carbon and hydrogen as exemplified by acetylene gas formed one of the most striking exhibits of the Atlanta Exposition. The gas was shown in practical shape, produced from a portable evolution apparatus, and also as burned directly from compression cylinders, in which it was stored in liquid form. The gas was burned from open burners and in different types of car lamps, one of its prospective uses being the lighting of railroad trains."

"A successful manufacturer of egg incubators has recently placed on the market an incubator which is heated and regulated by electricity. It is said that the temperature can be adjusted to be held for weeks within a fraction of a degree of the desired point. In the 'Electric Hen,' the heat is controlled by a resistance box, the current through which can be regulated with extreme nicety."

"According to consular reports, the existence of asphalt in the Jordan Valley has been ascertained, and it is supposed that petroleum will be found also. The opening up of the rich mineral resources of the Dead Sea basin is considered a very profitable undertaking, for which, however, foreign capital will hardly be found, as the legal status of property holders in those regions is very unsafe."

"A simple and inexpensive portable fire escape, which may be packed to take but little room in a traveler's trunk or bag, is shown in the accompanying illustration. It consists of a clamp adapted to slide upon a rope, to which may be attached body and shoulder straps. The clamping or frictional pressure upon the rope can be readily controlled by the person using the device. When the escape is permanently fixed in houses or factories, the rope is preferably attached to a hinged arm secured at the inside of the window."



The new portable fire escape

DECEMBER 1845

The work of Alexander von Humboldt, *Cosmos,* now publishing, speaks of comets as 'an innumerable host.' By the rules of probabilities, we find they must amount to such myriads as to make the imagination pause amazed. Johannes Kepler says there are more comets in the depth of space than there are fishes in the bosom of the ocean."

"It is a commonly entertained opinion, with those who have not given particular attention to the laws of mechanical motion, that the same quantity of force and power that would project a ball of ten pounds weight with a velocity of ten feet per second would also be sufficient to project a five pound ball with a velocity of twenty feet per second. And on this erroneous opinion, many have based their calculations with regard to the operation of new constructions of machinery, and have as often been disappointed in the results: the fact being that double the power is required to project the smaller ball with double velocity."

"A patent has been obtained in England for a new atmospheric railway, on which the cars are to be driven by a blast of wind blown through an iron pipe by a stationary engine working a bellows at the ends of the road. This pipe, extending the length of the road, has a crevice at the top to admit a plate which connects the car to the piston, and this crevice is closed with two strips of leather, which is parted by the plate in its passage, and closed immediately after it so as to exclude the external air from the interior. The proprietors offer to ensure the lives of all who travel on the road, without extra charge."

Tempest on the High Sea

The Ocean Drilling Program narrowly averts catastrophe

In 1985 a remarkable ship—built initially for oil exploration but converted for scientific research—set off on the first leg of an ongoing investigation of the seabed called the Ocean Drilling Program (ODP). For many geologists, the ODP's sophisticated 470-foot-long vessel *Resolution* represents their sole contact with "big science"—it is the floating version of the *Hubble Space Telescope* or the Superconducting Super Collider. And like these other large-scale scientific endeavors, the ODP has struggled to maintain its federal funding. Hence, hearing that the ODP nearly ended on the last day of the fiscal year might seem no surprise. But the threat this time was not Congress. Rather it was an unnamed North Atlantic storm that nearly sent the ship and some 120 passengers to the bottom of the east Greenland sea.

ROBERT OWEN *Sedco*

STORM OPERATIONS on the scientific drilling vessel* Resolution *made past examples of foul weather* (as shown here) *seem mundane.

The most recent voyage of the ship started calmly enough as the *Resolution* left Iceland. On board, four dozen scientists gathered from institutions around the world familiarized themselves with the floating laboratory and began to establish a routine. Most of the time, the *Resolution* carries its occupants serenely through what for a smaller research vessel would amount to a sizable storm. During this particular mission, however, the scientists had no easy ride—the North Atlantic became rough enough to start the large ship rocking.

To complicate matters, the *Resolution* had to dodge icebergs floating out from Greenland's coastal glaciers. Captain Edwin G. Oonk had already experienced one near miss when a great iceberg veered toward the ship unexpectedly; so when the barometer began to plummet on the last days of September, the captain's choices were few. Separate storms were raging to the north and east; he dared not drive much farther toward them. Yet the iceberg-laden waters behind him gave no better shelter near shore. Oonk initially attempted to ride out the growing storms by steaming gently forward into the wind and waves. As the barometer continued to drop, it became obvious that the usual tactics would not suffice. The two storms coalesced, and the winds mounted. Often the gusts became so intense that the ship's wind-speed indicator pegged at its maximum reading of 100 knots (115 miles per hour). The storm buffeted the ship with waves that were 70 feet tall yet strangely compact. "They were like walls," recounts James F. Allan, the ODP staff scientist on board.

At times, the main pair of propellers would lift entirely out of the water, causing them to spin wildly and creating concerns that the shaft bearings would give out. Riding against the onslaught of wind and water proved impossible. Yet the waves were so fierce that Oonk could not risk letting the ship turn: to be struck broadside at that point would have capsized the vessel. Although massive and typically steady, the *Resolution* is not particularly seaworthy: tall racks of steel pipe on deck make it top-heavy, the towering derrick catches wind like a sail, and a 20-foot central hole through which the drill pipe passes does nothing to add to the hull's structural integrity.

As equipment began to break loose on deck—floodlights were knocked over, ventilation shafts broke open and lifeboats shifted in their fastenings—Oonk let the ship slide backward, taking advantage of the *Resolution*'s extraordinary maneuverability. To allow drilling into the seabed miles below, the ship is outfitted with a secondary propulsion system made up of 12 electric thrusters arrayed around the hull. These massive motors can keep the ship in a fixed position even in changing winds and seas. A sophisticated computer senses the ship's motion and commands the set of motors to keep the vessel where it is, a technique called dynamic positioning.

Normally, the dynamic positioning mode of operation is used only for drilling. It was not at all clear that in the midst of this tempest, with the main screws in the stern periodically lurching out of the water, whether the "DP" system could keep the ship from turning sideways and capsizing. Fortunately, the maneuver worked. Running the thrusters 20 percent above their rated capacity seemed to be enough to keep the ship pointed into the waves. Still, the *Resolution* drifted backward at about three knots, requiring lookouts to strap themselves in under the helicopter deck in the stern of the ship to watch that it did not overtake an iceberg.

When Allan arose on the morning of September 30, after a fitful attempt to sleep, the ship's operations manager Ron Grout informed him that the *Resolution* was "in danger of sinking." Such words are not used lightly at sea. People began to carry their rubberized survival outfits with them as they walked the corridors, well aware that the "Gumby suits" would probably do little to protect them from drowning.

As the day progressed, thrusters began to give out. Suddenly, a giant wave crashed over the bow, blasting out a window and dousing the bridge with several feet of water. Grout immediately remembered the *Ocean Ranger,* a drilling platform that sank in the North Atlantic when a window to its ballast control room gave way. As seawater lapped to within an inch of the critical rack of computers that operated the electric thrusters, a disaster-control team of 11 people quickly formed to repair the window with plywood and two-by-fours. Allan notes that those people braved "hideous conditions on the bow" and could have easily been washed overboard had a wave broken just then.

Despite repeated pounding, the wooden window patch held, as did the DP computers and enough of the remaining thrusters to see the ship through another 15 hours of horrific seas. With radar, floodlights and much of the communications gear gone, the *Resolution* might still slam into an iceberg—but that must have seemed a pleasantly manageable worry compared with the capsizing the ship had just escaped.

Lorraine Southey, one of the ODP staff members, used her video camera to document the ordeal. Initially, she feared that others might resent the intrusion, but she found that most of her shipmates were more comfortable speaking to her camera than wrestling alone with their thoughts for the two days that the storm raged. After the seas finally calmed enough so that the damaged ship could limp back to port, Southey composed a design for a T-shirt (as each group of participants does at the end of an expedition). Hers showed a floating life preserver and read, "East Greenland Sea. Force 12+ storm. 100+ kt winds. 60+ ft seas. Maxed Out. Survival is: a good crew."

In early 1994, I had sailed with Southey on the *Resolution.* After explaining that I now worked as an editor and journalist, I asked her about the terrifying voyage. Before we parted, she took the time to congratulate me on finding such an interesting new job. I said I had gotten lucky, and she replied offhandedly—not appreciating the relevance of her remark—"I think people make their own luck." On her ship, at least, people certainly do. *—David Schneider*

FIELD NOTES

Plug and Play

Imagine the frustration. A group of high-energy physicists have painstakingly built a sophisticated neutrino telescope to help unlock the secrets of the universe. After years of research and development, the necessary electronics have been assembled, and the sensitive detectors are ready to go. But the scientists are unable to try out their marvelous new astrophysical instrument because they cannot figure out how to plug it in.

ROBERT BALLARD *Woods Hole Oceanographic Institution*

Strangely, the University of Hawaii's Deep Underwater Muon and Neutrino Detector (DUMAND) faces just such a problem—and the solution is not a matter of a longer cord. The ambitious project aims to monitor neutrinos by placing sensors under nearly five kilometers of Pacific Ocean. The thick blanket of seawater provides both the means to sense the subtle subatomic particles (when the rare neutrino interacts with water, it gives off a faint flash of light) and a shield from cosmic rays.

Two years ago the physicists succeeded in laying an undersea cable between Hawaii's big island and Kaho'olawe Deep, a carefully chosen site 25 kilometers offshore and 4,760 meters down. At that time, they installed an underwater junction box and a single "string" of detectors to test out the fundamental design. But soon it became clear that the physicists would have to reach the junction box to replace the test string and, later, to install the full array of detectors. What was not clear was how exactly those deep-sea tasks were to be accomplished.

Because the Department of Energy, which has been the main funding source for the experiment, had no expertise in underwater operations, the DUMAND project relied on the U.S. Navy's Submarine Development Group One—a team specializing in finding lost military hardware. John G. Learned, director of DUMAND, explains that "SubDevGrp1" had originally allocated 60 days every year to doing science, and his astrophysical experiment benefited from that policy: "They didn't charge us for it—it was wonderful."

DUMAND took advantage of the navy's submarine *Seacliff* and its tethered robot vehicle. But the navy group, so good at recovering lost objects, has now decided it also needs to recover expenses. Getting the undersea vehicles and support ship from their base in San Diego to Hawaii is pricey. "It costs $100,000 to get [them] out here and back," Learned laments.

To obtain more reliable assistance, Learned approached the National Science Foundation, hoping to use that agency's remotely operated undersea vehicle *JASON* (*left*). But the NSF—already stretched to satisfy the needs of its own investigators—was reluctant to donate support to a DOE project. "There is no way that sitting at NSF I could say I'll start providing ship time to other agencies," explains Donald F. Heinrichs of the NSF. And according to Learned, the DOE claims never to have promised to pay for ship time.

Having been so thwarted, Learned could justify some bitterness. Instead he seems understanding of what ensues when too many worthy science projects chase too few federal dollars—room for generosity quickly disappears in the resulting struggle between managers and agencies. Learned acknowledges, "I have great sympathy for all those poor devils in Washington." One wonders whether Washington will yet show sympathy for him. *—David Schneider*

A Sign Is Born

Language unfolds among deaf Nicaraguan children

HOLLY MARVIN *Princeton University*

SANTOS, age 9, communicates with a sign language only slightly older than he is.

Linguists have long fantasized about experiments that might demonstrate just how deeply ingrained the human capacity for language is. They have wondered, for instance, what would happen if one could isolate a group of children from any linguistic input from adults: Would those children form their own language and, if so, how rapidly? A remarkable experiment of this kind has occurred in the Central American nation of Nicaragua, where more than 500 deaf children have created a sign language over the past 16 years.

Researchers have never previously had an opportunity to observe a language—signed or spoken—as it was emerging, says Judy Kegl, a linguist at Rutgers University who began studying the Nicaraguan children in 1985 and has directed the research project ever since. "At a time when the death of languages is being reported at a phenomenal rate," Kegl wrote recently in *Signpost,* a journal of sign-language research, "it is exciting to have been present at a birth."

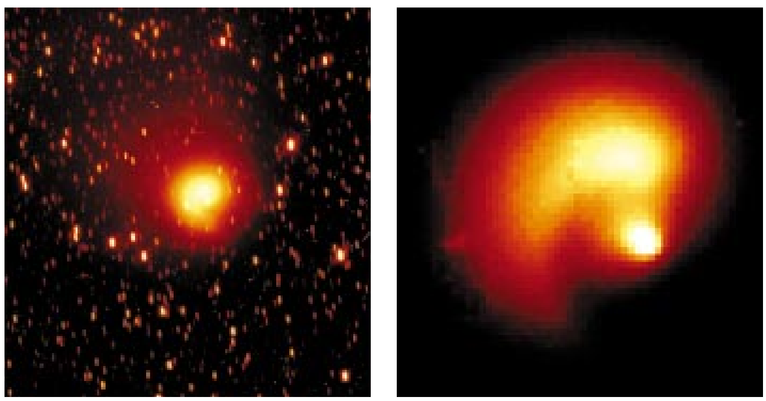
The date of conception was 1979, when the newly victorious Sandinista party instituted an education program that extended to deaf children, who had been neglected by the educational system. By far the largest program for deaf children, and the one studied most intensively by Kegl and her fellow linguists, was established in Managua, Nicaragua's capital.

Because congenital forms of deafness are rare in Nicaragua, most of the children had had little or no contact with other deaf persons. They communicated with their hearing families and neighbors through "home signs," which usually consisted of a few dozen gestures for common objects or functions; these signs were often similar to gestures accompanying spoken language.

When they began attending the school in Managua in the early 1980s, the children were put in classes supervised by hearing teachers who knew no sign language. The children learned writing and other skills through imitation. On their own initiative, however, they quickly constructed a "pidgin" sign language, which came to be called the Lenguaje de Signos Nicaragüense, or LSN—a rela-

Great Expectations

Hurtling sunward at 33,800 miles (54,000 kilometers) per hour, Comet Hale-Bopp is sputtering gas and dribbling debris into a pinwheel-shaped coma more voluminous than the sun. The unusual behavior, and speculation that it portends a spectacle to come, has excited amateur astronomers. "This could be the comet of the century," proposes Robert Burnham, editor of *Astronomy*. A recent issue of that magazine promised that by late March 1997, Hale-Bopp will blaze with the brilliance of Jupiter, extending a grayish-green tail over a swath of sky seemingly as wide as your outstretched palm.



HUBBLE SPACE TELESCOPE

JETS OF DEBRIS pinwheeling around the slowly rotating nucleus* (lower bright spot in right image) *of Comet Hale-Bopp may make the object the brightest in decades—or might burn it out. (A video clip of the jet formation can be downloaded from* Scientific American *on America Online.)

Perhaps. It is equally likely that Hale-Bopp will fizzle into a barely visible fuzzball. As it approaches the apex of its 1,000-year voyage from deep space, the comet is glowing exceptionally brightly. Comet Austin began similarly in 1989 but ended up several magnitudes fainter than expected, notes Daniel W. E. Green of the Harvard-Smithsonian Center for Astrophysics. Whether Hale-Bopp develops a prominent dust tail or a much darker (but more common) gas tail also remains to be seen.

The comet was discovered by two independent observers within minutes of each other this past July. Alan Hale, a professional astronomer in New Mexico, spotted the object during a routine comet scan. Thomas Bopp, a shift supervisor for a construction materials company in Phoenix, noticed the slowly moving blob while peering through a friend's home-built telescope at a "star party." Now all the high-powered eyes of the earth's telescopes are turned on the two men's namesake, trying to decide whether Hale-Bopp is as giant a comet as it appears or is simply burning out early. *—W. Wayt Gibbs* tively crude, variable communication system, Kegl remarks.

But as younger children entered the schools, they rapidly molded LSN into what Kegl calls a truly "rich" language with a complex and consistent grammar, now called the Idioma de Signos Nicaragüense (ISN). Users of ISN have techniques for indicating whether nouns are subjects or objects, for example, and whether the subject of a verb is the speaker or some other person or object.

The experiment provides powerful corroboration of a thesis first put forth in the 1950s by the linguist Noam Chomsky of the Massachusetts Institute of Technology. Language is an innate human trait, Chomsky argues, that manifests itself in spite of what seems to be insufficient input or "poverty of stimulus." "These kids have been exposed to an insufficient model of language," remarks Ann Senghas, a cognitive scientist at the University of Rochester's Sign Language Research School who first visited the school in Managua five years ago, "and yet they have created something highly developed."

Even Chomsky has acknowledged that for language to flourish, the exposure of children to linguistic stimuli must exceed some minimal threshold—particularly during the peak learning years before the age of five. The Nicaraguan experiment bore out this assumption. The oldest students, those who are now in their early thirties, entered the schools in their late teens, before a language had fully emerged, and never achieved the fluency of those who followed them. Children who entered the schools at an early age, after their predecessors had started shaping ISN, have become by far the most fluent signers, Senghas says.

In recent years, some of these young adepts from Managua have begun teaching ISN to students at schools for the deaf elsewhere in Nicaragua. Deaf Nicaraguans of all ages have also begun using their brand-new communication skills to lobby for more resources from the Nicaraguan government and to make contact with other deaf communities around the world, Kegl notes.

Kegl and Senghas and their colleagues hope to show precisely how the relatively primitive home signs of individual students evolved into LSN and, later, the more sophisticated ISN. Time, and the human desire to communicate, is working against the researchers. Older students who still employ LSN are abandoning it as their younger compatriots teach them the more versatile signs of ISN. "That's a call to us to document quickly what the older signers are doing," Senghas adds, before the protolanguage vanishes. —*John Horgan*

Crime and Punishment

Meeting on genes and behavior gets only slightly violent

Perhaps the most surprising accomplishment of the University of Maryland's recent conference on research in genetics and criminal behavior was that discussion remained largely civil. Violence did flare briefly when one participant slugged another, but left-leaning historians and behavioral geneticists who would never usually be in the same conference hall, let alone on the same panel, were able to agree on a few symbolic points. "As a dialogue it was a smashing success, but it also revealed how intractable the differences are," sighs David Wasserman, the legal scholar who organized the three-day event.

The conference, initially scheduled for 1992, had been postponed after African-American groups protested, saying it countenanced racism. When it took place this September, the participation by critics of studies linking genes and crime had been expanded. Opponents of such research—and some of its practitioners—fear that politicians might exploit genetic findings to develop involuntary screening programs that would stigmatize and trample the civil rights of those identified as prone to crime. And while the geneticists emphasized their commitment to develop only voluntary treatments, historians pointed out that many of the abominable excesses of eugenics have been carried out in the name of public health.

Nevertheless, everyone agreed that both genes and a person's environment—not one or the other—shape body and mind. So studies suggesting

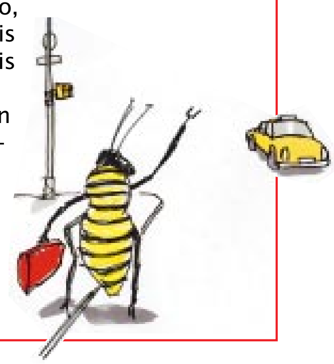
ANTI GRAVITY

Home, Sweet Home

Just the fact that bees try to fly with such unusual aerodynamics suggests that they jump to conclusions. Now a study in the *Canadian Journal of Zoology* reveals that at least one aspect of bee behavior seems to be controlled by an incredibly simple mechanism, reinforcing the idea that bees do indeed rush to judgment.

The researchers discovered that if bees fly to their food, they assume they are away from the hive. If they walk to it, they assume they are at home. The mode of locomotion is such a strong indicator to the bees that travel distance appears not to be a factor in the decision. The University of Ottawa group, led by Catherine M.S. Plowright, points out that captive bees were already known to finish the food in feeders hanging in flight cages much faster than food placed in tubes adjacent to their combs. As an adaptive behavior, the leisurely attitude about closer resources probably keeps bees from wasting time and effort moving honey from one part of the comb to another.

The researchers had thus thought that the distance bees traveled would inform their decision to gather more food. The bees, however, turned out to be just as nonchalant when forced to walk more than a meter—a decent hike for a bee—as when the food was right next door. That casual attitude went out the window, as did the bees, when they had to fly: they lingered four times longer at feeder tubes flown to rather than walked to, even when the distances were identical. "If a food source is walked to, it is treated as being within the hive (consumption is low)," the Canadians concluded. "If it is flown to, it is treated as being in the field (consumption is high)."

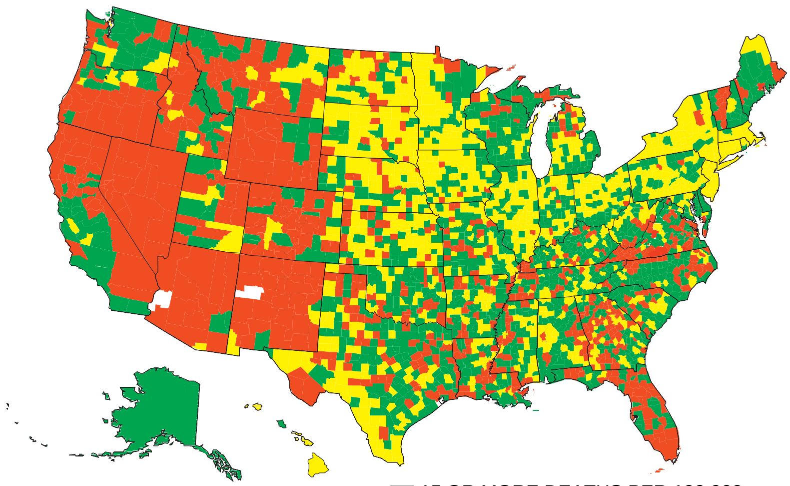


Admittedly, further studies are needed to nail down whether the bees' cue is strictly behavioral or whether the energy requirements of flight overwhelm those of strolling. In the meantime, the researchers point out that greenhouse crop growers should consider coaxing their bees to walk—those long, post-flight yellow-collar lunches could be at the expense of pushing pollen around. —*Steve Mirsky*

MICHAEL CRAWFORD

heritability for violent tendencies in male whites in Denmark provide no reason to think genes explain why rates of criminality might differ among races or groups in another country. Such data also offer no support for the notion that attempts to reduce crime by improving social environments are doomed to failure. Indeed, the rapid increase in rates of homicide in the U.S. during the 1960s and the 1970s amounts to sad proof of the importance of environmental effects: the change was too rapid for any conceivable genetic explanation.

Suicide



SOURCE: National Center for Health Statistics, 1979–1992

Two epidemics of suicide have been documented in the U.S. during this century. The first occurred between 1902 and 1917, which may reflect high rates among recent immigrants, and the second came about in the 1930s, which was probably a result of high unemployment during the Great Depression. Over the past 15 years or so, the rates have been remarkably steady, with about 30,000 Americans killing themselves every year. Men are four times more likely than women to take their own lives, possibly because alcoholism, a known risk factor for suicide, is more widespread among men.

Suicide increases with age. Compared with the rate among teenagers, that among those 75 years and older is four times greater—reflecting the stress of poor health and diminished prospects. The rate among whites is twice that of blacks, which may stem in part from less participation in religion. Compared with other countries, the U.S. is in the middle range, with a rate of about 11 suicides per 100,000 people in recent years.

Lack of family and community support is one of several factors that determine whether a distressed person actually commits suicide. It is not surprising, therefore, that the proportion of divorced people follows, in rough fashion, the regional pattern depicted by the map, which shows age-adjusted suicide rates for white men and women. (The geographical pattern for black people is somewhat similar, except that rates are comparatively lower in the South.) The patterns of interstate migration—an indicator of limited family and community support—also basically reflect the incidence of suicide. Areas with high suicide rates tend to be areas of low church membership. The regional pattern of alcoholism, as measured by deaths from alcohol-related disease, also roughly parallels the pattern of suicide. Three other measures—unemployment, foreign birth and availability of guns (as measured by gun murders during the same period)—do not correlate well with the pattern of suicide.

Almost two thirds of men kill themselves with guns, as compared with 40 percent of women. Poisoning, usually with tranquilizers or some other drug, is used by a quarter of all women and by fewer than 10 percent of men. Inhaling carbon monoxide and hanging are also common among women.

Among whites the lowest rates are in New Jersey, which had an annual average of only seven suicides per 100,000 between 1979 and 1992. The state with the highest rates is Nevada, at 24. *—Rodger Doyle*

Most participants also agreed that no genetic test currently exists that can predict criminality in a form useful for therapy. Given the crucial role of the environment in emotional development and the socially constructed nature of criminality, prospects for finding genes that reliably predict criminal behavior seemed remote to most. Franklin E. Zimring of the University of California at Berkeley elicited nods of approval when he said that "American crime is too normal and its genesis too socially determined for it ever to become a big part of the genetics business."

Yet despite the common ground, conflicts persist. Statistical links between violence and genes will likely be found, argued David Goldman, a neurogeneticist at the National Institute on Alcohol Abuse and Alcoholism. Research into illnesses such as manic-depression and alcoholism means that "we are going to make discoveries fortuitously," Goldman maintains. "There will not be a gene for violence or crime, but alleles that are found will influence them." Goldman listed several genetic factors that he says are incontrovertibly linked to violent behavior. The gene that causes Lesch-Nyhan syndrome, which often involves self-mutilation, is one. Another is a variant gene for the thyroid hormone receptor, which can lead to attention-deficit hyperactivity disorder.

Although numerous claims of links between genetic markers and manic-depression and alcoholism have been retracted in recent years, Goldman predicted that advances in technology will clarify how specific genes can influence behavior. "I think we can rationally use, and not misuse, this information," Goldman says.

Goldman's stance is unlikely to mollify those who fear the worst. "Any investigation into the effects of genes on social behavior is invalid," declared William Sachs, a physician who participated in the conference but allied himself with demonstrators who briefly disrupted proceedings. Others see genetic research as an excuse for society to avoid caring for its most disadvantaged members. Several participants signed a declaration that stated, in part, "The emphasis on a genetic basis for crime scapegoats those who are most hard-hit by current economic conditions."

Several geneticists expressed themselves as anxious as anyone to see an improvement in the lot of the worst-off. But society has different priorities, as Diana Fishbein, a Department of Justice official, noted. The fastest-growing budget item in the fight against crime is not education or drug treatment, but prisons. *—Tim Beardsley*

You May Already Be a Wiener

The Ig Nobel Prizes surprise again

On October 6 in greater Boston, two perennial tragedies played themselves out. At Fenway Park, the Red Sox lost to Cleveland, making it 77 years in a row without a World Championship. At Harvard University, the fifth First Annual Ig Nobel Prizes were announced.

The Igs, as they are fondly called by those who do not win them, are awarded to "individuals whose achievements cannot or should not be reproduced," according to the sponsors, among them the *Annals of Improbable Research.* Some 500 people who couldn't find a date on a Friday night watched the ceremony at Harvard's Lowell Lecture Hall, joined by five actual, honest-to-goodness Nobel laureates, who awarded the Igs: Sheldon Glashow (physics, 1979), Dudley Herschbach (chemistry, 1986), Joseph Murray (physiology or medicine, 1990), Richard Roberts (physiology or medicine, 1993) and William Lipscomb (chemistry, 1976). Lipscomb doubled as a member of the orchestra, revealing considerable ability as a clarinetist. "I can get a relief from the way my brain always works on science," he said of his playing—a description that may also explain his annual presence at the Igs.


STANLEY ROWIN

IG NOBEL REVELERS include some real laureates.

This year's theme was DNA, or "deoxyribowhatever," as a slide informed the audience. Twelve-year-old Kate Eppers, allegedly the spokesperson for Kids for DNA, delivered a position statement. "My favorite singer is Mariah Carey," she explained. "She's really, really beautiful and a really good singer. If it weren't for DNA, she'd be a fish or something. So that's why I think DNA is great."

The first Ig of the evening, the Nutrition prize, went to John Martinez of J. Martinez & Company for the creation of Luak Coffee—the most expensive in the world—made from beans ingested and excreted by the luak, a bobcatlike native of Indonesia. Martinez accepted with a poem, the last stanza of which read, "Luak, luak, after you've gorged/ A new taste sensation though has been forged/We're all gathered here, this is the scoop/We're drinking coffee made from your poop." The Nobelists sampled the brew, which Herschbach promptly spit into a handy ice bucket.

The Medicine Ig went to the researchers who published "The Effects of Unilateral Forced Nostril Breathing on Cognition" in the *International Journal of Neuroscience.* This decision forced the awarding committee to fall back on the Literature prize for the authors of an article in the journal *Surgery* entitled "Rectal Foreign Bodies: Case Reports and a Comprehensive Review of the World's Literature." The items physicians documented removing from various patients included a magazine, the identity of which this reporter was too apprehensive to attempt to discover.

A Japanese research team won the Psychology Ig for turning pigeons into art students. Their paper, "Pigeons' Discrimination of Paintings by Monet and Picasso," appeared in the *Journal of the Experimental Analysis of Behavior.* No word yet on whether the birds can distinguish between Monet and Manet.

Along with the awarding of Igs, the ceremony featured the Heisenberg Certainty Lectures, named for the Heisenberg uncertainty principle, which describes limitations of knowledge about position and velocity of elementary particles. Because quantum mechanics on the macroscopic level collapses to auto mechanics, the hosts of National Public Radio's popular "Car Talk," Tom and Ray Magliozzi, also known as Click and Clack, gave a Heisenberg: "Is it possible for two people who don't know what they're talking about to know less than one person who doesn't?"

Nobelist Roberts apparently regarded that question as a challenge. "I have an amazing discovery about certain DNA, cDNA, which is made by copying RNA," he said in his allotted half-minute. "Now, RNA contains four bases: A, C, G and U. If C stands for certain, then U must be uncertain. Since base pairing says that C is opposite G, then G must be uncertain, too. Thus, in RNA, both G and U are uncertain. With all this uncertainty about RNA, no wonder DNA decided to become the genetic material."

Last year's Entomology winner, Robert Lopez, who proved that cats' ear mites could attack human ears by experimenting on himself, delivered the keynote address: "Dare to Be Bold." Lopez tried to quell fears about American health care. "Don't worry about germs and bugs," he said. "If your time ain't come, not even a doctor can kill you."

The final Ig, for Chemistry, went to designer Bijan Pakzad for DNA Cologne and DNA Perfume, neither of which contains any DNA and both of which come in triple-helix-shaped bottles. James Watson commented on tape, saying that Francis Crick, codiscoverer of the structure of DNA, always said that an idea was good if it smelled right. "The double helix smelt right," Watson noted. "I have to ask now, Would the double helix have received a better reception if on the manuscript we sent off we had sprayed DNA Perfume? I don't think so. My feeling is, if you want to succeed in science, don't smell." *—Steve Mirsky*

And Those Other Ig Winners Are…

ECONOMICS Awarded jointly to Nick Leeson and his superiors at Barings Bank and to Robert Citron of Orange County, California, for using the calculus of derivatives to prove that every financial institution has its limits.

PEACE The Taiwan National Parliament, for demonstrating that politicians gain more by punching, kicking and gouging one another than by waging war against other nations.

PUBLIC HEALTH Martha Kold Bakkevig of Sintef Unimed in Trondheim, Norway, and Ruth Nielson of the Technical University of Denmark, for their study "Impact of Wet Underwear on Thermoregulatory Responses and Thermal Comfort in the Cold," published in *Ergonomics.*

PHYSICS D.M.R. Georget, R. Parker and A. C. Smith of the Institute of Food Research in Norwich, England, for their report "A Study of the Effects of Water Content on the Compaction Behaviour of Breakfast Cereal Flakes," published in *Powder Technology.* *—Mervin Stykes*

The Struggle Within

Conflict between fetus and mother may trouble pregnancy

Leave it to an evolutionary biologist to spoil one of the few symbols of harmony left in this sordid world: the pregnant woman. Far from exemplifying symbiosis, cooperation and other virtues, a pregnancy entails the same conflicts and compromises that characterize the rest of human affairs.

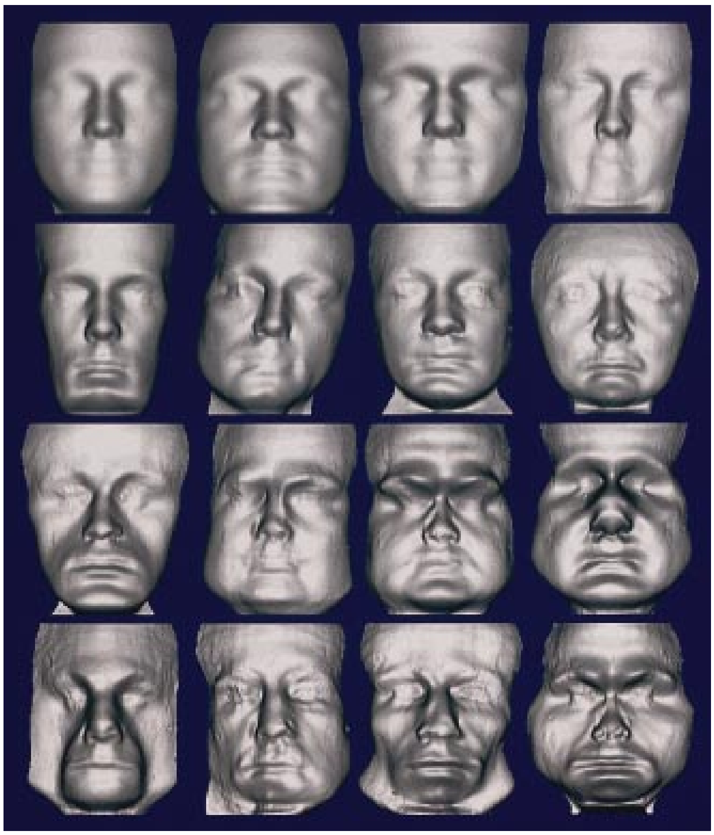
That is the view set forth over the past three years in the *Quarterly Review of Biology* and elsewhere by David Haig of Harvard University. Haig compares the relationship between fetus and mother to that between baseball players and team owners; although their interactions are generally cooperative, each side may occasionally pursue its own interests so aggressively that both are damaged. Problems in pregnancy, Haig says, are "the equivalent of a protracted baseball strike."

Haig's theory, which he concedes needs to be supported by empirical tests, builds on a concept advanced in 1974 by Robert L. Trivers of Rutgers University. Because parents and children share only half of one another's genes, Trivers argued, their genetic interests are at least partially divergent. Each child thus strives to monopolize the parents' "resources"—primarily food and affection—at the expense of his or her siblings and even of the parents.

Haig believes that what Trivers called parent-offspring rivalry may begin at conception. The fetus's "goal" is to be born as healthy as possible, even if its pursuit of that goal diminishes the fitness of the mother or of other siblings, Haig explains. He points out that human pregnancy evolved well before the modern era—in which food is abundant and hospitals can save even extremely lightweight infants. For a baby born to a tribe of hunter-gatherers, Haig contends, a birth weight slightly higher than average might have conferred a considerable advantage.

Natural selection may have designed the fetus and its enveloping placenta to extract as many nutrients as possible from the mother—within certain limits.

About Face



JOSEPH J. ATICK *Rockefeller University*

Accurately re-creating a three-dimensional face from the subtle shading in a photograph has long challenged computer scientists. Their algorithms, it now seems, were too general—aspiring to describe the moon's surface as well, or rather as poorly, as the human head. But by recognizing the fact that head shapes are astonishingly regular, Joseph J. Atick, Paul A. Griffin and A. Norman Redlich of the Rockefeller University have found a quick means of reproducing the unique contours of a person's face from a snapshot.

The discovery may revolutionize the treatment of burn victims. Clear plastic masks, fitted over a patient's face to control the formation of scar tissue, end up determining his or her appearance. Currently the masks are made by taking a painful plaster cast of the burnt face. The Rockefeller technique will instead allow the masks to be constructed from a photograph taken prior to the burn, by generating the three-dimensional face. Scientists at the Computerized Anthropometric Research and Design (CARD) Laboratory at the Wright-Patterson Air Force Base are working to develop such masks.

The insight that led to this breakthrough may be even more informative. "Any human face is a combination of a few dozen primary shapes," Atick maintains. The researchers analyzed 347 three-dimensional scans of heads of air force pilots—mostly white men—taken at the CARD lab. From 200 of these, they derived an average, adult white male head shape—dubbed the meanhead (*top row, far left*)—and a set of 200 standardized variations from that shape, the eigenheads (15 of which are shown in consecutive rows). The latter are so called because they are eigenfunctions, solutions to a set of linear equations that offer the most economical way to store information. The eigenheads thus vastly simplify the derivation of a full face from the shading in a picture, a problem that would otherwise involve an infinite number of variables. Each of the remaining 147 heads in the database was reproduced to within 1 percent by combining the meanhead with no more than 40 eigenheads.

The eigenheads may be more than a mathematical aid. The inferior temporal cortex has "face cells," neurons that fire selectively when a human visage is presented. Why certain cells respond to a given face is not known. But brains have a penchant for eigenfunctions: color, for example, is analyzed via the blends of red, green and blue that form eigencolors. Our brains may also have figured out that head shapes are best coded as eigenheads. "Each cell might fire in response to a particular eigenhead," Atick suggests—giving humans their incredible capacity to recognize individual faces. —*Madhusree Mukerjee*

PENNY COLEMAN *Impact Visuals*

PREGNANCY may entail disorders, such as diabetes, stemming from tension between fetal and maternal genes.

The fetus's strategy will obviously backfire if it endangers the mother's health or if it becomes too large to pass through the birth canal. Before those limits are reached, Haig maintains, the fetus may garner enough nutrients to maximize its prospects for survival while diminishing the mother's ability to reproduce again or to nurture children already in her care.

The fetus manipulates the mother's physiology in several ways, Haig says. For instance, the placenta releases hormones, such as placental lactogen, that boost the mother's blood glucose levels after she eats. In response, the mother can produce more insulin, which lowers sugar levels. Haig suspects that gestational diabetes, which occurs in roughly 3 percent of all pregnancies, may stem from the mother's inability to counteract her fetus's hormone production. (Most obstetricians blame the disorder on overeating or genetic factors without pointing to an underlying cause.)

Haig offers a similar explanation for the rise in blood pressure observed in most women during pregnancy. The fetus, Haig speculates, may secrete substances into the mother's blood in order to increase the flow of blood and nutrients through the placenta. As a consequence, about one in 10 women acquires hypertension; in rare cases, the pregnancy results in preeclampsia, a disorder that can lead to stroke, heart attack and death. Haig adds that despite the risks of hypertension to both mother and child, several investigations—notably one done in England in 1980 involving 9,182 women—have found a correlation between hypertension and low infant mortality rates. In other words, the fetal strategy is paying off.

This hypothetical drama is further complicated by the role of the father, whose genetic interests, again, diverge from those of the mother. Conflict between parental genes, Haig suggests, may have contributed to the emergence of the puzzling phenomenon of genetic imprinting. Geneticists once thought that it made no difference whether genes were transmitted to a child from the mother or the father. But researchers have found that genes in sperm cells or maternal eggs are occasionally altered, or imprinted, before they are passed on in such a way that their expression in the fetus is affected.

A form of genetic imprinting observed in mice, Haig says, reveals a possible link between imprinting and conflict between parental interests. Mice often possess a gene that, when activated, makes embryos grow faster by producing copious amounts of insulinlike growth factor II (IGF II). Mice in which the gene for IGF II has been expressed are 40 percent larger at birth than those in which it is not expressed. The gene is expressed if it comes from the father, but if it comes from the mother it remains dormant, in which case the pups are born small but healthy.

Yet another gene in mice counteracts the effects of the gene for IGF II. The gene produces a protein that accelerates the degradation of IGF II and thereby slows down the embryo's weight gain. This gene is expressed in a fetus only if it is passed on by the mother. Haig expects research on humans will turn up similar imprinting phenomena.

Perhaps Haig's most intriguing proposal is that the imprinting of paternal genes may be affected by the duration of the relationship between the father and mother. If the relationship is brief, Haig observes, chances are that any other children borne by the woman will bear the genes of another man. The longer the relationship has lasted, the more likely it is that future children borne by the woman will also bear the father's genes. In this case, the father's interests may be best served if a fetus bearing his genes pursues a less aggressive nutrient-hoarding strategy.

If this view is correct, Haig asserts, then hormones released in the male during a long-term relationship may deactivate genes in his sperm that would cause a fetus to pursue intensive nutrient-extraction strategies. As far-fetched as this scenario may sound, Haig says, there is evidence to support it. French researchers recently reported in the *Lancet* that they had found an inverse correlation between the length of a sexual relationship and pregnancy-induced hypertension. Although mainstream obstetricians remain skeptical about Haig's theory, he hopes further research will convince doubters. —*John Horgan*

Puzzling with Martin Gardner

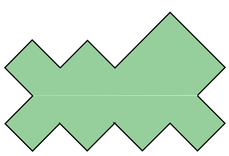
For solutions to problems compiled by the gamester, please turn to the "Profile" on page 41.

1. Reversed Trousers

Each end of a 10-foot length of rope is tied securely to a man's ankles. Without cutting or untying the rope, is it possible to remove his trousers, turn them inside out on the rope and put them back on correctly? Party guests should try to answer this confusing topological question before initiating any empirical tests.

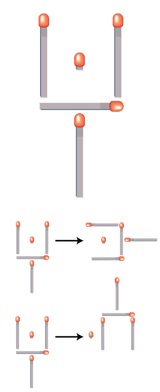
2. Crazy Cut

This one looks much easier than it is. You are to make one cut (or draw one line)—of course, it needn't be straight—that will divide the figure into two identical parts.



3. Out with the Onion

Arrange four paper matches on a table as shown in the top right figure. They represent a martini glass. A match head goes inside to indicate the onion of a Gibson cocktail. The puzzle is to move just *two* matches so that the glass is re-formed, but the onion—which must stay where it is—winds up *outside* the glass. At the finish, the glass may be turned to the left or the right, or even be upside down, but it must be exactly the same shape as before. The middle right figure is not a solution, because the onion is still inside. The bottom figure doesn't work, because *three* matches have been moved.



Buy High, Sell Low

Congress tries to get cash out of a faulty oil reservoir

When the bombs began falling on Iraq early on the morning of January 16, 1991, the country controlled 10 percent of the world's oil production. Oil prices responded by edging downward. After all, there was plenty of excess capacity in nearby Saudi Arabia.

DAN CONNOLLY

PIPELINE at Weeks Island in Louisiana will be used to transfer 70 million barrels of crude oil.

Oh, yes, there was one more thing. The U.S. government announced that it would sell, for the first time ever, oil from its strategic petroleum reserve (SPR). Some 34 million barrels of crude were offered, but there was so little worry by this time that only about a third of it was actually purchased. Five years after that brief and not quite shining moment, the SPR is enmeshed in bureaucratic and political controversy.

Conceived at the height of the oil embargo in 1973, the SPR is a collection of underground reservoirs that store a total of 590 million barrels. The main purpose of the reserve is to keep oil prices from skyrocketing in the event of another crisis. The U.S. consumes about 14 million barrels of crude oil a day, of which about half must be imported.

The current controversy stems from the discovery, in 1992, that water is leaking into one of the SPR's reservoirs, at Weeks Island in Louisiana. Concerned that the water might eventually push oil out into the surrounding marsh, the U.S. Department of Energy began in October to drain the 70 million barrels at Weeks Island and to transfer them by pipeline to two other sites.

To pay for the move, which is expected to cost about $105 million, the DOE said it would sell seven million barrels of the Weeks Island crude at the going rate—about $15 a barrel. Apparently some members of Congress then began to see the SPR in a whole new light. The Senate Budget Committee proposed selling all of the oil, to raise money for the U.S. Treasury. In September the Senate Energy Committee recommended selling 38 million barrels to cover a shortfall that opened up in the DOE budget.

"They all somehow got the notion it's a cash cow, and they can sell it off any time they need money," fumes Congressman W. J. (Billy) Tauzin of Louisiana. Tauzin notes that the oil to be sold at $15 a barrel was purchased by the DOE for much more. It cost roughly $29 a barrel, according to a DOE spokesperson. With the effects of inflation and the expenses of facilities and labor figured in, the total amount spent by the DOE on the oil per barrel shoots up to $56.

Nevertheless, some observers argue that the price of maintaining the oil each year—about $200 million, the DOE reckons—is a loss that should be cut now. "We're using a very expensive weapon to accommodate a relatively minor problem," says William L. Fisher, a geologist and petroleum expert at the University of Texas at Austin.

Of course, the mother of all oil crises could be but a few years away. Robert A. Speir, a senior policy analyst at the DOE, notes that a 1990 U.S. government interagency study found that a major, worldwide oil disruption lasting six months could set the U.S. back $100 billion in escalated oil prices.

Around Weeks Island, meanwhile, environmentalists fear a much different kind of disaster. After the oil is drained from the reservoir there, which is actually a former salt mine, the empty cavern is to be filled with brine. In theory, the brine's high salinity will keep it from dissolving, weakening and cracking the salt-lined walls of the shafts. But if fissures do develop, for example, after the oil has been removed but before the brine is pumped in, they could release the relatively high salinity brine and oil residues into a nearby marshy ecosystem that now supports crab, shrimp and other fisheries. "They [DOE officials] don't seem to be willing to step forward and accept liability for the long-term monitoring of the site," complains Wilma Subra, a chemist and environmental consultant in New Iberia, La.

Richard D. Furiga, DOE deputy assistant secretary in charge of the strategic petroleum reserve, says the department expects to have the brine-filled mine "certified as being stable and environmentally sound. We are complying, and will comply, with state laws governing things like this." *—Glenn Zorpette*

Some Like It Hot

Thriving tunicates may help clear the air of excess CO_2

How quickly will the world warm? The question is as difficult as it is important. To come up with an accurate answer, scientists have to figure out how the myriad intertwined cycles that regulate the earth's life and climate are reacting to increasing amounts of carbon dioxide and other greenhouse gases that humans are releasing into the atmosphere. One major source of uncertainty is a "missing sink": undiscovered dead ends in the carbon cycle that researchers estimate pull roughly two billion tons of carbon (plus or minus about two billion tons) out of circulation every year.

Scientists searching for the sink have focused mainly on forests and other plant life on land that inhale carbon dioxide. But recent reports from marine biologists at Rhodes University in South Africa suggest that gelatinous, tubelike animals called salps may also be responsible for a portion of the missing carbon. If the complex and dynamic ecosystem in which salps live is any indication, predicting how oceanic life will respond to rising temperature and carbon dioxide levels will be a tricky task indeed.

Evgeny A. Pakhomov and Renzo Perissinotto have been observing salps in the waters below the 30th southern parallel, where the Atlantic, Pacific and Indian oceans merge into a region around Antarctica known as the Southern Ocean. During the past 40 years, Perissinotto says, "the Southern Ocean's temperature has increased an average of 2 to 2.5 degrees." Salps, which thrive in warmer waters, have blossomed, replacing krill as the dominant form of zooplankton in the area. "There was a fourfold increase in salp biomass between 1980 and 1990, according to convincing data from Soviet researchers," Perissinotto adds. "We found in our voyage this past [austral] summer that salps have continued to spread much further south than before."

These zooplankton are important for what they eat—and excrete. Salps rise to the surface to graze all day on phytoplankton, tiny plant particles that draw carbon dioxide from the air for their photosynthesis. At night, the salps return to the depths as much as a kilometer below. There they dump the refuse of a day's work: fecal pellets that, Perissinotto describes enthusiastically, "are very rich in carbon and are very compact and fast-sinking. In fact, the pellets can sink at a speed of up to 2.7 kilometers per day!"

"What this means," explains Christopher D. McQuaid, director of the Southern Ocean Group at Rhodes, "is that where there are salps, the efficiency of the transfer of carbon from the atmosphere to the deep sediments—what we call the biological pump—is improved dramatically." Once buried on the seafloor, the carbon is out of the system for millennia. Because salps seem to proliferate as water temperatures rise, the biologists think they may provide a kind of feedback mechanism. "So basically," McQuaid says, "it might work like this: more CO_2, more warming, more salps; more efficient carbon transfer, less CO_2, less warming."


RENZO PERISSINOTTO *Rhodes University*

SALPS like global warming—but may help slow its effects.

Reality may well be more complicated than that simple hypothesis. "Salps are ideal grazers for removing carbon from the atmosphere," says Laurence P. Madin of the Woods Hole Oceanographic Institution. "The question is whether there are enough of them. My experience sampling much of the Atlantic is that there are large areas where salps are present but not very abundant."

Moreover, the Rhodes researchers have observed that too much of a good thing can be lethal to salps. When phytoplankton in the water gets unusually dense—a condition that might be more frequent as CO_2 levels rise—the mucus net that a salp uses to strain plants from the water can clog the animal's digestive tract. "We've seen the salps starve to death literally *because* they are in the midst of plenty," McQuaid says.

The biologists note that it will take much more research to determine with any accuracy how this ecosystem will respond to—or affect—rising CO_2 and water temperatures. Of course, there may be hundreds of other cycles, biological and chemical, that will have greater impact. Perhaps the most pertinent question about global warming is: Can we expect an answer in time to do anything about it? —*W. Wayt Gibbs*

THE ANALYTICAL ECONOMIST

The Confusing Price Index

After more than a decade of single-minded focus on battling inflation, the industrial world's central bankers—particularly in the U.S.—have throttled back average annual price increases from 10 percent a year to less than three. The cost in jobs and economic growth has been painful, and now policymakers are arguing whether achieving zero inflation is really a good idea. Complicating their debates is the oh-so-minor technicality that widely used statistical tools such as the consumer price index (CPI) probably aren't accurate enough to determine whether prices have stopped rising.

The CPI measures how much more (or less) it costs to buy a particular "market basket" of goods today, as compared with previous times. Surveyors for the U.S. Bureau of Labor Statistics (BLS) sample prices every month. If everyone in the country bought the same products (from toilet paper to insurance) in the same proportions, that would be fine. They don't. As a result, the CPI is subtly skewed, explains Stephen G. Cecchetti of Ohio State University.

Although the BLS has managed to compensate for some of these distortions, the adjustments it makes introduce errors. Cecchetti and his collaborator Michael F. Bryan of the Cleveland Federal Reserve Bank found, for example, that inflation "rises" between January and April because adjustments intended to smooth out well-known jumps—such as new car prices in the fall and clothing in the spring—don't always succeed.

The two have developed techniques for correcting this flaw, but a multitude of other, less tractable problems remain. Substitution bias, for instance, arises when people change their purchase habits in response to shifting prices: if beef goes up, buy chicken; if fresh vegetables are too expensive, buy frozen. Economists such as Michael J. Boskin of Stanford University say the CPI overstates inflation because it ignores tactics consumers can use to soften the impact of local price hikes.

Boskin chaired a congressional commission that studied the CPI; he and his colleagues pointed out that the fixed "market basket" approach has trouble accounting for new or improved products. Personal computers, for instance, are so much more powerful today that it might be impossible to buy a machine that performs as slowly as one built 10 years ago. The introduction of high-tech products, such as microwave ovens or VCRs, also muddies inflation measurements: How does one compare overall welfare now to that of an era when such gadgets did not exist?

On the other hand, some other qualitative changes may cause the CPI to understate the amount of money needed to maintain living standards. As Boskin notes, if crime forces people to spend more on burglar alarms, they may consider themselves less well off even if the price of security equipment is falling.

Such arguments may appear increasingly arcane, but the amount of money at stake is substantial. Social Security, taxes and a host of other government payments and levies are all indexed to account for inflation. Every percentage point by which the CPI increases will add $140 billion a year to the deficit by 2005, forecasters say. Cecchetti is one of those who would not be averse to lopping a point off the index before using it to adjust government taxes.

A more principled approach to the issue would involve rethinking the CPI so that it more accurately reflects the quantity that policymakers want to measure. Although many economists (including Cecchetti) have developed alternative inflation measures that seem to do a more unbiased job, Congress is slashing the BLS's budget. The bureau will be hard-pressed to maintain its statistics, much less introduce new ones, laments James Stock of Harvard University. Indeed, if cutbacks continue, estimates of any future inaccuracies in the CPI will be difficult to come by, he says. —*Paul Wallich*

The GOP Strikes Back

More Star Wars to come

In 1983, when Ronald Reagan unveiled his vision of a U.S. protected from Soviet nuclear missiles by high-tech defensive weaponry, filmmaker George Lucas brought to the screen the third episode of the most famous movie series ever—*Star Wars.* Reagan's defense system and Lucas's films were forever linked by the same name, and now both are coming back.

Lucas recently announced plans to resume the film series, but Star Wars has made the most dramatic comeback in Washington, D.C., thanks to Newt Gingrich. The House Speaker's "Contract with America" made the defense of the U.S. from missile attack a central tenet of its legislative platform, and so far the Republican-led Congress has succeeded in putting the taxpayers' money where its mouth is by pouring funds into missile defense budgets. "I think the single biggest turnaround in Clinton administration defense policy is going to be missile defense because of what we've done in Congress," says Representative Curt Weldon of Pennsylvania, a pugnacious Republican who has led his party's fight in the House of Representatives.

Weldon is also leading another fight, to get rid of the Star Wars label. He says it is anachronistic and misleading, the product of a "liberal" media kept alive by Democrats who believe spending billions of dollars on homeland defense is not warranted by any realistic threat to the U.S. But the name sticks. Look up "Star Wars" in the dictionary, and you're not likely to find any mention of the wildly popular film series. *Webster's* defines it as "a weapons research program, begun by the U.S. in 1984, to develop high-tech methods of attacking missiles launched from Earth or space: called Strategic Defense Initiative (SDI)."

SDI has since become the Ballistic Missile Defense Organization (BMDO), renamed by the Clinton administration to reflect a change in priorities spawned by the collapse of the Soviet Union and with it the cold war's nuclear guarantee. When George Bush left the White House in early 1993, SDI seemed relegated to history as the new Pentagon shifted its focus away from Reagan's idea of a system to protect the entire U.S. from intercontinental ballistic-missile (ICBM) attack to building short-range missile defense systems such as the Patriot, famous for its still disputed performance in the Persian Gulf War. Such so-called theater missile defenses, designed to protect troops and civilians in overseas conflicts, commanded the largest share of the BMDO budget, which President Bill Clinton reduced to about $3 billion a year. Although Star Wars never went away—hundreds of millions of dollars were still earmarked for research on national missile defense—Reagan's vision of a space- and ground-based umbrella defense was fading from public consciousness.

U.S. ARMY

MISSILE DEFENSE is being resurrected.

That held until the Republican Party took over Capitol Hill. Many Republicans (and a few Democrats) have joined forces to double the administration's requested funding for national missile defense to $750 million in 1996. They have also added money for the development of more far-flung weapons, such as space-based lasers. (At the time of writing, the fate of the defense spending bills was unclear.)

But by and large, the current Star Wars program has nothing to do with stars—and only a little to do with space. The idea is to station about 20 ground-based interceptor missiles in North Dakota, where Pentagon planners believe the army, with the help of satellite sensors, will be able to shoot down some ICBMs and protect most of the continental U.S. Later, if thorny arms-control questions can be ironed out with Russia and the other successors to the Soviet Union, more sites could be added.

More than 10 years after Reagan first made Star Wars part of the national vocabulary, however, questions linger about the feasibility of intercepting incoming warheads with missiles. "Despite the billions of dollars spent on missile defense for nearly four decades, the main technical barriers to developing a capable system remain," wrote a group of prominent scientists, including two Nobel Prize winners and veterans of the Manhattan Project, to lawmakers this summer.

Patriot, the best-known missile defense system, did not actually hit many of Saddam Hussein's unsophisticated Scud missiles during the Gulf War; some say it intercepted none. No other defense system has reached serious testing phases, and little national missile defense experimentation has been undertaken. Yet many experts contend that if a nation like North Korea wanted to, it could quickly develop or buy the technology and know-how to launch a long-range missile at the U.S. within a few years. And it is a fact that the U.S. currently has no means of disabling or otherwise destroying such missiles—and will not for several years, at least.

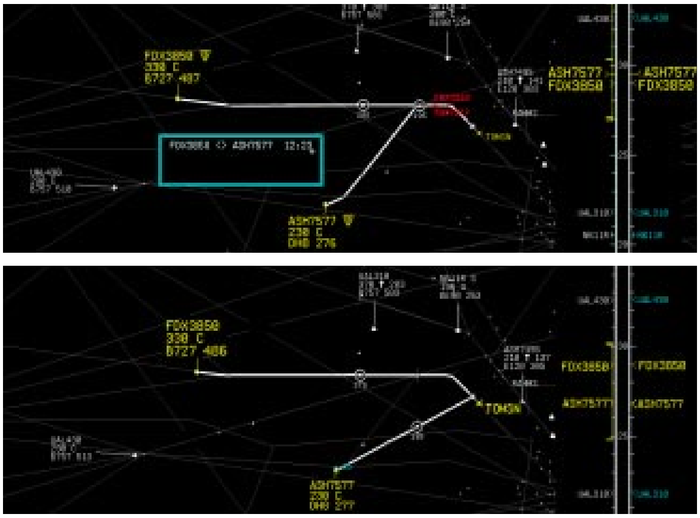
The question is, would North Korea or any other country risk the consequences? Weldon and other supporters of bolstering national defense efforts say the possibility of a missile attack by a terrorist nation or an accidental launch of a former Soviet ICBM is enough to warrant developing a robust system. Kurt Gottfried, professor of physics at Cornell University, believes otherwise. "It's such a crazy idea, that some small nation is going to commit suicide by launching a few ICBMs at the U.S.," he says.

Representative Patricia Schroeder of Colorado, a Democrat who preceded Weldon as chair of the House military research and technology subcommittee, agrees. She says that the GOP push to rejuvenate Star Wars does not reflect an accurate reading of the threat but amounts instead to misplaced hero worship. "This is a tribute to Ronald Reagan," she says with a laugh. "And I think, couldn't we just get him a library? Didn't we already get him a library? It's billions of dollars, for heaven's sake." —*Daniel Dupont*

Free-for-All Flights

The FAA plans a revolution in air-traffic control

This past year the Federal Aviation Administration (FAA) has taken the first bold steps down a road that it hopes will lead to the biggest change in air-traffic control since the introduction of radar. Since January, the agency has been allowing airplanes cruising at high altitudes on long flights to break out of the interstate airways to which jets are normally restricted and to fly whatever path their pilots desire toward their destination. In October controllers were to extend that freedom to all airplanes flying at 29,000 feet and higher—more than 20,000 flights a day.



NASA AMES RESEARCH CENTER

***"CONFLICT PROBE" software running at Denver International Airport can warn controllers of potential collisions. These screens, shot during a live test, show converging Federal Express and Air Shuttle planes* (flagged in yellow at left); *the red X's indicate that they will pass too closely in 12 minutes. A controller redirected the Air Shuttle to increase the airplanes' separation* (shown in bottom screen).**

The change is just one of many that the FAA wants to make as it moves away from active air-traffic control toward a more passive role in a system known as free flight. Faced with increasing congestion—the agency expects domestic air travel to double over the next 12 years—FAA administrator David R. Hinson has decided that the best way to boost airspace capacity is to let aircraft fly the route, altitude and speed they wish. Government "air-traffic managers" would step in for only as long as they are needed to prevent collisions, airport delays and flight over protected areas.

The tricky part, of course, is knowing when to intervene. Juggling thousands of crisscrossing jets is difficult enough when they are strung like beads along a web of preset trajectories. To keep less predictable free-flying airplanes separated, controllers will rely on a complex computer system that integrates several advanced technologies.

Aircraft will pinpoint their current location with the U.S. military's Global Positioning System, a set of satellites whose precise signals allow more accurate navigation than the radio beacons used today. That position information, along with airplanes' speed and intended flight paths, will be beamed over new digital communications links to tracking stations on the ground. These technologies are relatively mature and well understood.

The final piece of the system—a computer program that assembles the data from hundreds of aircraft and warns controllers about potential collisions—will not be so straightforward. Every 10 seconds or so, this so-called conflict probe and resolution software will have to predict where all the aircraft in its sector will fly during the next 10 to 20 minutes, taking into account the latest flight plan, wind and weather data.

Artificial Art

© MARTIN CENTRE, UNIVERSITY OF CAMBRIDGE

For decades, computer graphics has been defined by the pursuit of realism. Almost to a person, researchers have tweaked and tuned 3-D model renderers—the programs that create images out of the mathematical equations describing the shapes in a scene—so as to produce views that are indistinguishable from photographs. As a result, the state of the art in 3-D software, as reflected by *Jurassic Park* animals and shape-shifting Terminators, has little to do with art at all.

That could change if a more expressive rendering program built by Simon Schofield of the University of Cambridge catches on. Schofield's Piranesi system, named after the 18th-century master draughtsman Giovanni Battista Piranesi, turns conventional 3-D models into painterly images in a wide range of styles. Whereas conventional software might render a model of Cambridge's new history building to simulate reality (*left*), Piranesi can generate an architect-style sketch (*center*). With different brush, ink and media settings, the software can produce highly stylized scenes (*right*) with minimal human assistance.

Schofield, himself a painter turned computer programmer, suggests that one day certain kinds of art may be fully automated. He predicts that future generations of the Piranesi system, supplied with semantic details about a scene, might even be able to create truly artistic images that express new levels of meaning. —*W. Wayt Gibbs*

When it detects aircraft headed for trouble, it must suggest course corrections to the controller. And the program will have to exchange data constantly about the airplanes it is watching with similar programs running at nearby airports and in adjacent regions. Developing such software is "a huge systems problem" that represents "a high technical risk," says Herbert Schlickenmaier, a flight systems manager at the National Aeronautics and Space Administration.

Yet a special free-flight task force set up by the FAA (and of which Schlickenmaier is a member) recommended "accelerated implementation of conflict probe" in a draft report released in February. The committee suggested that the as yet unwritten software could allow jets flying between mainland U.S. and Hawaii to follow one another as closely as 15 nautical miles by January 1997. They currently must remain 50 nautical miles apart. The report strongly urged the FAA to initiate free flight "no later than the year 2000." The FAA was to set target dates in November.

FAA officials "are under tremendous pressure from the industry and especially from somewhat libertarian pilots who are pushing in an almost evangelistic way for free flight," observes Heinz Erzberger, a senior scientist at the NASA Ames Research Center. Erzberger led the development of the Descent Adviser, a conflict probe and resolution system that helps airport controllers pick the most direct and fuel-efficient descent routes for incoming aircraft. That system, which is being tested at the Denver and Dallas/Fort Worth airports, has been cited as proof that a national conflict probe system is feasible.

It may in fact hold other lessons. The Descent Adviser and its associated traffic-management systems took nearly a decade to reach the current test stage. Once finalized, the system will probably not be deployed nationwide until 1998, when air-traffic controllers get new workstations. (Those workstations were supposed to be in place six years ago, but after major parts of the software project derailed, some systems were canceled, and others were redesigned last year.)

Moreover, the Descent Adviser uses tube-shaped trajectories to predict the path each airplane will take in the next few minutes. The FAA wants its free-flight software, in contrast, to be based on hockey-puck-shaped "alert zones" that surround aircraft. "The alert-zone concept comes from fighter combat. There has been no analysis or hard-[nosed] review" of whether it works well for conflict detection, Erzberger complains. The mismatch could make it difficult for the programs to communicate.

It is not yet clear how long it could take for the benefits of free flight to pay for the investment required to achieve it. To date, the only published simulation, which compared the actual paths of some 45,000 flights flown one day last year with the most direct routes possible, found that under free flight, each would have shaved an average of just 110 seconds off flying time, but would have waited an extra 15 seconds for a runway to land on. Near misses between free-flying airplanes would have been lower en route but higher near terminals. Benefits might be limited for some time to U.S. domestic flights, given that all other countries and the International Civil Aviation Organization

Nice Legs

The machine tools that shape the gears and engine blocks of a Honda Accord greatly resemble the ones that formed the metal parts on a Model T Ford. A cutting or finishing head moves along a vertical or horizontal guideway to shape the parts. These tooling heads can sometimes be tilted at an angle.

This prosaic world has started to change. A few U.S. and European machine-tool manufacturers have introduced prototypes of a device that has a name derived from entomological, rather than engineering, jargon. These six-legged contraptions, which their makers call hexapods, permit a tool to approach a part flexibly from various angles, as if it were a giant insect proboscis (*left*). The technology, unlike most other machine tools, allows freedom of movement in three linear dimensions as well as in three rotational axes (yaw, pitch and roll). In late September the National Institute of Standards and Technology (NIST) announced the beginnings of a research program to investigate the technology's potential to move a tool faster and more accurately than conventional machine tools.

MARTIN SIMON SABA

In the version of the hexapod purchased by NIST, three pairs of legs, or struts, extend down from the underside of an eight-sided support frame. The cylindrical struts converge to hold a small platform to which the cutting or finishing tool is attached. Computer software directs some struts to shorten and others to lengthen until the tool is positioned properly over a part.

The hexapod is a close cousin of a flight simulator in which aircraft movement is replicated using struts that contract and extend to move an ersatz cockpit. Although a machine tool with this design has been contemplated for decades, it took personal-computing technology to provide an inexpensive means of performing the complex calculations of a tool's position in free space.

Higher accuracy and speed may result from the dynamics of this odd-looking machine. The cantilevered beams and columns on a conventional machine tool are subject to slight bending motions from the forces exerted while cutting small metal chips out of a part. These deflections cause a loss of machining precision. In conhave not begun moving toward a free-flight system.

Where safety is concerned, the FAA remains conservative. “We will not reduce separation standards without a thorough scientific analysis that shows it can be done safely,” promises L. Lane Speck, the FAA’s director of air-traffic-control rules and procedures. “We cannot afford to rush this.” Perhaps the agency should temper its enthusiasm for purchasing new technology with similar caution. *—W. Wayt Gibbs*

Putting Greens

Clean, hydrogen-powered golf carts hit the streets

With legislation calling for the sale of zero-emission vehicles passed by several states, work on electric cars has shifted into high gear. But limited battery capacity remains a stumbling block, and some automotive engineers are pinning their hopes on devices that once helped to

trast, the hexapod’s three pairs of struts apply force to the cutting tool as simple pushing or pulling motions and so minimize displacements that can impair accuracy. In addition, the machines are lightweight and move a cutting head around the contoured surface of a part more rapidly than can a more massive tool.

Hexapods may soon transcend their current status as geeklike attractions at machine-tool trade shows. “There’s still a cultural block—manufacturers tend to be conservative about new technologies,” says Albert Wavering, a NIST robotics researcher. But earlier this year NIST bought a hexapod for $1.2 million from Ingersoll Milling Machine Company, and it has invited industry to test the machine at the agency’s headquarters in Gaithersburg, Md. Pratt & Whitney, a maker of aircraft engines, has begun to experiment with the hexapod at NIST as a means to reduce the time required for machining and finishing jet-engine parts.

If it proves a success on the factory floor, this half machine tool, half robot may find its way further afield. Mick Fitzgerald, a researcher at the University of Texas at Arlington, foresees hexapods on movable platforms. These spindly creatures might traverse ship hulls to perform painting, inspection and drilling operations. Other uses might be as varied as the positions assumed by the hexapod’s six legs. A prospective purchaser might one day ask: Does your hexapod do windows? *—Gary Stix*

JAMES ARONOVSKY

ELECTRIC VEHICLES are already a reality in Palm Desert, Calif., where golf carts are street-legal.

power the Apollo moon missions: fuel cells. These electrical generators cleanly combine hydrogen with oxygen to produce electricity, with only water as a by-product. But will this space-age technology ever truly take off on earth?

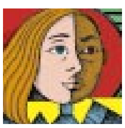
Fuel cells currently appear too expensive for ordinary passenger cars, and without many such vehicles on the road, there is little incentive for filling stations to offer hydrogen at the pumps. Lacking places to tank up, few people would be willing to buy fuel-cell-powered autos. This chicken-and-egg problem might be gently overcome if fuel-cell developers found a commercial niche so that the economies of scale could reduce manufacturing costs. One intriguing opportunity may come, strangely enough, from the nation's golfers.

Electric vehicles have been widely used in airport terminals, on factory floors and, of course, over golf courses. Fuel cells could readily replace the heavy lead-acid battery banks now employed and would provide improved performance at a comparable price. That promise has prompted workers at Humboldt State University's Shatz Energy Research Center in Arcata, Calif., to convert golf carts to fuel-cell power. They plan to introduce the new carts and hydrogen-refueling stations in Palm Desert in southern California's Coachella Valley, just miles from Palm Springs.

Peter Lehman, director of the Shatz Center, explains that Palm Desert seemed a natural spot for launching the hydrogen project because residents were "already enthusiastic about environmental technology." But the chief attraction was the extraordinary concentration of golf carts, more than 20,000 in the valley. The ubiquitous vehicles now ferry golfers around the region's 90 courses—or on jaunts about town.

Initially, this traffic was restricted to golfers who drove their carts along public roads to nearby courses (a practice long allowed by local ordinance), but soon many residents caught on to the advantages of small personal transporters for trips off the fairway. City councilman Richard S. Kelly explains that many people were driving carts around town, "but they were getting tickets." So he spearheaded an initiative with the state legislature that in the past year has made Palm Desert's carts street-legal.

Paul W. Shillcock, economic development director for the town, notes that most of the funding for the hydrogen initiative is coming from the Department of Energy. But he is confident that the program will eventually demonstrate that hydrogen-based transport can offer a commercially feasible alternative to petroleum—one that is environmentally benign. Shillcock boasts in anticipation: "The oil companies are not going to be pleased with us." Neil P. Rossmeissl of the DOE is similarly enthusiastic about this attempt to spin up a local hydrogen economy. Compared with many more costly and less practical proposals he has reviewed, Palm Desert's plan "was a breath of fresh air." —*David Schneider*



PROFILE: MARTIN GARDNER

The Mathematical Gamester

The clerk at the Barnes and Noble bookstore in downtown Manhattan is not all that helpful. Having had limited success with smaller retailers, I am hoping that the computer can tell me which of Martin Gardner's 50 or so books are available in the store's massive inventory. Most of his books, of course, deal with recreational mathematics, the topic for which he is best known. But he has also penned works in literature, philosophy and fiction. I am looking specifically for *The Whys of a Philosophical Scrivener,* Gardner's essays that detail his approach to life. The clerk tells me to try the religion section, under "Christian friction." Is he kidding?

A scowl breaks across Gardner's otherwise amicable face after I relate the story. He is puzzled, too, but for a different reason. The book has nothing to do with that, Gardner insists. He makes it a point to describe himself as philosophical theist—in the tradition, he says, of Plato and Kant, among others. "I decided I couldn't call myself a Christian in any legitimate sense of the word, but I have retained a belief in a personal God," Gardner clarifies. "I admire the teachings of Jesus, but to me it's a little bit dishonest if you don't think Jesus was divine in some special way"—which Gardner does not.

Theology and philosophy weigh heavily in our conversation, something I did not expect from a man who spent 25 years writing *Scientific American*'s "Mathematical Games" column and who, in the process, influenced untold numbers of minds. "I think my whole generation of mathematicians grew up reading Martin Gardner," comments Rudy Rucker, a writer and mathematician at San Jose State University. It is not uncommon to run into people who subscribed solely because of the mathematical gamester, a realization not lost on the magazine's caretakers when he resigned in 1981. "Here is the letter I have been dreading to receive from Martin Gardner," memoed then editor Dennis Flanagan to then publisher Gerard Piel. "I had a lot of books I wanted to write," Gardner explains of his decision. "I just didn't have time to do the column. I miss doing it because I met a lot of famous mathematicians through it."

In his living room in Hendersonville, N.C., near the Great Smoky Mountains at the Tennessee border, he rattles off several of these notables. Roger Penrose of the University of Oxford, now a best-selling author about consciousness and the brain, first became famous after Gardner reported Penrose's finding of tiles that can coat a plane without ever repeating the same pattern. John H. Conway of Princeton University saw his game-of-life computer program, a metaphor for evolution, flourish after appearing in the column. Most surprising to me, though, is Gardner's mention of the Dutch artist M. C. Escher, whose work he helped to publicize in 1961. He points to an original Escher print over my head, between the shelves of his wife's collection of antique metal doorstops. If he had known Escher would become famous, Gardner says, he would

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have bought more. "It's one of the rare pictures with color in it," he remarks. "It's based on Poincaré's model of the hyperbolic plane." Uh, okay.

The 81-year-old Gardner seems more comfortable talking about others than about himself. Perhaps part of the reason is that he has no formal training in mathematics. In discussing his youth, he muses on religion and philosophy, topics to which we keep veering back. "When I grew up in Tulsa, it was called the oil capital of the word," he says. "Now it's known as the home of Oral Roberts. That's how far Tulsa has gone down the hill." He describes his father, a petroleum geologist, as a tolerant fellow who put up with his mother's Methodist devotion and Gardner's own early fanaticism. Influenced by a Sunday school teacher and a Seventh-Day Adventist, the young Gardner became convinced the second coming was near and that 666 was the number of the pope. "I grew up believing that the Bible was a revelation straight from God," he recounts. "It lasted about halfway through my years at the University of Chicago."

University life, however, slowly eroded his fundamentalist beliefs. "Certain authors have been a big influence on me," Gardner says and enumerates them. Besides Plato and Kant, there are G. K. Chesterton, William James, Charles S. Peirce, Miguel de Unamuno, Rudolf Carnap and H. G. Wells. From each, Gardner has culled a bit of wisdom. "From Chesterton I got a sense of mystery in the universe, why anything exists," he expounds. "From Wells I took his tremendous interest in and respect for science." That's why he does not accept the virgin birth of Christ or a blood atonement for the sin of Adam and Eve, as he writes in the afterword of his semiautobiographical novel, *The Flight of Peter Fromm.* "I don't believe God interrupts natural laws or tinkers with the universe," he remarks. From James he derived his notion that belief in God is a matter of faith only. "I don't think there's any way to prove the existence of God logically."

Pondering existence for a living, however, was not his calling. "If you're a professional philosopher, there's no way to make any money except to teach. It has no use anywhere," Gardner offers. Instead he turned to writing, becoming assistant oil editor for the *Tulsa Tribune* and then returning to Chicago to assume a post in the university's press office. In 1941 he began a four-year stint on a destroyer escort (fittingly, the U.S.S. *Pope*). After World War II, Gardner returned to Chicago, selling short stories to *Esquire* and taking more courses in philosophy under the GI bill.

Freelance writing is unstable, and Gardner found himself in New York City in the early 1950s, where he landed a regular job with the children's periodical *Humpty Dumpty's Magazine,* writing features and designing activities. "I did all the cutouts," he beams. But it was his lifelong interest in magic, still his main hobby, that led him to mathematical games. Every Saturday a group of conjurers would gather in a restaurant in lower Manhattan. "There would be 50 magicians or so, all doing magic tricks," Gardner reminisces. One of them intrigued him with a so-called hexaflexagon—a strip of paper folded into a hexagon, which turns inside out when two sides are pinched. Fascinated, Gardner drove to Princeton, where graduate students invented it. (A magician also played a pivotal role in another major step in Gardner's life: he introduced Gardner to his future wife, Charlotte.)

Having sold a piece on logic machines to *Scientific American* a few years prior (which, incidentally, included a cardboard cutout), he approached the magazine with an article on flexagons. "Gerry Piel called me in and asked, 'Is there enough material similar to this to make a regular column?' I said I thought there was, and he said to turn one in," Gardner recalls. It was a bit of a snow job: Gardner did not even own a mathematics book at the time. "I rushed around New York and bought as many books on recreational math as I could," he states. Gardner officially began his new career in the January 1957 issue; the rubric "Mathematical Games" was chosen by the magazine. "By coincidence, they're my initials," Gardner observes. "I always had a private interest in math without any formal training. I just sort of became a self-taught mathematician. If you look at those columns in chronological order, you will see they started out on a much more elementary level than the later columns."

Gardner's timing was perfect. Only a few outlets for recreational mathematicians existed at the time. "A lot of creative mathematicians were making discoveries, but the work was considered too trivial by professional math journals to publish. So I had the pleasure of picking up this stuff." Perhaps more important to the success of the column was his nonmathematical background. "His references were so wonderfully cross-cultural and broad," Rucker states. "He talked about experimental literature, about cranks, about philosophers—relating mathematics to the most exciting things around." He was also able to form a network of associates who passed on ideas. "Martin was very good at giving attribution," says mathemati-

ELLIOTT ERWITT *Magnum*

FIND MARTIN Gardner among his collection of mathematical and magical props.

cian Ronald L. Graham of AT&T Bell Laboratories. "That inspired people to work on problems."

Gardner has a natural penchant for fun and games. In an April Fools' piece, he claimed Einstein's theory of relativity was disproved and that Leonardo da Vinci invented the flush toilet. At the suggestion of a friend, he harshly panned his own *Whys* book in a review written under the pseudonym George Groth. "I heard that people read the review and didn't buy the book on my recommendation," Gardner comments.

Although his home seems to display order and formality, Gardner's playfulness is everywhere. Optical illusions abound, including an inside-out face mask illuminated from below that appears holographic, eerily seeming to track a viewer's motions. He demonstrates several magic tricks with rubber bands, at one point rummaging through a closet to extract a fake, blood-dripping severed arm through which he wiggles his own fingers. This Wonderland feeling is appropriate, for Gardner is an expert on Lewis Carroll. His best-seller is *The Annotated Alice,* in which he shows that Carroll encoded messages, chess moves and caricatures of people he knew. In Los Angeles recently, wealthy electronics store owner John Fry inaugurated a new outlet containing 15-foot statues of the Alice characters—and Gardner was the honored guest.

After nearly 40 years of presenting math, Gardner says the biggest transformation in the field has been the entrance of the computer. "It's changed the character of all mathematics, especially combinatorial math, where problems are impossible to solve by hand. A good example is the four-color map problem, which was finally solved by a computer." The theorem states that at least four hues are needed to paint all planar maps so that no adjacent regions are the same color. Chaos theory, fractals and factoring of prime numbers are a few other examples.

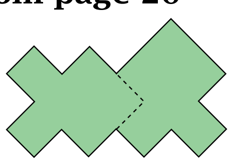
Gardner himself does not own a computer (or, for that matter, a fax or answering machine). He once did—and got hooked playing chess on it. "Then one day I was doing the dishes with my wife, and I looked down and saw the pattern of the chessboard on the surface of the water," he recalls. The retinal retention lasted about a week, during which he gave his computer to one of his two sons. "I'm a scissors-and-rubber-cement man," Gardner says, although he feels he ought to get another computer despite the lasting impression his first one left.

Retirement does not find Gardner at rest. He writes for the *Skeptical Inquirer,* although he is planning to switch to topics that are not outright shams, such as Freud's dream theory and false memories evoked by therapists. And there is time for games. During my visit, an editor called to say that his firm wants to publish Gardner's manuscript on Lewis Carroll's mathematical puzzles. Gardner describes a recent problem he received from Japan, which dealt with an ant crawling on an extended cube. A mathematician phones to inquire whether Gardner heard anything about a rumor of a new result in Penrose tiling. And every afternoon at 4:30, he and Charlotte investigate fluid dynamics by mixing vodka martinis. For Gardner, the game is the life. —*Philip Yam*

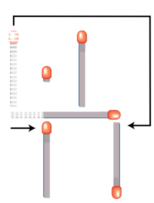
Solutions to Gardner's Puzzles from page 26

1. To reverse a man's trousers while his ankles are joined by a rope, first slide the trousers off onto the rope, then push one leg through the other. The outside leg is reversed twice in the process, leaving the trousers on the rope right-side out but with the legs exchanged and pointing toward the man's feet. Reach into the trousers from the waist and turn both legs inside out. The trousers are now reversed on the rope and in position to be slipped back on the man, zipper in front as originally arranged but with the legs interchanged.

2. The figure is cut into congruent halves like this:



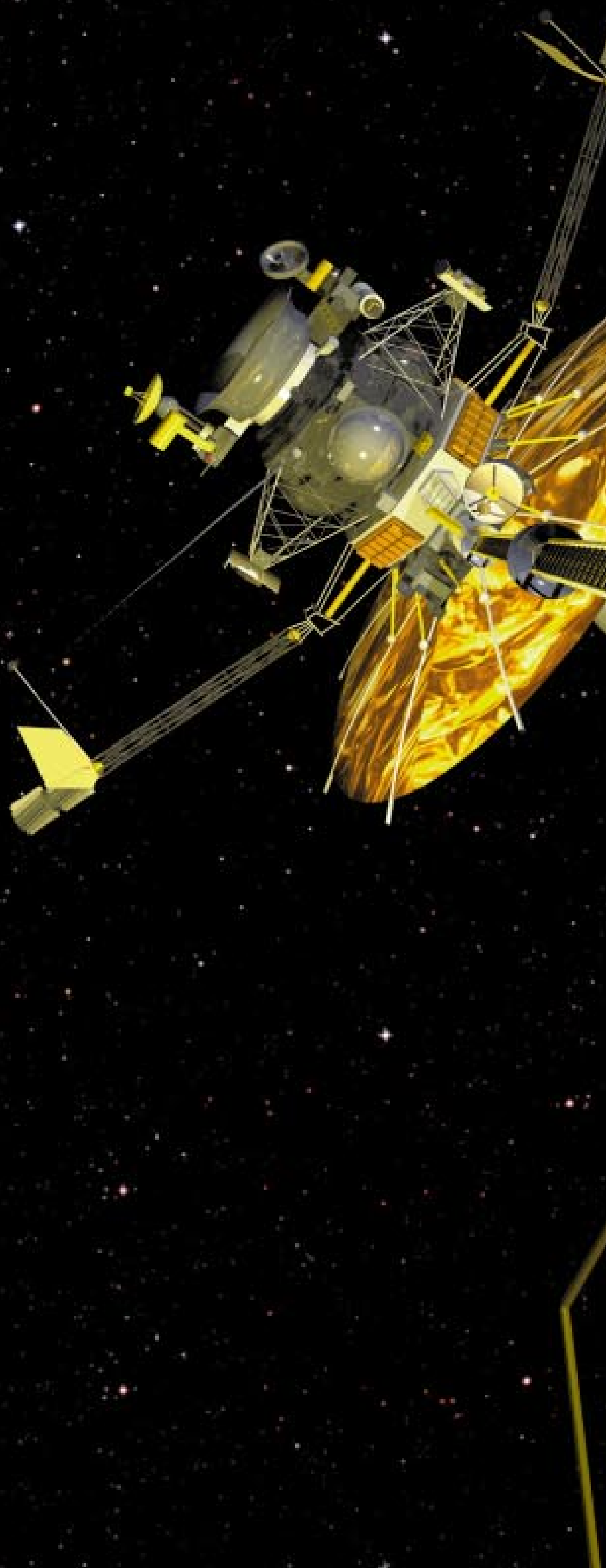
3.



The Galileo Mission

From orbit around Jupiter, the Galileo *spacecraft will take the closest look ever at the planet and its natural satellites*

by Torrence V. Johnson



On December 7, 1995, a new form of shooting star will blaze briefly in Jupiter's sky. It will be not a meteor or comet but a device manufactured on the earth that will slam into the thin gases of the upper Jovian atmosphere at nearly 50 kilometers per second. Within minutes a parachute will unfurl to slow the projectile, and the remains of its heat shield will fall away. For a little more than an hour, the exposed instrument will descend, sending data on composition, temperature, pressure and cloud structure to its parent craft, *Galileo,* passing 200,000 kilometers overhead.

Galileo will store the signals for transmission to scientists waiting on the earth. As the probe's signals fade away, a rocket on *Galileo* will fire for almost an hour, placing the craft in a large, looping orbit around the planet. After visiting two other planets and two asteroids on its six-year journey—and on the way making some unexpected discoveries—the spacecraft will finally be at its intended destination: Jupiter. Three hundred and eighty-five years after Galileo Galilei discovered the Jovian moons, a man-made satellite bearing his name will join their endless circuit.

Project Galileo was born in the mid-1970s, after *Pioneer 10* and *Pioneer 11* had flown by Jupiter and the ambitious Voyager missions to the ends of the solar system had been initiated. It was clear that Jupiter and its peculiar moons—forming a type of miniature solar system—were worth more than a passing glance. In 1976 a team led by James A. Van Allen of the University of Iowa presented to the National Aeronautics and Space Administration a dual mission plan: an entry probe to study Jupiter's atmosphere as well as a sophisticated device that would circle the planet about 12 times over two years, transmitting information about Jupiter, its moons and its mammoth magnetic field [*see box on pages 48 and 49*].

The mission was approved by Congress, and *Galileo* was slated to become, in January 1982, the first planetary spacecraft launched by shuttle. But the shuttle program ran into technical hitches, as did the three-stage solid-fuel rocket needed to send *Galileo* all the way to Jupiter. After several other schemes had been considered and discarded, the propulsion system was replaced by one using a single, powerful rocket fueled by liquid hydrogen, and the launch was reset for May 1986.

Then, in January 1986, soon after *Galileo* was trucked from the Jet Propulsion Laboratory (JPL) in Pasadena, Calif., to the Kennedy Space Center in Cape Canaveral, Fla., the tragic *Challenger* accident occurred, killing seven people on board. All subsequent shuttle launches were put on hold for an indefinite period. Moreover, *Galileo's* liquid-hydrogen rocket was deemed too dangerous to transport in a shuttle's cargo bay and was dropped from consideration. The only propulsion system that *Galileo* was now allowed, a two-stage solid-fuel rocket, would not be energetic enough to get it to Jupiter.

Fortunately, a mission design team at JPL came up with an innova-

DIGITAL COMPOSITION BY SLIM FILMS; PHOTOGRAPH OF IO COURTESY OF JET PROPULSION LABORATORY

GALILEO will approach Io, Jupiter's volcanic moon, on December 7, 1995. The combined action of *Galileo's* thrusters and Io's gravitational pull will place the spacecraft in orbit around Jupiter. Because of a malfunctioning tape recorder, however, *Galileo* may not be able to make observations during this closest encounter with Io.

tive solution. *Galileo* could swing by Venus and the earth, gathering energy from the planets' motions around the sun to supplement its inadequate rocket. It would, in the end, be able to reach Jupiter—and on the way provide even more scientific observations than had been planned.

The Inner Solar System

Galileo and its solid-fuel rocket boosters went into space on October 18, 1989, riding in the cargo bay of *Atlantis.* After deployment from the shuttle, the rockets fired, making the spacecraft fall, paradoxically, toward the center of the solar system. The new VEEGA trajectory (for "Venus Earth Earth gravity assist") would take the spacecraft to Venus and twice past the earth before it finally left for Jupiter. Apart from the planetary encounters, the devious route included two passages through the asteroid belt. They involved close encounters with two asteroids, members of the solar family that had never been seen at close range.

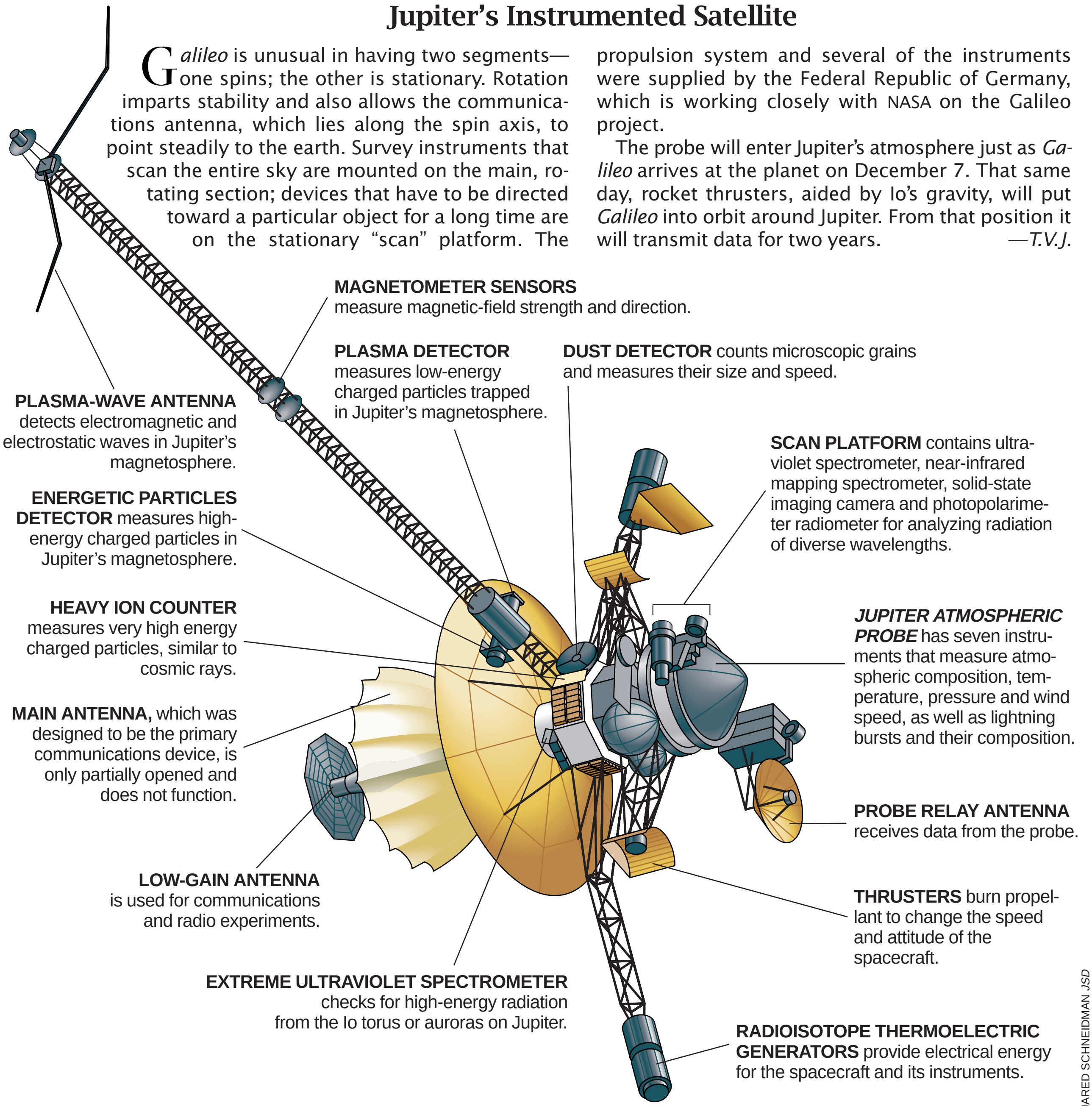
On the way to Venus and, indeed, all through its long cruise, some of *Galileo*'s instruments were kept busy scrutinizing interplanetary space. The magnetometer monitored the interplanetary magnetic field and the solar wind, made of charged particles flowing from the sun over enormous distances. The extreme ultraviolet instrument also proved immediately useful. *Galileo*'s measurements were used to calculate how radiation from the sun varies with the latitude from which it is emitted, allowing researchers to update models of the sun's dynamics.

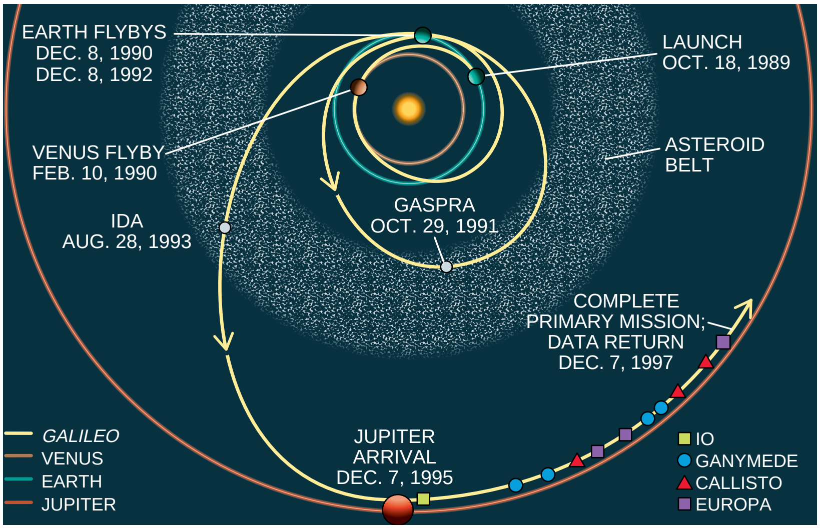
The radio transmitters, which are used for communications, also turned in valuable science. From the opposite side of the sun, *Galileo* sent radio waves to JPL that just grazed the visible solar surface. Turbulent processes on the sun and the ways in which material spurts off into the solar wind were measured

Jupiter's Instrumented Satellite

Galileo is unusual in having two segments—one spins; the other is stationary. Rotation imparts stability and also allows the communications antenna, which lies along the spin axis, to point steadily to the earth. Survey instruments that scan the entire sky are mounted on the main, rotating section; devices that have to be directed toward a particular object for a long time are on the stationary "scan" platform. The propulsion system and several of the instruments were supplied by the Federal Republic of Germany, which is working closely with NASA on the Galileo project.

The probe will enter Jupiter's atmosphere just as *Galileo* arrives at the planet on December 7. That same day, rocket thrusters, aided by Io's gravity, will put *Galileo* into orbit around Jupiter. From that position it will transmit data for two years. —*T.V.J.*





JARED SCHNEIDMAN *JSD*

WINDING ROUTE to Jupiter has taken *Galileo* past Venus, past the earth twice and through the asteroid belt twice. Once in orbit around Jupiter, *Galileo* will have 11 close encounters with the planet's four largest moons.

via their effects on the radio waves.

Galileo had to fly the first leg of its mission with its main, umbrellalike antenna furled and hidden behind a sunshade that protected it from the direct rays of the sun. The configuration made this important device, designed to transmit data at high rates, unusable. The spacecraft also has a small antenna at either end, but these were too weak to send much information over long distances.

As a result, *Galileo*'s tape recorder was programmed to store information about Venus during the few hours of closest approach. The bits were relayed to the earth over one of the two low-gain antennae—the one pointing to the earth—when *Galileo* returned for its first visit in December 1990. The proximity ensured that the signals were received loud and clear despite the low power at which they were transmitted. Infrared images taken by *Galileo* penetrated deep within the atmosphere of Venus and gave the closest view ever of the structure and dynamics of its lower cloud layers.

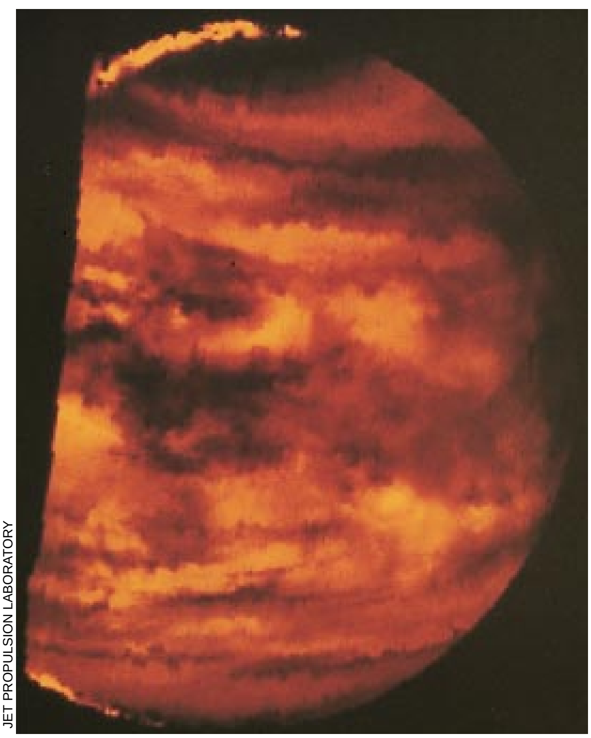
Galileo was also able to observe the earth from the perspective of an interplanetary explorer, producing a stunning movie of our watery planet. The spacecraft examined the outer expanses of the earth's magnetic field and took the first measurements of the moon's far side since the days of the Apollo program. These images revealed ancient volcanic processes in regions not visited by astronauts and beautifully confirmed the existence of an ancient, huge impact basin on the far side, the South Pole–Aitken basin.

A Communications Disaster

Soon after swinging past the earth for the last time, *Galileo* encountered a major technical problem. Now that the spacecraft was far enough from the sun, ground controllers commanded its large antenna to unfurl. The motors ran for less than 10 seconds and stalled. Later analysis showed that several, probably three, of the antenna's ribs were not deployed, leaving the instrument a useless, twisted sack of metal mesh.

Intense efforts over several years have failed to open the antenna. The best engineering judgment is that the ribs are permanently jammed, probably because of the loss of lubricant during the long truck rides the spacecraft took from the Pacific coast to the Atlantic in 1986, back to the Pacific when launch was delayed and again to the Atlantic in 1989.

For a few devastating months, the team thought it had lost much, if not all, of the orbital mission. The probe's data could be returned to the earth with the small antenna that had served since launch for communications. But plans for gathering data during orbit depended heavily on the undeployed antenna, designed to transmit at 134,000 bits per second. A series of brainstorming sessions slowly convinced the planning team that a good deal of the science could still be done with the small antenna.



JET PROPULSION LABORATORY

VENUS'S NIGHTSIDE was imaged in infrared light by *Galileo* during its flyby. The heat radiation originates deep within the atmosphere, allowing the inner layer of clouds to be seen for the first time.

Of immediate concern was the upcoming rendezvous with Gaspra, the first meeting of a spacecraft with an asteroid. Plans for the Gaspra observations were already far along, relying on fast communications through the main antenna, both for maneuvering *Galileo* close to the asteroid and for sending back information.

Working feverishly, engineers figured out how to replace the planned 20 or more pictures needed for navigation with only five. (The camera shutter was left open so that the stars appeared as streaks; one picture therefore served for several.) There was just enough time to receive these critical images, which helped to fix the exact position of *Galileo,* from the low-gain antenna. The international astronomical community pitched in with a campaign of observations of Gaspra's orbit, a vital element in determining where the spacecraft would be with respect to the asteroid.

The gigabit magnetic tape recorder on *Galileo* that had served for the Venus flyby was recruited for storing the Gaspra images. Because *Galileo* was to visit the earth one more time, the recording could be played back over the low-gain antenna while the spacecraft was nearby. This strategy made it possible to retain the most important experiments despite the loss of immediate transmissions from the main antenna.

Meeting Gaspra and Ida

Nevertheless, we reclaimed a few images immediately after the encounter to see what our efforts had netted. The navigation had been extraordinarily precise. The pictures offered the first close-up look at an asteroid, revealing an irregularly shaped rock with many small impact craters but fewer large craters than expected. Many of the particles in the asteroid belt were apparently smaller than had been estimated. And it seemed that Gaspra must have fragmented quite recently, about 300 to 500 million years ago, from a larger body made of rock.

The remaining data were returned when *Galileo* came home for the last time, in late 1992. It showed, intriguingly, that the interplanetary magnetic

Why Jupiter?

The *Voyager* flybys of 1979 convinced astronomers that Jupiter and its moons are far more interesting than they could have imagined. With its planet-size moons in circular, coplanar orbits, the Jovian system looks remarkably like a small solar system.

Jupiter itself is in many ways like a star. It contains 70 percent of the mass of all the planets in our solar system combined and is composed mainly of hydrogen and helium. Gravitational energy released when the planet formed 4.5 billion years ago is still trapped deep inside and seeps out slowly, so that the planet radiates almost twice the amount of energy it receives from the sun.

In addition, Jupiter's atmosphere most likely represents the best sample of the original nebula from which the solar system formed. The nebula contained mainly light elements, especially hydrogen and helium, which rocky planets such as the earth either never had or lost a long time ago. In the sun itself, the gases have been modified by thermonuclear burning. But on the giant planet everything has been preserved, held by the massive gravity. *Galileo*'s probe will reveal the composition of this gas and dust, refining our understanding of how the solar system came to be.

Jupiter has no surface in the usual sense. The hydrogen becomes denser with depth, condensing into a hot liquid at rather shallow levels. Through this hydrogen ocean falls a perpetual rain of helium. Further down, hydrogen behaves like a metal, very likely providing the high electrical conductivity required for generating Jupiter's powerful magnetic field.

Jupiter is also a massive natural laboratory. A global atmospheric model should be applicable not only to the earth but also to other planets; Jupiter, with its high gravity, fast spin and unusual chemistry, provides a testing ground as different as possible from the earth. Many of the entry probe's measurements are designed to provide "ground truth" for calibrating atmospheric models, which will ultimately help in understanding the earth.

Jovian Satellites

Jupiter's 16 satellites are believed to have formed out of a cloud of gas, dust and ice surrounding the planet, much as the planets formed around the sun. The large rocky moons, Io and Europa, are closest to Jupiter—

JUPITER WITH TWO OF ITS SATELLITES, IO (*LEFT*) AND EUROPA (*RIGHT*)

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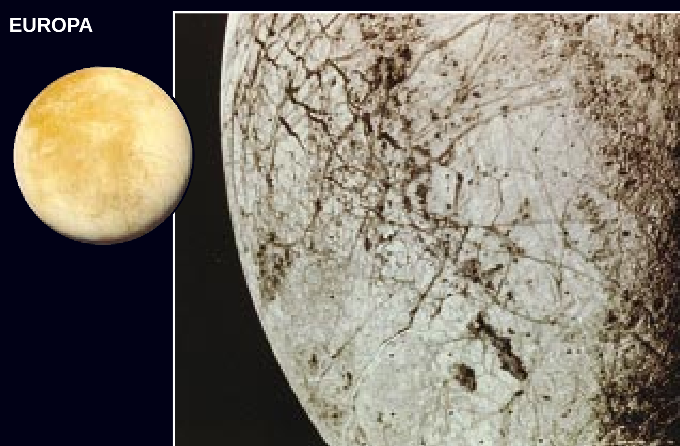
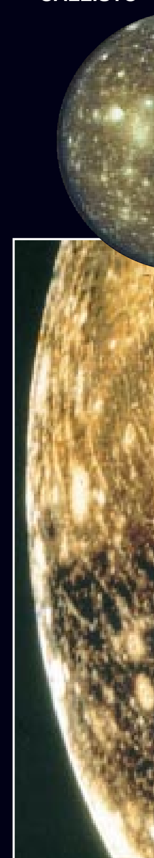
EUROPA



JPL

CALLISTO



GANYMEDE

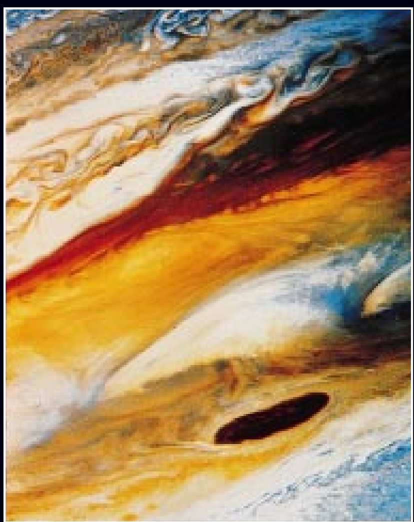
JPL

field had changed direction close to Gaspra, as though encountering a magnetic obstacle. If Gaspra has a magnetic field, it could have affected the solar-wind field in a similar way. Evidently, the magnetic properties of asteroids were far more interesting than had previously been believed.

The second encounter with the earth was an opportunity to conduct vital calibrations. It also provided excellent views of the poorly studied north polar regions of the moon and, as a final "bon voyage" gift, a beautiful movie of the moon and the earth together.

The gravitational boost from the earth sent the craft toward its final destination on December 8, 1992. (Incidentally, it also slowed the earth down by a minuscule fraction; luckily, this amount is tiny compared with the gravitational jostling from other planetary bodies, and we were not required to file a new environmental impact statement!) The

ATMOSPHERIC STREAMS ON JUPITER



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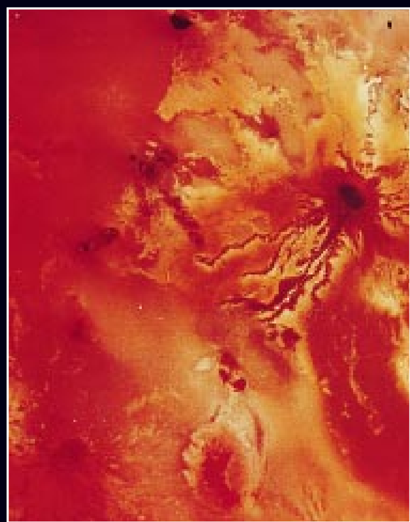
VOLCANIC ERUPTION ON IO



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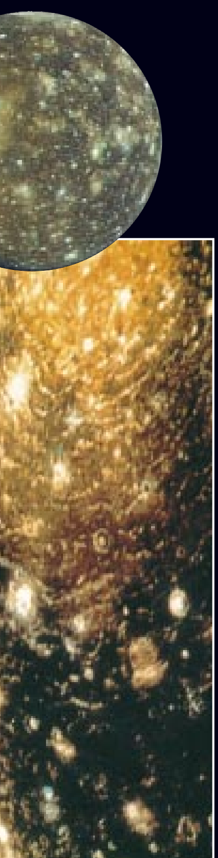
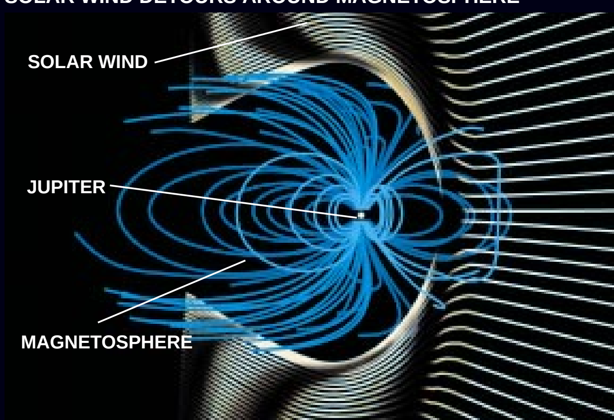


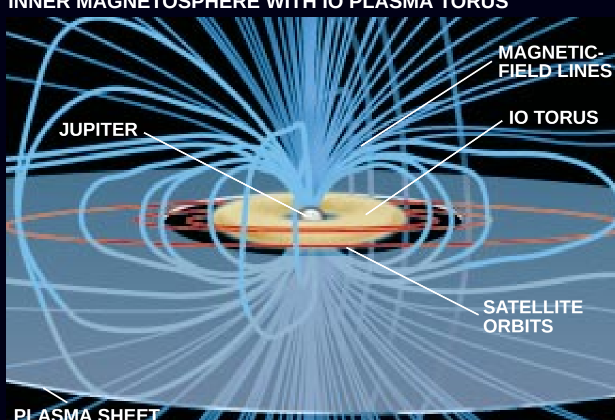
JPL

SOLAR WIND DETOURS AROUND MAGNETOSPHERE



LAURIE GRACE

INNER MAGNETOSPHERE WITH IO PLASMA TORUS



LAURIE GRACE

just as terrestrial planets such as Mercury and Mars are the innermost ones in the solar system. Farther out, Ganymede and Callisto have far more of the lighter elements, such as hydrogen (in the form of ice).

Each of these large satellites is also a fascinating body in its own right, worthy of a visit if it were instead orbiting the sun as a small planet. Io, about the size of the earth's moon, is the most volcanically active body in the solar system, being totally resurfaced by lava every few hundred years. Unlike the earth, whose volcanoes are energized by heat from radioisotopes, Io's are heated by tidal distortions created by Jupiter and its other moons. The volcanic clouds form a patchy atmosphere of sulfur dioxide, part of which escapes from the planet; the remainder freezes onto the surface.

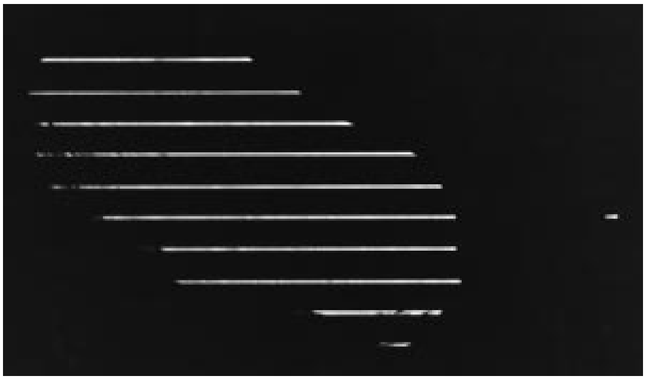
Europa, also the size of the earth's moon, has a strange cracked, icy surface that makes it 10 times as bright in reflected light. Ganymede and Callisto are heavily cratered, aged moons, both about as large as Mercury, containing large amounts of ice. *Galileo*'s 11 close encounters with these four largest satellites will answer many questions, such as how thick Io's crust is, what Callisto's rocks are made of and whether Europa has an ice-covered ocean.

A Strong Magnetism

The area around a planet that is dominated by its magnetic field is called the magnetosphere. Jupiter has the most extensive magnetosphere in the solar system: if the volume of space it encloses could somehow be made visible to the human eye, it would look larger than the full moon in our night sky.

The magnetosphere forms a barrier to the electrically charged particles in the solar wind, forcing it to detour around the invisible block. A shock wave forms at the upstream, or sunward, edge of the magnetosphere; downstream, the magnetic field is elongated to form a so-called magnetotail. The magnetosphere is home to highly energetic charged particles, immense currents and a bewildering array of electromagnetic waves.

A huge spinning ring, or torus, of sulfur and oxygen ions surrounds Jupiter and makes up the inner part of the magnetosphere. The material is stripped from Io, which must supply about a ton of it per second. *Galileo* will study regions and processes in the Io torus and the magnetosphere that were inaccessible to previous spacecraft. —*T.V.J.*



JET PROPULSION LABORATORY

JAILBARS, slices of images taken of the asteroid Ida, were returned to the earth so that the interesting parts could be located without the entire image having to be sent. (The failure of the main antenna necessitated such extreme economy in the transmission of data.) The jailbars (*left*) revealed a small speck alongside Ida; the full image (*right*), when reclaimed, revealed the object to be a rock about a kilometer wide, orbiting Ida—the first known asteroidal moon.

trajectory was adjusted so that *Galileo* would arrive at Jupiter on December 7, 1995. On the way, it would also encounter asteroid Ida on August 28, 1993.

The Ida meeting presented new challenges. There was no prospect of using the stuck main antenna, and no more passages by the earth to sidestep the communications bottleneck. The transmission rate for sending Ida's data would never exceed 40 bits per second. Yet the scientists wanted to make observations twice as close to Ida as to Gaspra. Because Ida is about twice the size of Gaspra, any portrait would also have four times the surface area.

An intense navigational effort was set into motion to get even better data for Ida than for Gaspra. Techniques were developed to search the recorded tape so that the empty "black sky" frames need not be returned, leaving the antenna free to transmit only the essential images. Nature helped somewhat: Ida has a period of 4.65 hours, about two thirds that of Gaspra, so that *Galileo* would see all the sides of Ida from closer range.

The initial images showed Ida to be an extremely irregular object about 56 kilometers long, with a very heavily cratered surface. Ida is a member of an asteroid group called the Koronis family, believed to be left over from the breakup of a larger parent body about 100 kilometers across. Some theorists had argued that the breakup occurred no more than tens of millions of years ago. Ida's crater-scarred, apparently ancient surface suggests instead that the Koronis family and perhaps others as well may be one or more billion years old.

There was another surprise in store. In February 1994 scientists began to screen the remainder of the Ida tape. Small parts of some of the image frames had been obtained as "jailbars"—sequences in which a few scanned lines were sent, many were skipped, then a few more were returned and so on to the end of the frame. The regions containing Ida were located so that they could be played back in full later.

Examining the jailbars for the first time, imaging team associate Ann Harch noticed an odd speck alongside Ida. Ruling out a UFO as somewhat unlikely, the team checked for astronomical sources that might inadvertently have appeared in the background. Finding none, they concluded that they had found a small asteroid, probably a moon, next to Ida.

The infrared team, which also had jailbars, confirmed the asteroid's presence. The imaging and infrared groups quickly realized they had slightly different views of the same object. A rapid calculation of parallax angles showed that the rock was about 100 kilometers from the center of Ida and had not moved much in the few minutes separating the observations. The small body, close to a larger asteroid and moving very slowly, was almost certainly a satellite. The International Astronomical Union named it Dactyl, after the Dactylos, the sons of Ida and Jupiter.

It happened that essentially every view taken of Ida also contained Dactyl. The high-resolution images revealed the moon to be a potato-shaped, pockmarked object, clearly not some recent collisional fragment. It was in an orbit with a period of 24 hours or more. The range of possible orbits that fit the observations can help constrain the mass and therefore the density of Ida, which turns out to be similar to that of many rocks and stony meteorites.

The discovery of Ida's moon raised many questions. What, for instance, was its origin? A collision could have sent a piece of debris from Ida itself into orbit. (A variant of this idea is that the earth's moon formed when a "mega-impact" blasted material off the earth, which then coagulated with debris from the impactor [see "The Scientific Legacy of Apollo," by G. Jeffrey Taylor; SCIENTIFIC AMERICAN, July 1994].) But then the fragment would have had to collide with some other strategically placed debris, or else it would simply have fallen back to Ida. More likely, both Dactyl and Ida were produced when the parent body of the Koronis family broke up. If the two fragments stayed relatively close to each other, they could have become gravitationally bound.

Scientists are divided about how likely an asteroid is to acquire a satellite and how long the latter can survive. Since the early part of this century, there has been scattered evidence that some asteroids might actually be binaries, two bodies orbiting each other at close quarters. But small rocks get pulled out of orbit easily by the perturbing effects of the sun and the other planets, especially Jupiter. Dactyl, orbiting within a few radii of Ida, is well within its sphere of influence, but it remains to be seen how long it will stay there.

Nearing Jupiter

In July 1994, when still one and a half years from Jupiter, *Galileo* was unexpectedly treated to a grand show: Comet Shoemaker-Levy 9 impacting on the nightside of the planet [see "Comet Shoemaker-Levy 9 Meets Jupiter," by David H. Levy, Eugene M. Shoemaker and Carolyn S. Shoemaker; SCIENTIFIC AMERICAN, August]. *Galileo*'s computer sequence had, however, to be specified months before the event, when the times of impact were still very uncertain. To cover for these uncertainties, many more images had to be recorded than could be returned to the earth over the low-gain antenna. Tape-searching techniques such as those used during the Ida flyby were invoked. Moreover, analysis of the events observed from the earth and the *Hubble Space Telescope* helped astronomers to locate and play back only the sections of the recording that held data from the impact.

Galileo was able to observe the visible and near-infrared light from the entry and explosion of several fragments of the comet. Among the most spectacular images were those of the last event. Taken in green light at intervals of 2.33 seconds, these pictures show a gibbous Jupiter with a bright point of light appearing, brightening and then fading away on the nightside of the planet, marking the fiery death of the prosaically named W fragment.

Critical data on the large "G" event were also recorded by ultraviolet, photopolarimeter radiometer and infrared experiments. They allowed direct calculation of the size, temperature and altitude of the fireball. It emerged as a glob of about eight kilometers in width and 7,500 kelvins in temperature, rapidly cooling and expanding as it rose in the atmosphere. To analyze all the data will take years.

From mid-1994, *Galileo's* dust detector, which measures impacts from micrometeoroids no larger than the particles in cigarette smoke, had begun to record dust streams from the direction of Jupiter. This past August, while still 62 million kilometers from the planet, *Galileo* plowed through the most intense dust storm ever measured. Every day for four weeks the detector was spattered by up to 20,000 particles traveling at 40 to 200 kilometers per second. The dust grains, which are too small to damage the craft, may originate either from the rings of Jupiter or from the volcanoes of its moon Io. They probably are electrically charged grains that were accelerated by Jupiter's magnetic field and flung far out into space.

In October *Galileo's* mission planners experienced one more unexpected jolt. The tape recorder did not stop rewinding as expected on reaching the beginning of the tape. As of this writing, the team's best guess is that the recorder may be seriously limited in its capabilities. The spacecraft still has some solid-state memory, however, which can be used to store and transmit high-resolution images—perhaps as many as half the number the tape recorder would allow.

Galileo's arrival at Jupiter on December 7 will mark the start of its primary mission. The information from the probe, an extremely valuable but small data set (it can fit on a floppy disk), will be played back in its entirety. *Galileo* will then concentrate on a multitude of measurements of the giant planet, its four largest moons and its mammoth magnetic field.

JET PROPULSION LABORATORY

***JUPITER ATMOSPHERIC PROBE* will penetrate the planet on December 7. Much of the heat shield will burn away; the rest will fall off after a parachute slows the probe, exposing its instruments. These devices will measure wind speed, cloud composition, lightning frequency and other aspects of the atmosphere.**

By that time, the spacecraft's capabilities will be significantly enhanced. When *Galileo's* computers were originally programmed, data-compression techniques were quite primitive. A completely new set of software for the computers on board will allow extensive processing, editing and compression of data on board the spacecraft, increasing the information content in each bit by a factor of 10 or more.

In addition, the Deep Space Network will have been modified to pick up the faint signals from the low-gain antenna. The DSN is a group of three tracking complexes: at Goldstone, Calif., Madrid, Spain, and Canberra, Australia. Set 120 degrees in longitude apart, the stations permit any spacecraft to be in view at any time. (Tracking time on the DSN is an important bargaining chip for NASA in collaborative space projects.)

The antennae are typically used separately to track different spacecraft. But when great sensitivity is required, they can be tuned electronically to create effectively a much larger receiving dish. *Voyager* used this capability when viewing Uranus and Neptune, and *Galileo* will make routine use of the technique while surveying Jupiter.

These improvements, combined with other changes in the way the spacecraft encodes data, will increase the information capacity of the telecommunications link up to 1,000 bits per second. With this capability, the primary goals of *Galileo*—those involving high-resolution data on the objects it will near and a survey of the magnetic field—will be realized. *Galileo* will view the Jovian satellites with the resolution that *LANDSAT,* for example, images the earth. It will also monitor the volcanoes on Io at 10 times better resolution than the *Hubble* can. Some other projects, such as observing Io during the first and closest encounter, measuring magnetospheric phenomena at very high time resolutions, or making a motion picture of, say, the Great Red Spot, will not be possible without the high-gain antenna and the tape recorder.

One can never say what might have been discovered by the broad, sweeping look at the Jovian system that was originally envisaged. But the Galileo team has already demonstrated that it can make remarkable discoveries by clever use of extremely low bit rates. I estimate that at least 50 percent of the mission's objectives will be met even if the tape recorder cannot be used as previously envisioned, and I eagerly anticipate some fascinating surprises. From these new data will flow the understanding and questions to fire the imaginations of the next generation of explorers.

The Author

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Further Reading

THE NEW SOLAR SYSTEM. J. Kelly Beatty and Andrew Chaikin. Sky Publishing and Cambridge University Press, 1990.

JUPITER: THE GIANT PLANET. Reta Beebe. Simon & Schuster, 1994.

ONLINE FROM JUPITER. Available on the World Wide Web at http://quest.arc.nasa.gov/jupiter.html or via gopher at quest.arc.nasa.gov in the Interactive Projects directory.

Cystic Fibrosis

The genetic defects underlying this lethal disease have now been shown to eliminate or hobble a critical channel through which a constituent of salt enters and leaves cells

by Michael J. Welsh and Alan E. Smith

Woe to that child which when kissed on the forehead tastes salty. He is bewitched and soon must die. This adage, from northern European folklore, is an early reference to the common genetic disease recognized today as cystic fibrosis. As the saying implies, the disorder once routinely killed children in infancy and is often identifiable by excessive salt in sweat. A salty brow is one of the more benign manifestations. The inherited genetic abnormality can also destroy the lungs and cause serious impairment of the pancreas, intestines and liver. Advances in therapy over the past few decades have brightened the outlook for afflicted children, enabling more than half of them to survive into their late twenties or beyond. But none of the approved treatments can yet correct the biochemical abnormality at the root of the condition, and none can remove the specter of an early death.

Hoping to do better, investigators began trying in the early 1980s to identify the specific genetic derangement that gives rise to cystic fibrosis. After almost a decade of struggle, they isolated the affected gene and pinpointed the mutation that most often leads to the disease. At the time, they could only guess at the gene's normal function—that is, at the role played by the protein produced from the healthy DNA. Since then, in an exciting series of discoveries, researchers have learned that the protein serves as a channel through which chloride, one component of salt, enters and leaves cells. They also have explained how damage to the gene blocks chloride transport, and they are exploring how the loss of chloride movement brings on the overt signs of cystic fibrosis. As was hoped, such findings are suggesting new ideas for therapy, some of which may one day cure the disorder.

The molecular advances that have led to this promising moment in medical history could not have been achieved without the pioneering efforts of physicians, many of whom gleaned their initial understanding of cystic fibrosis at the bedside. Indeed, for decades, clinical research yielded more information about the nature of the disease than did biochemical investigation.

One of the first major contributions came in 1938 from Dorothy H. Andersen of Columbia University. After performing autopsies on infants and children and reviewing the youngsters' case histories, Andersen provided the first comprehensive description of the symptoms of cystic fibrosis and of the changes produced in organs. Those changes, she noted, almost always included destruction of the pancreas (even in infants) and, often, infection of and damage to the lung airways. Andersen also gave the disease its name, calling it "cystic fibrosis of the pancreas," on the basis of microscopic features she observed in pancreatic tissue.

By the late 1940s physicians had further realized that ductal systems and other passageways in the organs affected by cystic fibrosis generally become clogged with unusually thick secretions. In the pancreas, for instance, ducts that deliver digestive enzymes to the intestines almost always become occluded, impairing the body's ability to break down food and extract nutrients from it.

In the lung it is the bronchial tubes and bronchioles that become obstructed. Those passages are usually bathed by a thin layer of mucus that traps inhaled particles and carries them to the throat for removal. But in patients with cystic fibrosis, the mucus is excessively thick and resistant to removal. This change by itself can narrow air passages and impair breathing. Moreover, when bacteria remain in the air passages, they can establish infections readily. These infections, which tend to recur, harm lung tissue by recruiting immune cells that secrete injurious chemicals and enzymes. As time goes by, chronic infection progressively destroys the bronchial passages and, together with the plugging of airways, ultimately leads to respiratory failure.

By 1946 studies of patients had also revealed something about the genetics of cystic fibrosis. After examining the pattern of disease inheritance in families, researchers deduced that cystic fibrosis was a recessive condition, probably caused by mutation of a single gene. If an infant inherited a damaged copy of the gene from both parents and therefore made no normal molecules of the protein specified by the gene, the child became ill; however, receipt of one good copy and one damaged copy did not produce disease.

Cystic fibrosis is now known to be among the most common genetic diseases and to strike mostly whites. About 5 percent of white Americans are asymptomatic carriers, harboring a single mutant version of the gene in their cells. One child in approximately 2,500 of European descent carries two defective copies and has the disease. In the U.S. such numbers translate into about 1,000 new cases a year and a total of some 30,000 people who live with the disorder today.

Help from a Heat Wave

Roughly seven years after the inheritance pattern was delineated, New York City baked in a heat wave. Hospitals saw a disproportionate number of children with cystic fibrosis, who apparently became dehydrated more readily than other youngsters. Paul di Sant'Agnese and his colleagues at Columbia University then found that boys and girls with cystic fibrosis lose an excessive amount of salt in sweat. The reason for the increased saltiness would not be discerned for many years, but the observation had great clinical value. It resulted in development of a test that remains the cornerstone of diagnosis: measurement of the chloride content in perspiration.

Over the years, such clinical work has led to earlier, more accurate diagnosis and better treatments. For example, pancreatic failure is rarely life-threaten-

ABRAHAM MENASHE

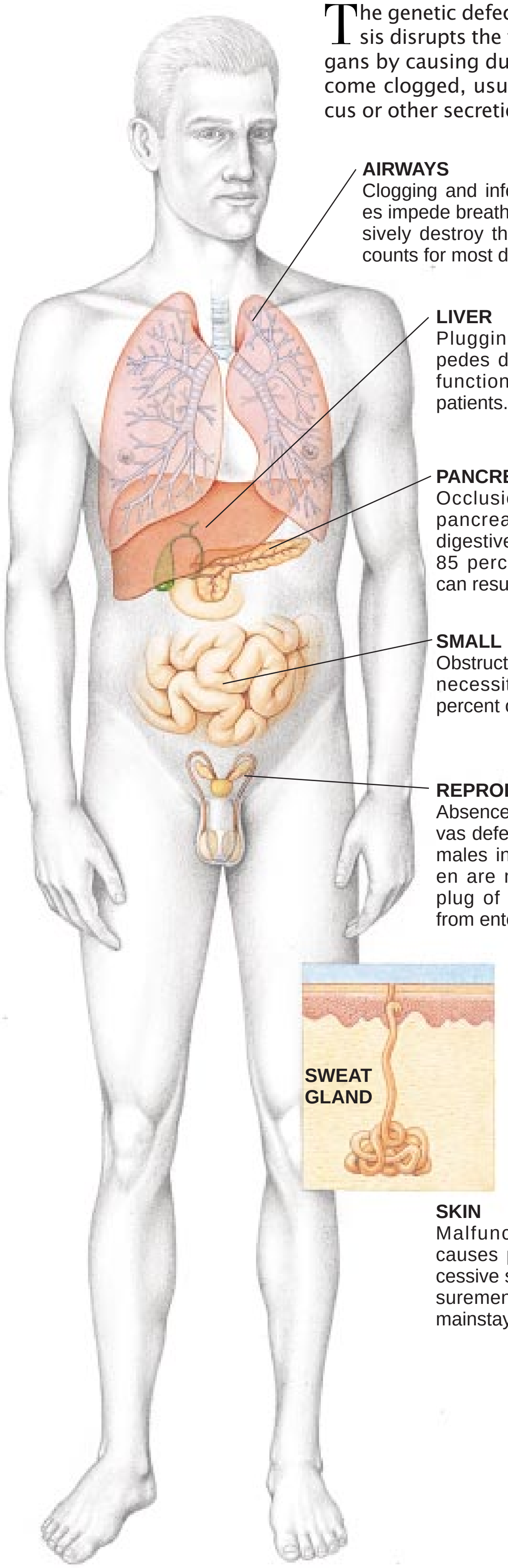
GENTLE POUNDING ON THE CHEST, or chest percussion, has long been a standard treatment for cystic fibrosis. The procedure aims to clear mucus from clogged airways in the lungs. Investigators hope that growing understanding of the molecular basis of the disease will lead to drug therapies that prevent airway obstruction in the first place. The child here is being tapped by her mother. The white unit on her arm delivers intravenous antibiotics to combat infection of the lung.

ing today because patients can replace their missing digestive enzymes with capsules taken when they eat. Now that the digestive problems can generally be controlled, the lung impairment accounts for more than 90 percent of the disability and death in patients with cystic fibrosis. Treatment options for the lung disease have expanded as well. Current therapy does include old standbys called postural drainage and chest percussion. Patients lie so that their head is tilted downward; someone then pounds gently and rapidly on their back or chest—as if hitting the bottom of a ketchup bottle—to try to clear mucus from the airways. But patients also benefit from a range of antibiotics that help to control the repeated infections (although usually without eliminating them). And about two years ago another treatment became available: inhalation of a drug called DNase. This compound aims to break up mucus by digesting long, sticky strands of DNA released from dying cells.

Research into the biochemical underpinnings of cystic fibrosis progressed more slowly than did the clinical work, but the pace intensified in the first half of the 1980s. During that time, scientists realized that malfunction of epithelial tissue was at fault in every organ impaired by cystic fibrosis. (An epithelium is a sheet of cells that forms a barrier between different compartments of the body; such sheets, which often secrete mucus, line the intestines and many ducts.) In particular, two avenues of investigation revealed that the epithelia of patients with cystic fibrosis were relatively impermeable to chloride. This discovery implied that some chloride-transporting channel in epithelial tissue was malfunctioning.

Organs Affected by Cystic Fibrosis

The genetic defect underlying cystic fibrosis disrupts the functioning of several organs by causing ducts or other tubes to become clogged, usually by thick, sticky mucus or other secretions.



AIRWAYS
Clogging and infection of bronchial passages impede breathing. The infections progressively destroy the lungs. Lung disease accounts for most deaths from cystic fibrosis.

LIVER
Plugging of small bile ducts impedes digestion and disrupts liver function in perhaps 5 percent of patients.

PANCREAS
Occlusion of ducts prevents the pancreas from delivering critical digestive enzymes to the bowel in 85 percent of patients. Diabetes can result as well.

SMALL INTESTINE
Obstruction of the gut by thick stool necessitates surgery in about 10 percent of newborns.

REPRODUCTIVE TRACT
Absence of fine ducts, such as the vas deferens, renders 95 percent of males infertile. Occasionally, women are made infertile by a dense plug of mucus that blocks sperm from entering the uterus.

SKIN
Malfunctioning of sweat glands causes perspiration to contain excessive salt (sodium chloride). Measurement of chloride in sweat is a mainstay of diagnosis.

In one set of those investigations, Paul M. Quinton of the University of California at Riverside found that the epithelia lining the ducts of sweat glands failed to take up chloride efficiently from the cavity, or lumen, of the glands. This finding finally explained why people with cystic fibrosis have unusually salty sweat. Sweat is normally produced at the base of sweat glands; it then flows to the skin surface through a narrow duct. Initially the sweat is a solution rich in sodium and chloride ions—that is, the constituents of salt. But as the fluid traverses the duct, the ions escape into the epithelium, leaving the water behind. Thus, the sweat that emerges to cool the skin surface is only slightly salty. In patients with cystic fibrosis, in contrast, the inability of epithelial tissue to absorb chloride and the consequent impairment of sodium absorption from the duct lumen cause sweat to retain excess sodium and chloride and to become abnormally salty.

In the other line of study, Michael R. Knowles and Richard C. Boucher of the University of North Carolina at Chapel Hill examined the lungs. They found that chloride movement from epithelial tissue into the airway lumen was diminished and that sodium uptake by the epithelium was enhanced. Reduced chloride transport has now been demonstrated as well in the epithelia of the pancreatic ducts in mice and of the intestines in patients.

Finally, the Gene Is Found

As these studies of chloride transport were progressing, many scientists were engaged in an intense race to find the gene responsible for cystic fibrosis. That effort culminated in 1989, when a large group of collaborators, led by Lap-Chee Tsui and John R. Riordan of the Hospital for Sick Children in Toronto and by Francis S. Collins, then at the University of Michigan, announced it had isolated the gene. Aware that the protein product of the gene probably influenced the movement of chloride directly or indirectly, they named the protein the cystic fibrosis transmembrane conductance regulator (CFTR). While searching for the gene, the team also identified an abnormality in the DNA that appeared to account for about 70 percent of cystic fibrosis cases. That aberration, often denoted as the ΔF508 mutation, consists of the deletion of three nucleotides (DNA building blocks) from the gene. That loss causes the protein product of the gene to lack a single amino acid: phenylalanine at position 508.

The report was extraordinarily exciting for everyone concerned with cystic fibrosis; it promised to open new vistas of understanding and new options for therapy. Nevertheless, investigators desired additional evidence that the correct gene had been isolated. Strong support could be obtained by inserting a healthy version into cells from a patient with cystic fibrosis and thereby correcting the chloride transport defect. Frustratingly, workers had difficulty constructing even a streamlined version of the gene. By the summer of 1990, however, our colleague Richard J. Gregory of Genzyme Corporation had solved the problem.

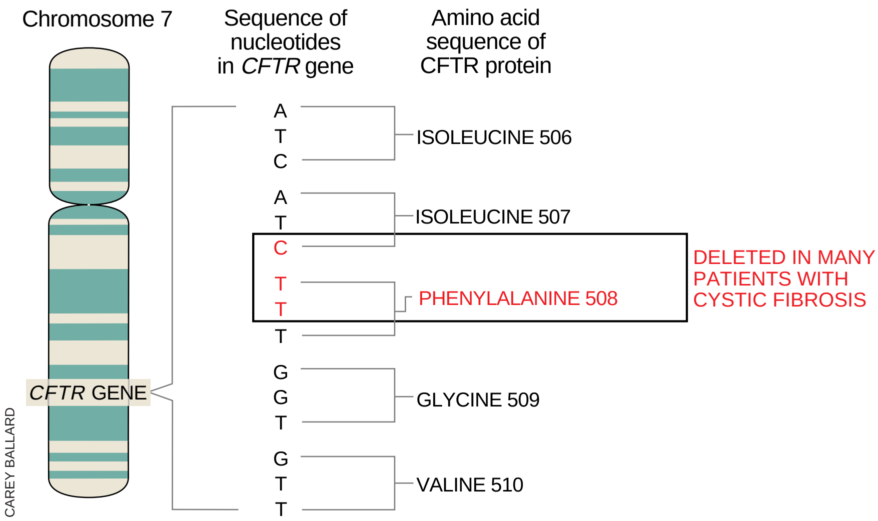
The two of us and our co-workers lost no time inserting the gene into epithelial cells isolated from the airways of patients with cystic fibrosis. Next we exposed the cells to cyclic AMP, a molecule that normally stimulates chloride transport in airway epithelium but has no effect on tissue from patients with cystic fibrosis. We were thrilled to see that cyclic AMP now caused chloride to stream out of the treated cells; the gene had apparently made the cells normal. We were not alone in our delight. Collins and a number of his colleagues had obtained similar findings using different methods in pancreatic epithelial cells.

The successes with cultured cells suggested that delivery of healthy *CFTR* genes to patients might correct their underlying biochemical abnormality—a tantalizing possibility. But we also knew, as will be seen, that there were many obstacles to attaining that goal. Meanwhile another obvious problem loomed over the field: resolving exactly how the CFTR protein influenced chloride movement.

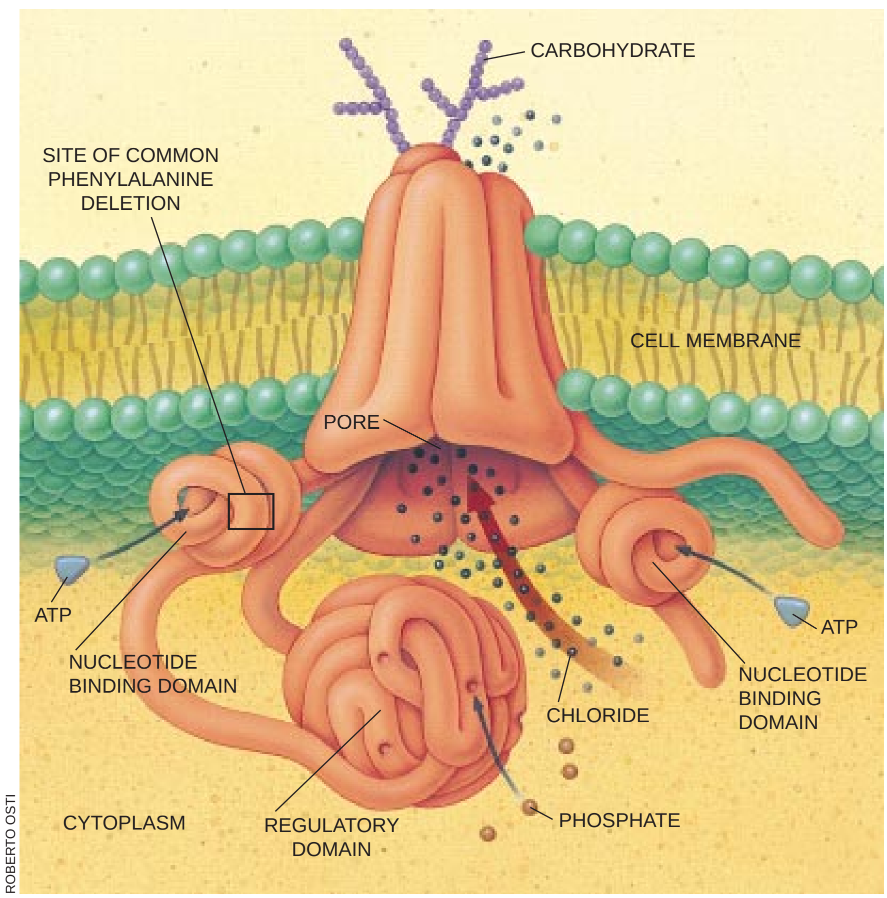
What Does This Protein Do?

The linear sequence of amino acids in the protein, which was easily deduced once the gene was isolated, offered some immediate clues to the protein's normal behavior. Notably, the sequence was much like that found in a family of proteins called traffic ATPases or ABC transporters (because they carry what is known as an *A*TP *b*inding *c*assette). The similarity implied that the CFTR protein might also resemble the family in its behavior and in its folded, three-dimensional structure.

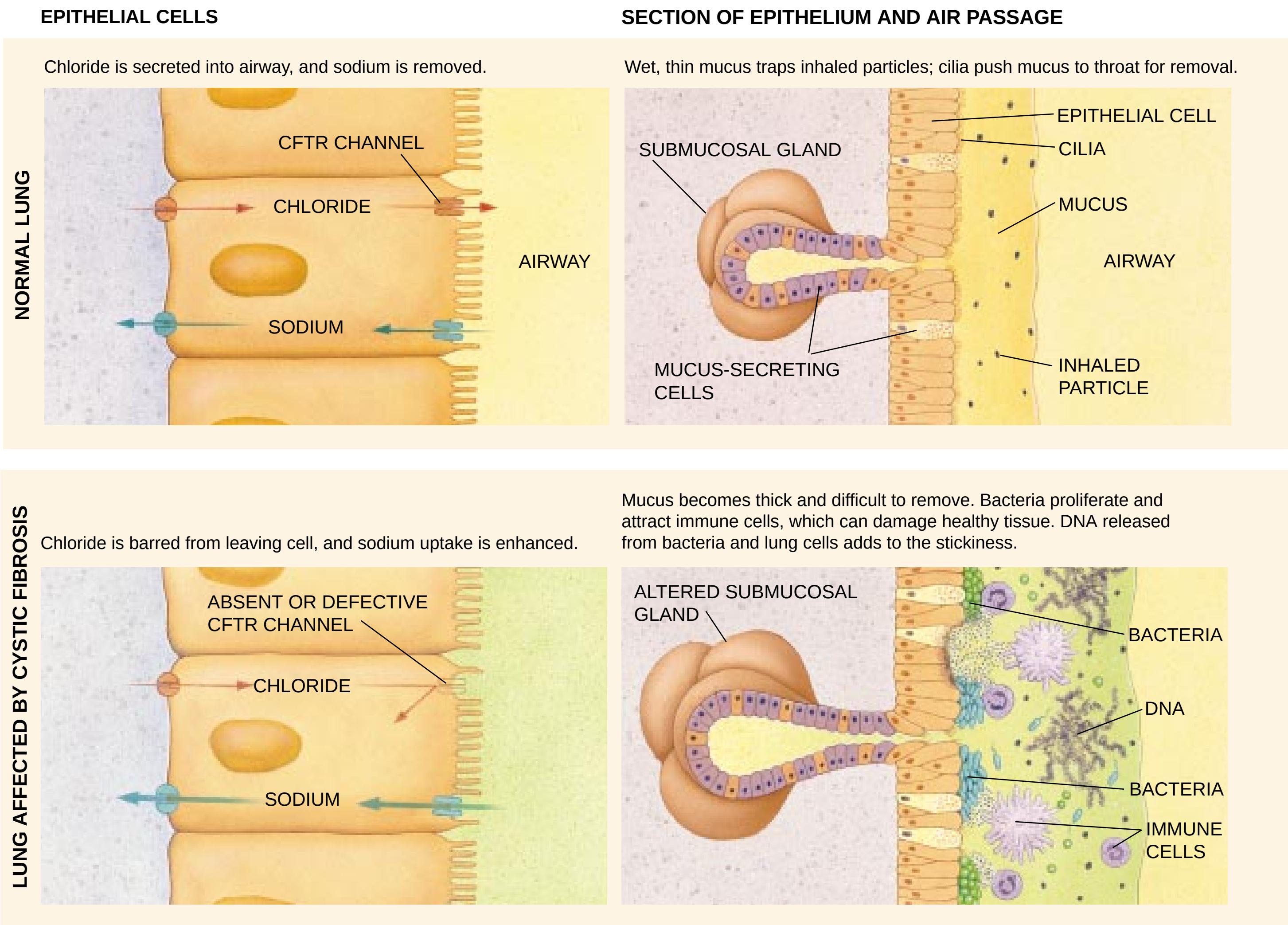
The traffic ATPase family includes a number of proteins used by bacteria to pump nutrients across their cell membrane; it also includes the drug-resistance protein that unfortunately ejects chemotherapeutic drugs from cancer cells [see "Multidrug Resistance in Cancer," by Norbert Kartner and Victor Ling; SCIENTIFIC AMERICAN, March 1989].



CYSTIC FIBROSIS GENE resides on chromosome 7 (*left*) and normally gives rise to a protein called the cystic fibrosis transmembrane conductance regulator (CFTR). The defect that most often leads to the disease is the deletion of three nucleotides from the gene (*red letters in center column*); this alteration, known as the ΔF508 mutation, results in the loss of one amino acid—phenylalanine at position 508—in the CFTR protein (*right*). Phenylalanine is lost because the protein-making machinery of the cell now sees ATT (an alternative way to encode isoleucine) at the gene region coding for the protein's 507th amino acid, followed by the GGT sequence for the glycine that normally follows phenylalanine.



INTACT CFTR PROTEIN forms a chloride-permeable channel in the outer membrane of many cells. The precise structure has yet to be determined, but movement of chloride through the pore is known to be regulated by three cytoplasmic domains of the protein. Passage is allowed only when the two nucleotide binding domains dock with and cleave adenosine triphosphate (ATP) and when the regulatory domain becomes studded with phosphate groups.



MOLECULAR BASIS OF LUNG DISEASE in patients who have cystic fibrosis is complex. In healthy individuals (*top row*), the main epithelial cells lining the airways (*left panel*) display at least two types of channels at the surface facing the air passage. One—the CFTR channel (*red*)—releases chloride into the passage; the other (*blue*) takes up sodium. This arrangement somehow enables mucus made by other cells to remain wet, thin and easy to remove from the airways (*center panel*), and so the airways remain open (*right panel*). In patients with cystic fibrosis (*bottom row*), absence or malfunction of the CFTR channel prevents chloride movement (*left panel*) and indirectly causes cells to take up extra sodi-

When folded, these ATPases generally have four main structural parts, or domains: two that span the membrane (each of which contains several transmembrane segments) and two that dwell in the cytoplasm. The last two units, known as nucleotide binding domains, take up and cleave ATP (the nucleotide adenosine triphosphate) to obtain the energy required for pumping. The CFTR molecule was predicted to take essentially the same shape and, as will be seen, to have an added component residing in the cytoplasm.

Based on the activities of the ATPases, some researchers favored the hypothesis that CFTR was an ATP-driven pump that actively transferred some substance into or out of epithelial cells; the transported substance then induced chloride transport across the cell membrane through a separate channel. They posited this complex scheme because no known ion channels (such as would be needed to move chloride more directly) resembled the predicted folded structure of CFTR.

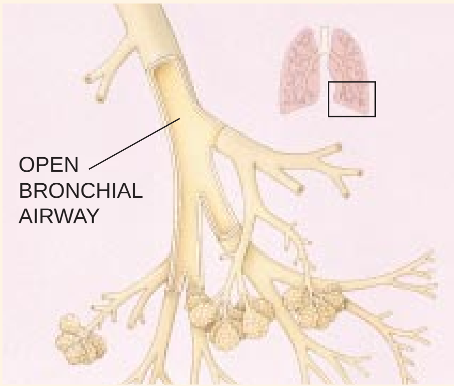
A second hypothesis proposed that CFTR itself attached to chloride channels and influenced their activity. And a third hypothesis held that CFTR might serve directly as a chloride channel even though its structure was unusual for any ion channel recognized at the time. In this scenario, the two membrane-spanning domains would form the pore through which chloride ions passed across the membrane.

As the work advanced, the data confirmed the third idea: CFTR formed a chloride channel on its own. We found that transfer of a gene for CFTR into chloride-impermeable cells conferred the ability to move that ion. If the gene was first altered in ways that affected parts of the CFTR protein thought to help chloride move through the channel, the channel's affinity for chloride decreased; this effect was shown by our colleague Matthew P. Anderson of the University of Iowa. Any last doubts were dispelled when Riordan and his colleagues inserted highly purified CFTR proteins into artificial cell membranes (lipid bilayers) containing no other channellike proteins. Addition of the protein allowed the ions to travel across the membrane.

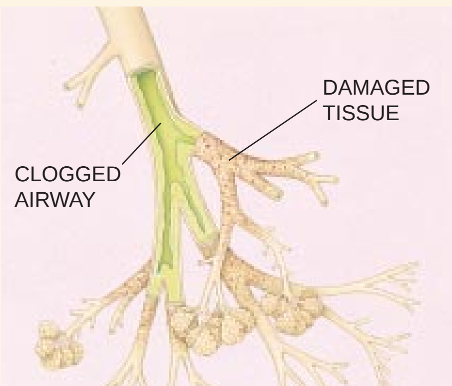
Subsequent investigations clarified the function of the "extra" CFTR component not found in traffic ATPases. On the basis of certain short sequences within that component, the mysterious

BRONCHIAL TUBES AND BRONCHIOLES

Airways stay clear for breathing.



Airways become plugged and begin to deteriorate.



ROBERTO OSTI

um (*thick blue arrow*). Then the mucus becomes thicker and more resistant to removal (*center panel*), and bacteria trapped there flourish. Together these changes plug the airways and lead to their destruction (*right panel*).

segment was deduced to be a regulatory domain—R—whose activity in the cytoplasm was controlled by the addition and removal of phosphate groups. Various experiments, including those by our colleagues Seng H. Cheng of Genzyme and Devra P. Rich of the University of Iowa, showed that when the R domain lacks phosphate groups, chloride ions cannot flow into the channel pore. But when chemical changes in a cell (specifically, rising levels of cyclic AMP) cause enzymes to dot the domain with phosphate, the addition promotes chloride movement through the pore.

It is helpful, though overly simplistic, to imagine that when the regulatory domain is not phosphorylated, it behaves like a gate blocking the cytoplasmic opening of the membrane pore. Addition of the phosphates somehow displaces the domain (opens the gate), allowing chloride ions to pass into the pore. Other analyses have demonstrated that the nucleotide binding domains influence the activity of the channel as well. For ions to go through the pore, those domains must bind to and probably cleave ATP.

How the Mutations Make Mischief

Knowing that the CFTR protein forms a chloride channel and having some idea of how the molecule functions leaves an important question still to be answered: Exactly how do mutations in the *CFTR* gene lead to loss of chloride transport? The effect of the most common DNA mutation—the deletion that leads to omission of phenylalanine 508 from the CFTR protein—has been the most extensively studied.

This deletion engenders what is known as an intracellular trafficking defect. Many proteins, among them the normal CFTR molecule, are processed after they are synthesized. They gain some sugar groups in a cellular compartment called the endoplasmic reticulum, after which they take up more sugar in the Golgi apparatus before being dispatched to the cell membrane. The mutant protein, in contrast, fails to leave the endoplasmic reticulum. Its travel is halted presumably because the quality-control system in the endoplasmic reticulum discerns that the protein is folded improperly. Proteins that are identified as defective are marked for degradation rather than being allowed to undergo further processing.

Although the phenylalanine 508 mutation is the most common one, hundreds of others have now been identified in people with cystic fibrosis. As is true of the 508 mutation, many of these changes block the protein from making its way to the cell membrane. Some prevent the CFTR protein from being made at all, and still others allow the protein to be produced and inserted into the cell membrane but bar the CFTR molecule from operating properly. In the last instance, the mutations may forestall chloride movement by disrupting the function of a nucleotide binding domain or by introducing a flaw into the lining of the ion-transporting pore.

In general, people whose cells carry two copies of the gene bearing the phenylalanine 508 mutation tend to have severe disease, probably because little if any of the mutated protein escapes from the endoplasmic reticulum. In people whose genes permit at least some CFTR to reach the cell membrane and to transport chloride to an extent,

Testing Dilemmas

Now that many genetic mutations leading to cystic fibrosis have been pinpointed, prospective parents can easily find out whether they are likely to be carriers of the disease—that is, whether their cells silently harbor a defective copy of the *CFTR* gene. Couples can also learn whether an already developing fetus has inherited two altered copies of the gene (one from each parent) and will thus be afflicted with cystic fibrosis.

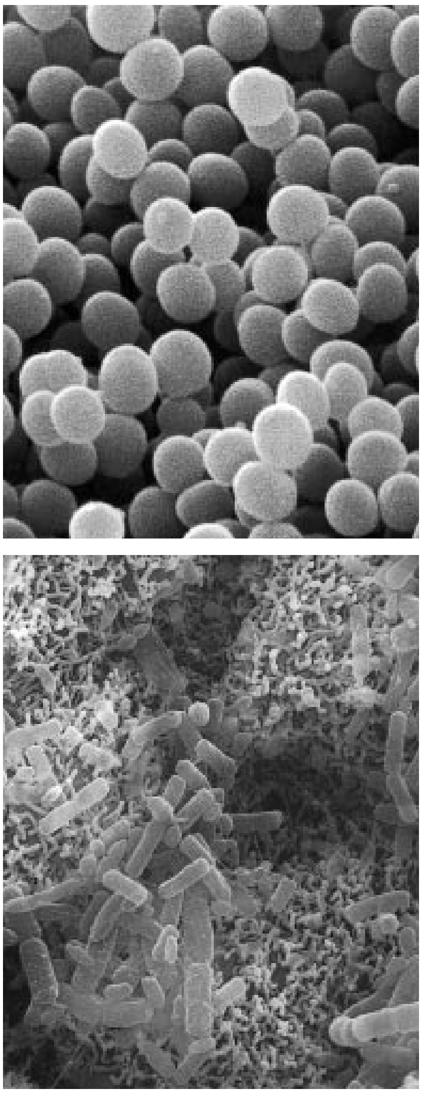
The difficulty for many people is deciding how to proceed once they receive their test results. The trouble arises in part because the laboratories that perform the genetic analyses do not detect every mutation in the *CFTR* gene. Consequently, a reassuring negative finding may not fully rule out the possibility that someone is a carrier or is affected with cystic fibrosis. (A favorable prenatal test result will be conclusive, however, if the fetus is shown to lack the specific *CFTR* mutants known to be carried by the parents.) Moreover, it is not yet possible to predict the extent of symptoms in a person who inherits two *CFTR* mutants; even if the inherited genes are usually associated with highly severe or less severe disease, such associations do not necessarily hold true in every individual.

Some couples may be tempted to think that research will progress fast enough to protect children born today from the life-threatening lung damage characteristic of cystic fibrosis. Yet medical investigations often hit unexpected obstacles and suffer setbacks before they achieve their ultimate goals. Hence, although it is probable that treatment will become more effective—perhaps markedly so—in the coming years, no one can foretell exactly when cystic fibrosis will become significantly easier to manage. Prospective parents need to understand, therefore, that a child born with cystic fibrosis today will still have to cope with the disease and may not be spared a premature death.

Such uncertainties render decision making extremely challenging. This is an exciting time in cystic fibrosis research, but it is also a trying one for couples caught in the gap between current technology and anticipated advances that have not yet become a reality.*—M.J.W. and A.E.S.*

the residual activity can make for somewhat less severe symptoms. These patterns do not always hold, however, and so making predictions in individual cases remains problematic. Indeed, two patients with exactly the same mutations in both copies of their *CFTR* gene can differ significantly in the extent of organ damage they suffer. This divergence arises because other genetic and environmental factors that remain poorly understood can probably influence the course of the disease.

It is humbling to note that burgeoning understanding of the genetic defects has not yet fully explained how disordered chloride transport in the lung epithelium alters sodium transport and how those changes result in the accumulation of mucus in the bronchial passages. It has also been discovered that submucosal glands—mucus producers that lie below the surface epithelium—produce a large amount of the CFTR protein. What role do these glands play in the disease? Scientists are further puzzled by the fact that the airways of patients with cystic fibrosis are predisposed to infection by some bacteria more than by others. For instance, infections by *Pseudomonas aeruginosa* and *Staphylococcus aureus* are particularly common. An understanding of why certain organisms thrive is only now beginning to emerge.



TONY BRAIN *Science Photo Library*

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BACTERIA that often cause severe infections in the lungs of patients with cystic fibrosis include *Staphylococcus aureus* (*top*) and *Pseudomonas aeruginosa* (*bottom*). Once the infections are established, they almost invariably recur.

Investigators wonder as well whether the CFTR protein has functions beyond its role as a chloride channel. Among the possibilities being considered is that CFTR may help regulate chloride channels distinct from CFTR. Researchers have also posited that the molecule may indirectly alter the mix of sugars on the epithelial surface in ways that favor colonization by certain bacteria.

Strategies for Treatment

In spite of the unanswered questions, the knowledge gained since 1989 has already suggested several avenues for attacking cystic fibrosis. One is to compensate for the loss of the CFTR chloride channel by increasing the activity of a different class of chloride channel. For instance, channels controlled by calcium ions are known to exist in the lumen-facing surface of epithelial cells. Those molecules usually fail to counteract the loss of the CFTR channel, but perhaps their chloride conductance can be increased artificially. This possibility is being tested in patients.

One day doctors also might deliver purified CFTR proteins to the cells that need them. Studies of cells in culture have shown that the protein molecules can correct chloride flow in cells carrying a mutant *CFTR* gene. In theory, another tactic would be to administer drugs able to escort mutant CFTR molecules from the endoplasmic reticulum through the Golgi apparatus and into the cell membrane. This idea seems worth pursuing because ΔF508 mutant CFTR proteins that become stuck in the endoplasmic reticulum usually function fairly well when experimentally inserted into the outer membrane of cells. At present, however, we know of no drugs that can correct the intracellular trafficking abnormality. A different approach, not yet tested, would be to use drugs to increase the activity of any mutant CFTR channels that do find their way into the cell membrane.

The treatment option attracting the most attention, however, is gene therapy, which aims to deliver a normal copy of the *CFTR* gene to the cells that need it. If all goes well, the DNA inserted into target cells should direct synthesis of the normal CFTR protein and reverse the primary biochemical abnormality at the root of cystic fibrosis. Introduction of the gene is a favored approach because it should replace all functions of the CFTR protein, including any that have not yet been recognized.

The best-studied method of gene therapy exploits the ability of viruses to enter cells, bringing their DNA with them. We and others have paid special attention to adenoviruses as gene carriers, or vectors, because those microbes are naturally able to infect human airways but will usually produce relatively innocuous disease, such as the common cold. The adenoviruses are altered in two ways: certain viral genes are removed to prevent the virus from reproducing in cells and causing symptoms. And the excised DNA is replaced with a normal *CFTR* gene. Our group, as well as those of Ronald G. Crystal, then at the National Heart, Lung and Blood Institute, and James M. Wilson, then at the University of Michigan, has demonstrated that such vectors can deliver the *CFTR* gene to cultured epithelial cells and to airway cells in animals. What is more, the cells use the DNA to synthesize CFTR molecules that function as healthy chloride channels.

On the basis of such experiments, several research groups have begun attempting to deliver the *CFTR* gene to patients via genetically engineered adenovirus vectors. The aim of these early experiments is primarily to assess safety. Even so, we and others have also tested the ability of a *CFTR*-bearing adenovirus to correct chloride transport in the nasal epithelium of patients. We chose the nasal epithelium because it is similar to that of the bronchial passages but is easier to reach.

Our first test was encouraging. For experimental purposes, we applied the altered virus directly to a small patch of epithelium in the nose. The treatment partially corrected chloride transport for a time. Since then, however, a similar study by us has been less successful, and one by another group showed no increase in chloride flow. These findings indicate that adenoviral vectors need to be improved substantially before they can serve as gene-delivery agents in therapy.

Even if ways are found to increase the efficiency of gene delivery by the viruses, another challenge would remain. Most cells in epithelial tissue are replaced every few months. Therefore, gene therapy would probably have to

Some Strategies for Treating Lung Abnormalities

The lung disease characteristic of cystic fibrosis can be attacked at many levels. Potential strategies range from reversing the genetic defect at the root of the pulmonary problems to replacing a failed lung with a healthy one.

ABNORMALITY	APPROACH	STATUS
Mutation in *CFTR* gene	Provide normal gene through gene therapy; provide normal CFTR protein to cells	Gene therapy is being tested in preliminary clinical trials; methods for protein delivery are inefficient
Defective delivery of CFTR protein to outer cell membrane	Supply drugs able to escort protein to cell membrane of epithelial cells	No candidate "escorts" have been identified
Defective movement of chloride ions through CFTR channels in cell membrane	Deliver drugs that increase activity of other classes of chloride channel in epithelial cells	Such drugs are being tested in preliminary clinical trials
Clogging of air passages by viscous mucus	Pound back and chest to help clear secretions; administer DNase and other drugs to liquefy secretions	Chest percussion is standard therapy; DNase is now in wide use, and similar drugs are being tested in animals
Development of recurrent infections that can damage lungs	Deliver antibiotics to destroy bacteria or provide antibodies (special molecules of immune system) to remove microbes	Antibiotics are in wide use; antibodies are being tested in preliminary clinical trials
Tissue damage caused by immune response to bacteria	Administer drugs that reduce harmful effects of immune response	Steroidal anti-inflammatory drugs are sometimes used; nonsteroidal anti-inflammatory agents (mainly ibuprofen) are being tested
Destruction of lung	Transplant healthy lung	Transplantation is sometimes an option

be administered a few times a year—at least until the rare, long-lived cells that give rise to the replacement cells can be induced to take up a normal *CFTR* gene permanently. Aside from inconvenience and expense, the need for multiple treatments is a concern because people respond to adenoviruses by mounting an immune response that ultimately eliminates the microbes and prevents repeated infection. For gene therapy to be successful, investigators will have to find ways to "hide" the adenoviruses from the immune system or to create viral or other vectors that do not elicit an immune response.

One appealing alternative to relying on viruses would be to coat the therapeutic gene with fatty molecules that are not recognized by the immune system but that nonetheless enable the DNA to enter cells. Recent studies conducted on human patients by Eric Alton and his co-workers at the Royal Brompton Hospital in London suggest this approach can restore chloride permeability to airway epithelium, although this group, like ours, has so far studied only nasal tissue. Moreover, delivery of genes by nonviral systems needs to be made more efficient.

Scientists have much to learn before they understand exactly how loss of the CFTR protein leads to the manifestations of cystic fibrosis. And a host of technical challenges must be eliminated before any therapy will routinely compensate for that loss. Nevertheless, progress is being made on many fronts. It is difficult not to be optimistic that the ongoing work will produce improved therapies within the next several years.

The Authors

MICHAEL J. WELSH and ALAN E. SMITH have collaborated for several years. Welsh, a Howard Hughes Medical Institute investigator, is professor of medicine and of physiology and biophysics at the University of Iowa College of Medicine. He earned his M.D. at Iowa in 1974 and held fellowships at the University of California, San Francisco, and the University of Texas Medical School at Houston before returning to Iowa in 1981. Smith is senior vice president of research at Genzyme Corporation in Framingham, Mass. He has also been head of the biochemistry division of the National Institute for Medical Research in Mill Hill, England, and scientific director and vice president of Integrated Genetics, also in Framingham.

Further Reading

CYSTIC FIBROSIS: MOLECULAR BIOLOGY AND THERAPEUTIC IMPLICATIONS. Francis S. Collins in *Science,* Vol. 256, pages 774–779; May 8, 1992.

CYSTIC FIBROSIS TRANSMEMBRANE CONDUCTANCE REGULATOR: A CHLORIDE CHANNEL WITH NOVEL REGULATION. M. J. Welsh, M. P. Anderson, D. P. Rich, H. A. Berger, G. M. Denning, L. S. Ostedgaard, D. N. Sheppard, S. H. Cheng, R. J. Gregory and A. E. Smith in *Neuron,* Vol. 8, No. 5, pages 821–829; May 1992.

THE CYSTIC FIBROSIS TRANSMEMBRANE CONDUCTANCE REGULATOR. J. R. Riordan in *Annual Review of Physiology,* Vol. 55, pages 609–630; 1993.

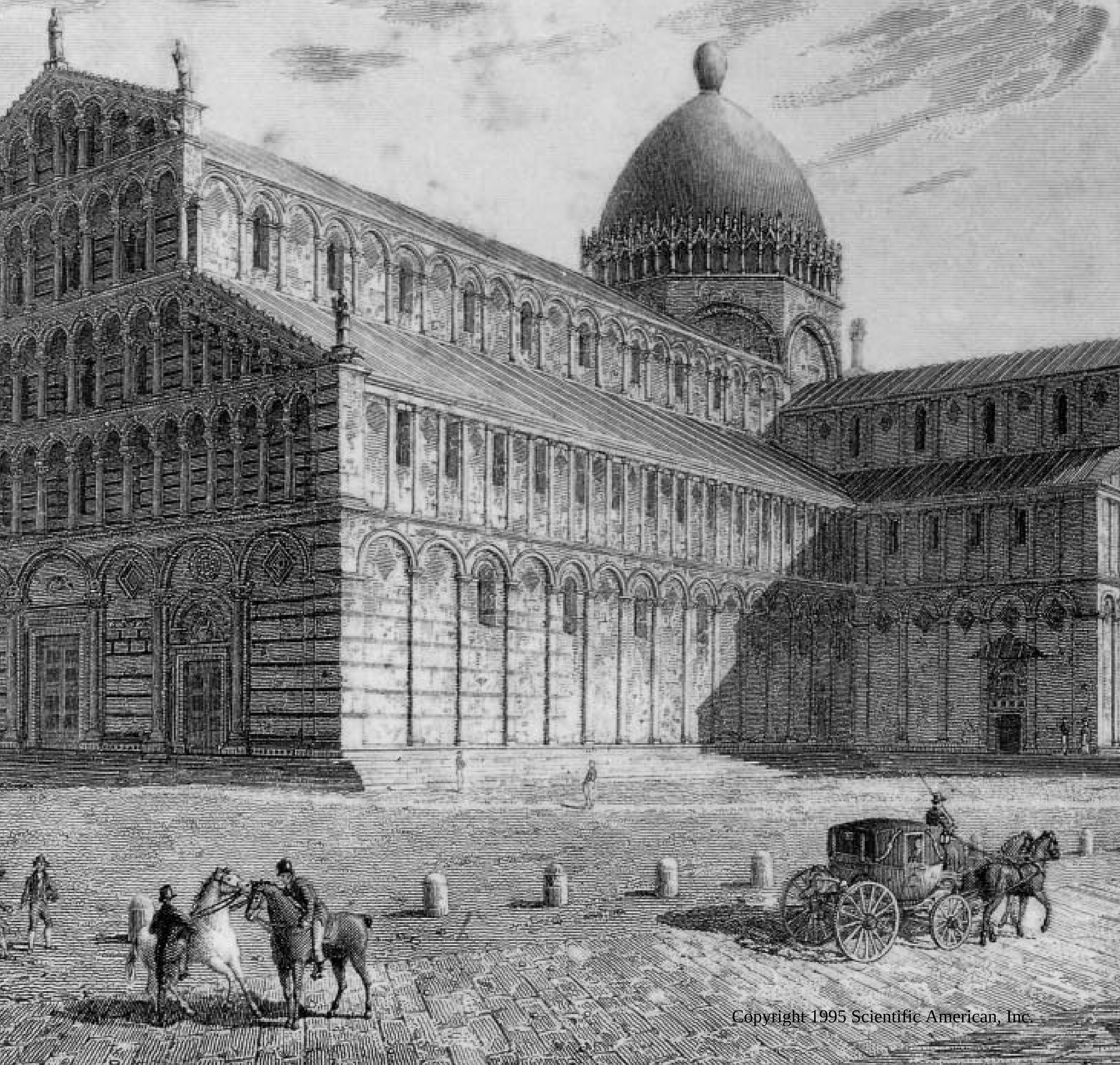
MOLECULAR MECHANISMS OF CFTR CHLORIDE CHANNEL DYSFUNCTION IN CYSTIC FIBROSIS. M. J. Welsh and A. E. Smith in *Cell,* Vol. 73, No. 7, pages 1251–1254; July 2, 1993.

CYSTIC FIBROSIS. M. J. Welsh, L. C. Tsui, T. F. Boat and A. L. Beaudet in *Metabolic and Molecular Basis of Inherited Disease.* Edited by C. R. Scriver, A. L. Beaudet, W. S. Sly and D. Valle. McGraw-Hill, 1994.

The Leaning Tower of Pisa

The famous tower has been tilting since the 12th century. Now engineers are using 20th-century technology in hopes of saving the ancient landmark

by Paolo Heiniger



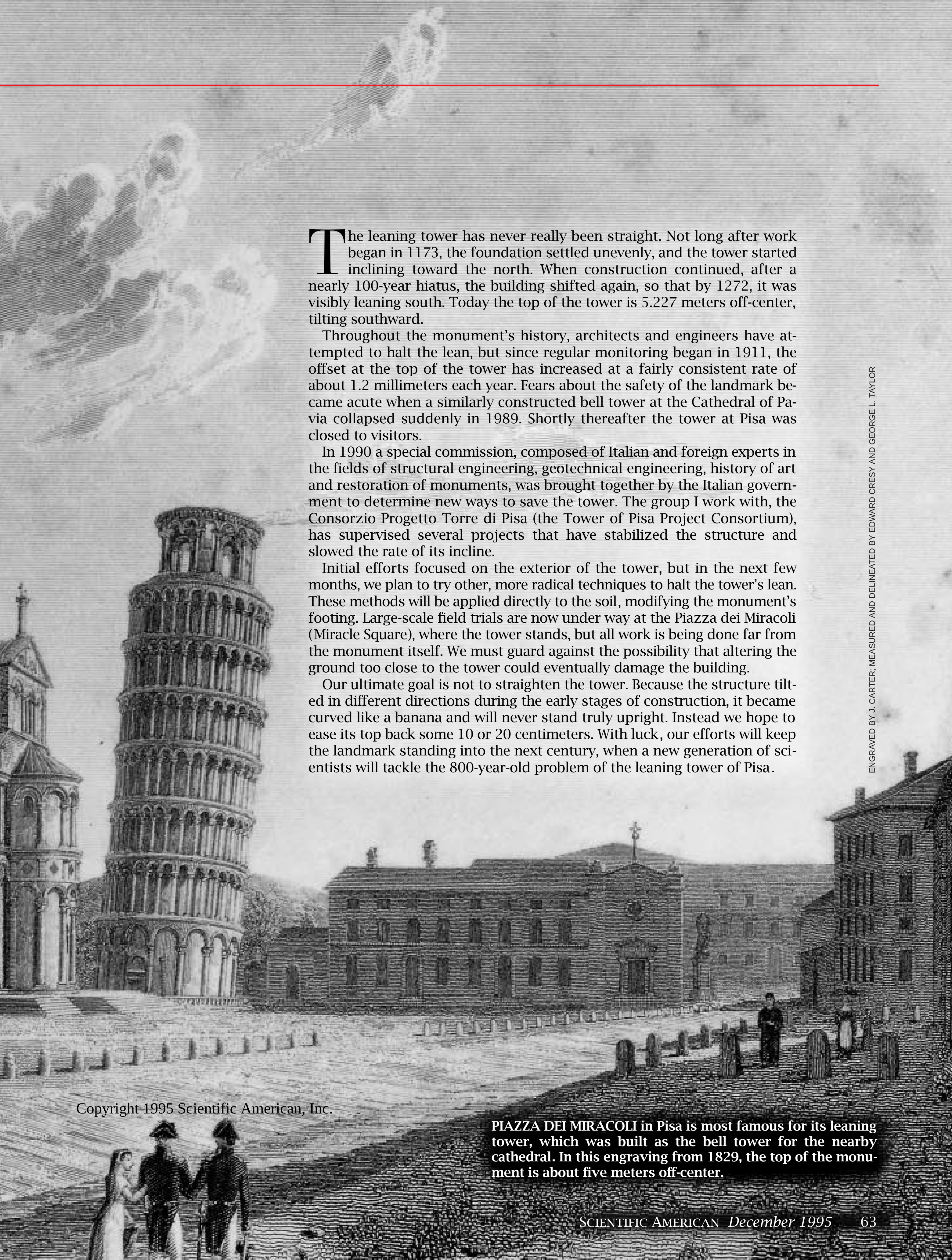
The leaning tower has never really been straight. Not long after work began in 1173, the foundation settled unevenly, and the tower started inclining toward the north. When construction continued, after a nearly 100-year hiatus, the building shifted again, so that by 1272, it was visibly leaning south. Today the top of the tower is 5.227 meters off-center, tilting southward.

Throughout the monument's history, architects and engineers have attempted to halt the lean, but since regular monitoring began in 1911, the offset at the top of the tower has increased at a fairly consistent rate of about 1.2 millimeters each year. Fears about the safety of the landmark became acute when a similarly constructed bell tower at the Cathedral of Pavia collapsed suddenly in 1989. Shortly thereafter the tower at Pisa was closed to visitors.

In 1990 a special commission, composed of Italian and foreign experts in the fields of structural engineering, geotechnical engineering, history of art and restoration of monuments, was brought together by the Italian government to determine new ways to save the tower. The group I work with, the Consorzio Progetto Torre di Pisa (the Tower of Pisa Project Consortium), has supervised several projects that have stabilized the structure and slowed the rate of its incline.

Initial efforts focused on the exterior of the tower, but in the next few months, we plan to try other, more radical techniques to halt the tower's lean. These methods will be applied directly to the soil, modifying the monument's footing. Large-scale field trials are now under way at the Piazza dei Miracoli (Miracle Square), where the tower stands, but all work is being done far from the monument itself. We must guard against the possibility that altering the ground too close to the tower could eventually damage the building.

Our ultimate goal is not to straighten the tower. Because the structure tilted in different directions during the early stages of construction, it became curved like a banana and will never stand truly upright. Instead we hope to ease its top back some 10 or 20 centimeters. With luck, our efforts will keep the landmark standing into the next century, when a new generation of scientists will tackle the 800-year-old problem of the leaning tower of Pisa.

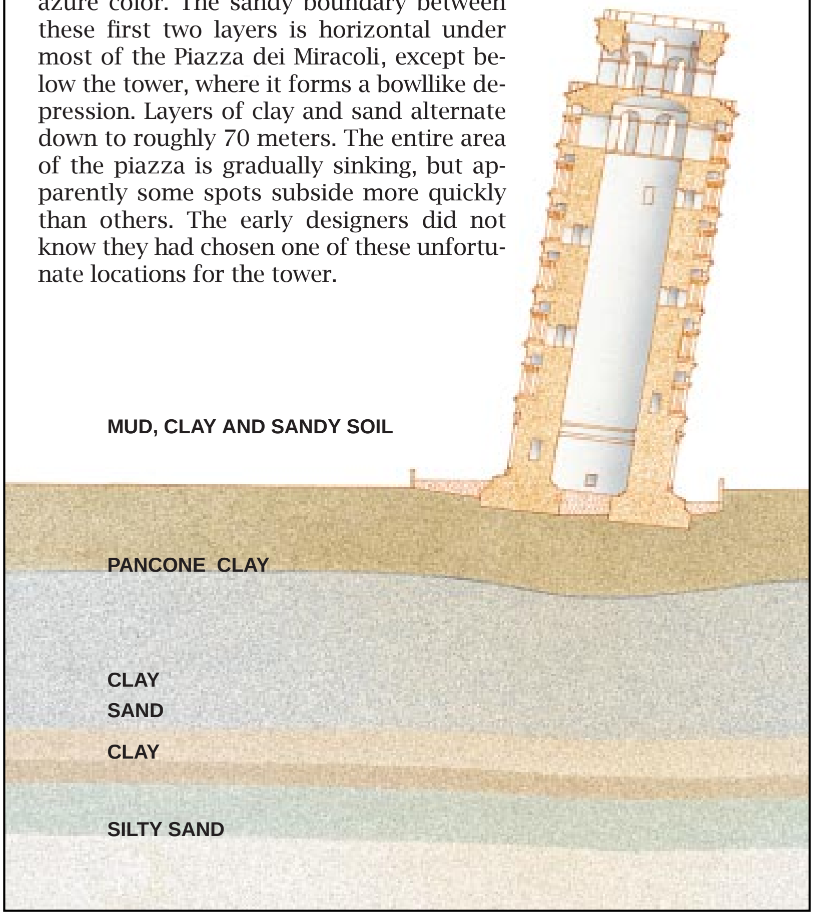


ENGRAVED BY J. CARTER; MEASURED AND DELINEATED BY EDWARD CRESY AND GEORGE L. TAYLOR

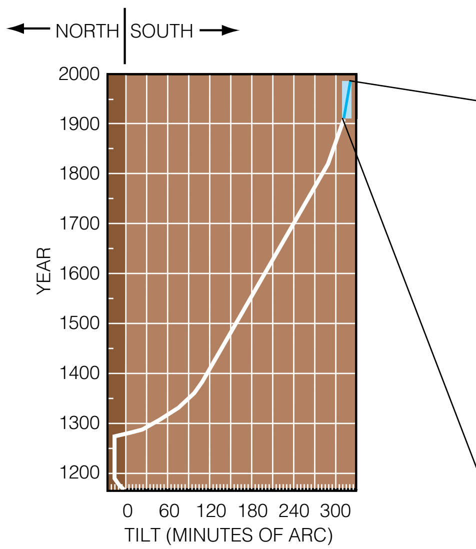
PIAZZA DEI MIRACOLI in Pisa is most famous for its leaning tower, which was built as the bell tower for the nearby cathedral. In this engraving from 1829, the top of the monument is about five meters off-center.

The foundation

Layers of clay and soil underneath the tower have compacted unevenly, leading to the monument's incline. The top seven meters or so below the structure consist of a mixture of mud, clay and sandy soil. Below that, down to about 20 meters, is a band known locally as Pancone clay, notable for its gray-azure color. The sandy boundary between these first two layers is horizontal under most of the Piazza dei Miracoli, except below the tower, where it forms a bowllike depression. Layers of clay and sand alternate down to roughly 70 meters. The entire area of the piazza is gradually sinking, but apparently some spots subside more quickly than others. The early designers did not know they had chosen one of these unfortunate locations for the tower.



TOMO NARASHIMA

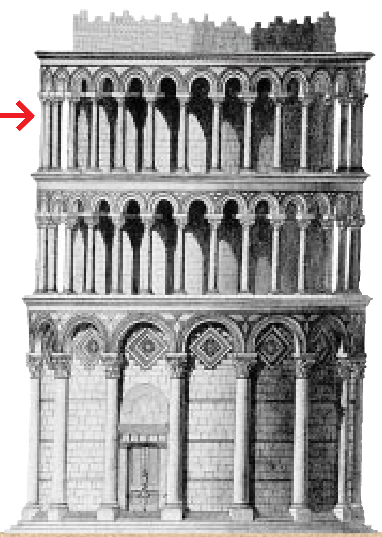


Eight centuries of lean

Initially, the tower tilted toward the north, but for most of its history, the building has leaned southward. The rate of incline was sharpest during the early part of the 14th century. Between 1911, when careful monitoring began, and 1990, the top of the tower moved at a rate of around 1.2 millimeters a year. In 1993 recent efforts to modulate the rate of incline began to take effect.

The first stage: 1173–1178

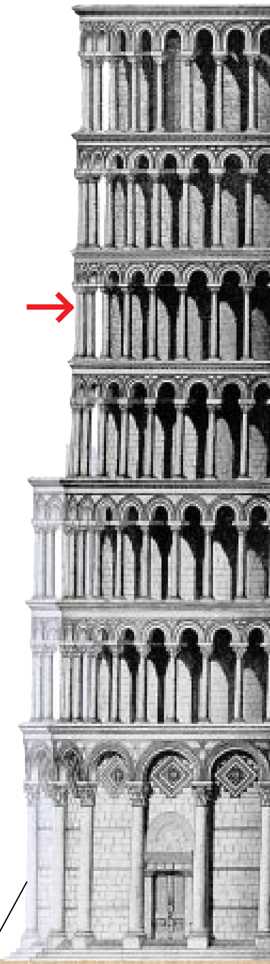
The bell tower at Pisa tilted gradually during its construction, which took place in three stages spanning nearly 200 years. The first stones were laid in 1173, and during the initial stage of work, the monument tilted slightly north. Evidence for this incline can be seen in the design of the tower itself: to keep the first few stories level, workers made the columns and arches of the third story on the sinking northern side just slightly taller than the features on the southern side. Political turmoil in Pisa halted construction in 1178, in the middle of work on the fourth level.



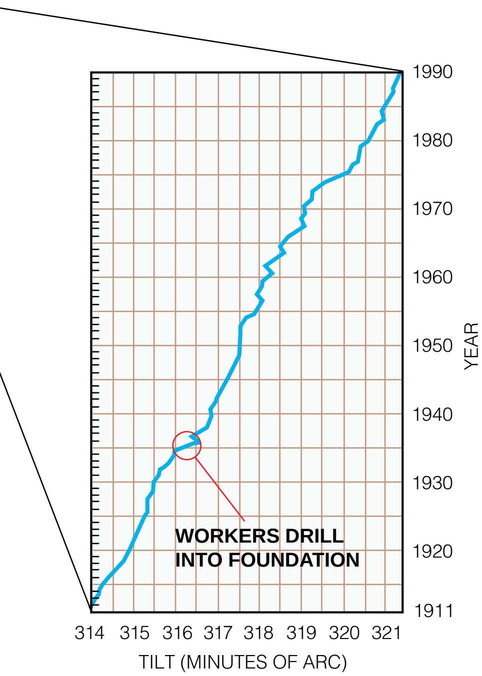
LEAN OF TOWER IN 1178

The second stage: 1272–1278

Work resumed almost 100 years later, in 1272, and by that time, the tower had tilted toward the south—the direction in which it still points today. Again, designers hoped to correct for the lean, this time by adjusting the height of the fifth story, making the southern side somewhat taller than the northern side. In 1278, with seven stories completed, work on the tower ceased once again because of political unrest. By 1292 the tower's tilt was so pronounced that a group of masons was asked to investigate the problem—the first of many commissions to study the tower appointed over the past 700 years.

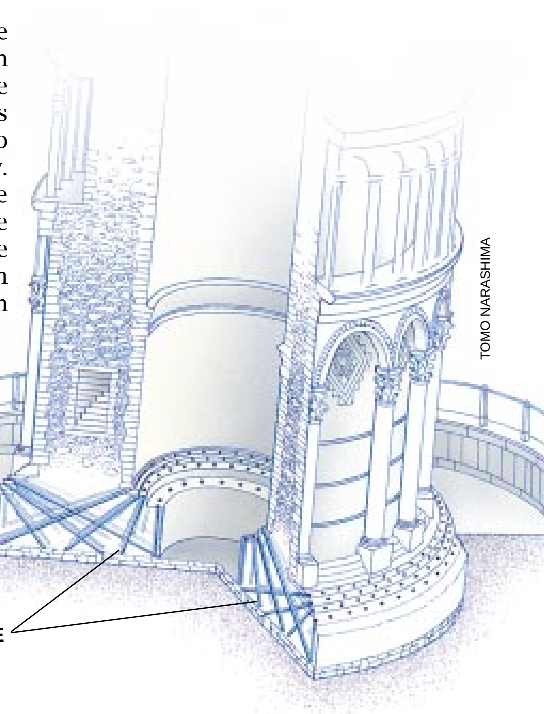


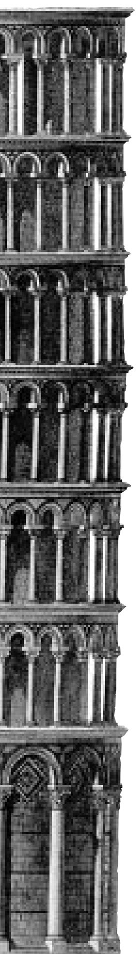
LEAN IN 1278



Sealing the tower's base

Historically, efforts to save the tower have had unintended side effects. For example, in 1935 some thought excess water under the tower weakened the foundation. So workers attempted to seal the base of the tower to prevent water from seeping in from below. The plan involved repeatedly drilling into the foundation at an angle and then filling these holes with cement grouting mixture. The effect can be seen in the graph at the left: in 1935 the rate of incline jumped to more than six times the rate of the previous year.

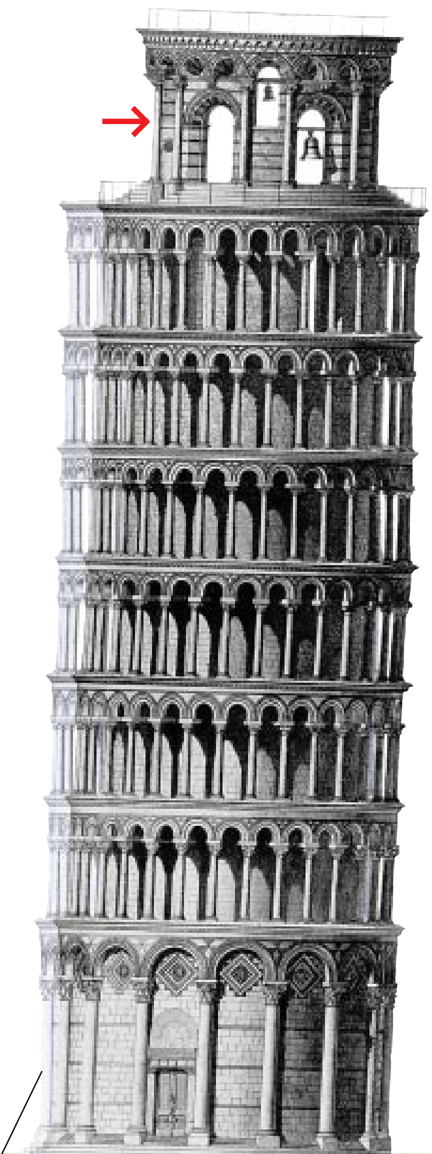




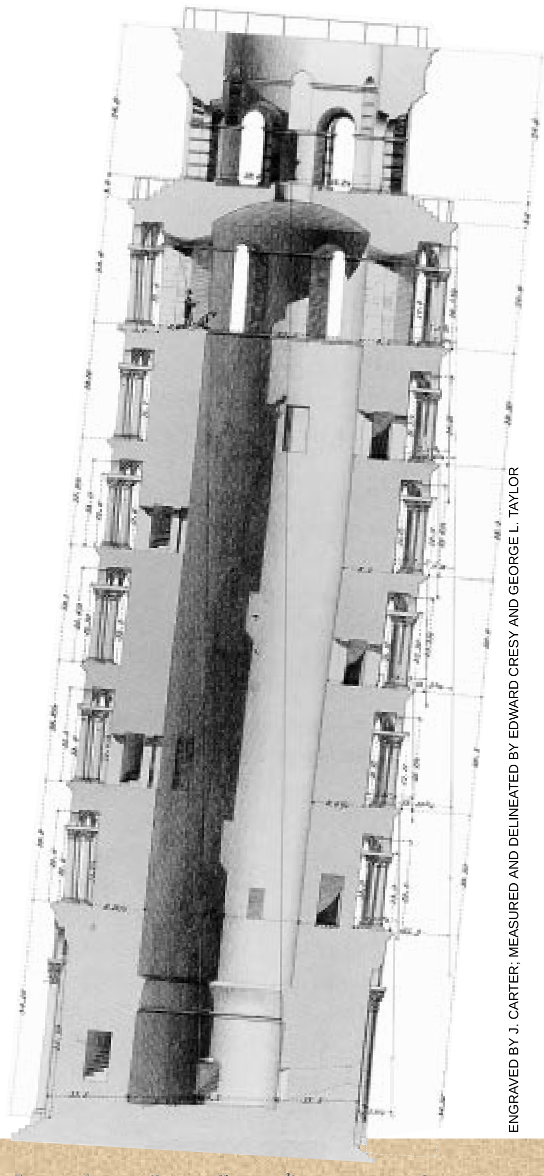
The third stage: 1360–1370

The eighth story and final addition, the bell chamber, was built between 1360 and 1370. Once more, architects attempted to correct for the southward lean, this time by angling the bell chamber northward. The various corrections by early designers can be seen best in a cross-sectional view of the tower (*shown at far right*). These efforts, combined with the slow time scale of construction (which gave the building's foundation time to compress and thereby gain strength to compensate for the slant), have so far prevented the tower from toppling over.

LEAN IN 1278



LEAN IN 1370

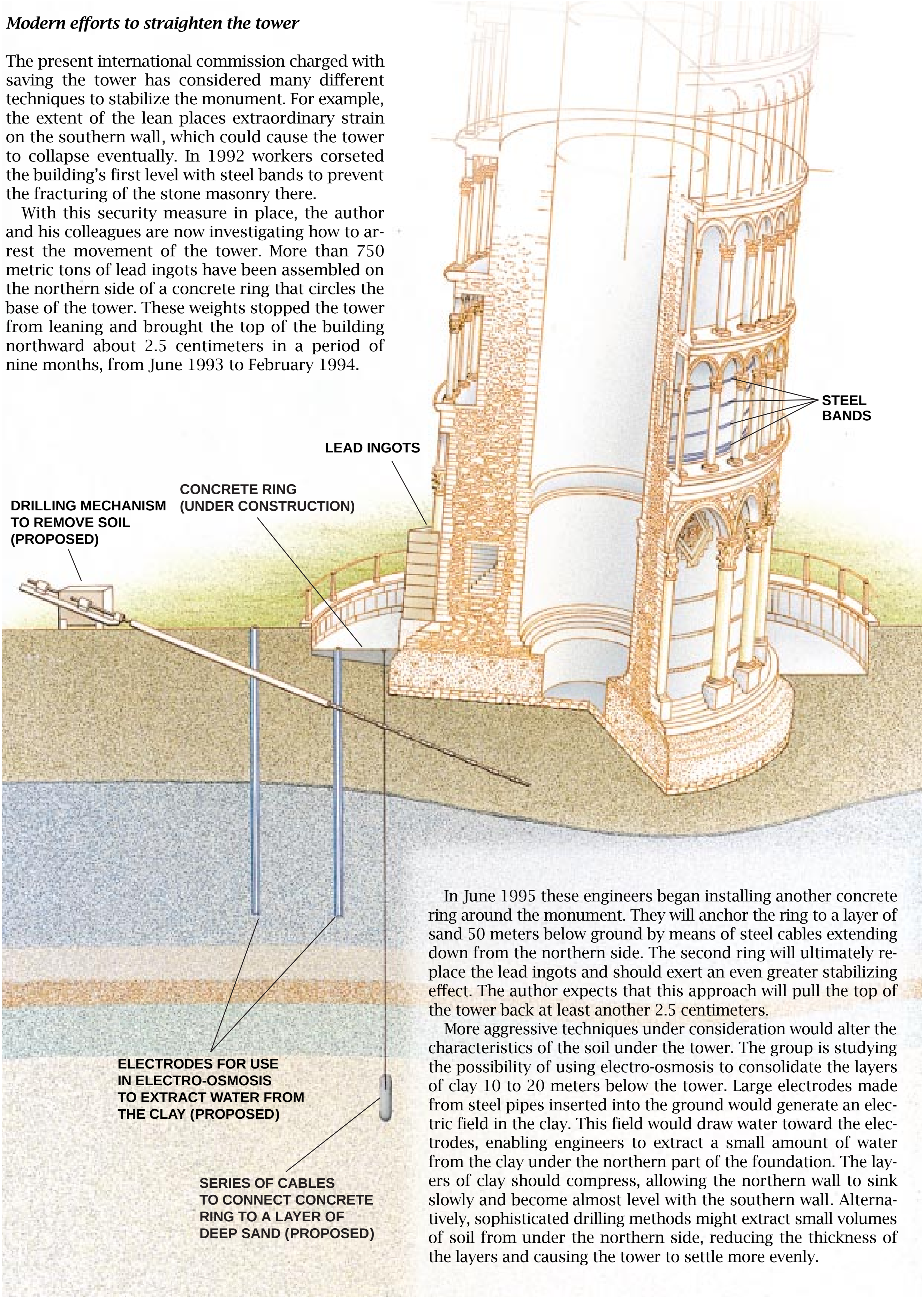


PRESENT LEAN OF TOWER

Modern efforts to straighten the tower

The present international commission charged with saving the tower has considered many different techniques to stabilize the monument. For example, the extent of the lean places extraordinary strain on the southern wall, which could cause the tower to collapse eventually. In 1992 workers corseted the building's first level with steel bands to prevent the fracturing of the stone masonry there.

With this security measure in place, the author and his colleagues are now investigating how to arrest the movement of the tower. More than 750 metric tons of lead ingots have been assembled on the northern side of a concrete ring that circles the base of the tower. These weights stopped the tower from leaning and brought the top of the building northward about 2.5 centimeters in a period of nine months, from June 1993 to February 1994.



In June 1995 these engineers began installing another concrete ring around the monument. They will anchor the ring to a layer of sand 50 meters below ground by means of steel cables extending down from the northern side. The second ring will ultimately replace the lead ingots and should exert an even greater stabilizing effect. The author expects that this approach will pull the top of the tower back at least another 2.5 centimeters.

More aggressive techniques under consideration would alter the characteristics of the soil under the tower. The group is studying the possibility of using electro-osmosis to consolidate the layers of clay 10 to 20 meters below the tower. Large electrodes made from steel pipes inserted into the ground would generate an electric field in the clay. This field would draw water toward the electrodes, enabling engineers to extract a small amount of water from the clay under the northern part of the foundation. The layers of clay should compress, allowing the northern wall to sink slowly and become almost level with the southern wall. Alternatively, sophisticated drilling methods might extract small volumes of soil from under the northern side, reducing the thickness of the layers and causing the tower to settle more evenly.

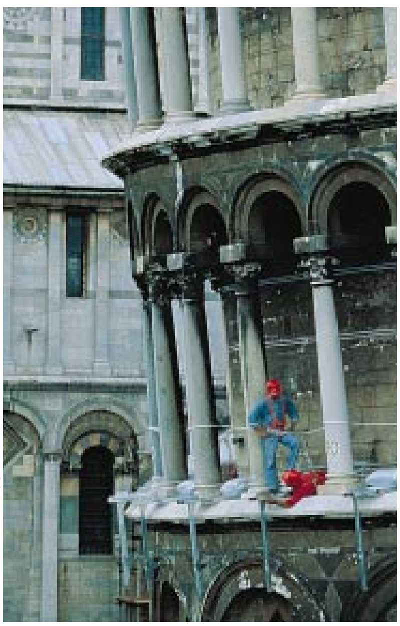
PHILIP VANOUTRIVE *SIPA*

More than 750 metric tons of lead have been placed on the northern side of the tower's base. The weights have pushed down the foundation under the northern wall, thereby straightening the tower a couple of centimeters.

The tower's interior now houses monitoring equipment that can detect small shifts in the lean. In September, for example, scientists determined that in the space of two days, the top of the tower moved southward 0.24 millimeter.

MASSIMO SESTINI *Gamma Liaison*

GIANNI GIANSANTI *Sygma*



Bands of steel embrace the second story, which is in danger of collapsing because of the pressure exerted on this part of the monument. Because of the tower's incline, much of its weight (14,700 metric tons) rests on the southern side.

MASSIMO SESTINI *Gamma Liaison*

The Author

PAOLO HEINIGER is the on-site director of the Tower of Pisa Project Consortium and has managed efforts at the monument for the past three years. He received his engineering degree from the Technical University of Milan and has worked in Italy, the Far East, the U.K. and Scandinavia on other projects related to foundation engineering. Heiniger was featured in the program *Scientific American Frontiers: Science, Italian Style.*

Editor's note: The engraved images in this article are from the book *Architecture of the Middle Ages in Italy: Illustrated by Views, Plans, Elevations, Sections, and Details, of the Cathedral, Baptistery, Leaning tower or Campanile, and Campo santo at Pisa: From Drawings and Measurements Taken in the Year 1817,* by Edward Cresy and George L. Taylor, published in London in 1829. The book was made available to *Scientific American* courtesy of the Avery Architectural and Fine Arts Library of Columbia University.

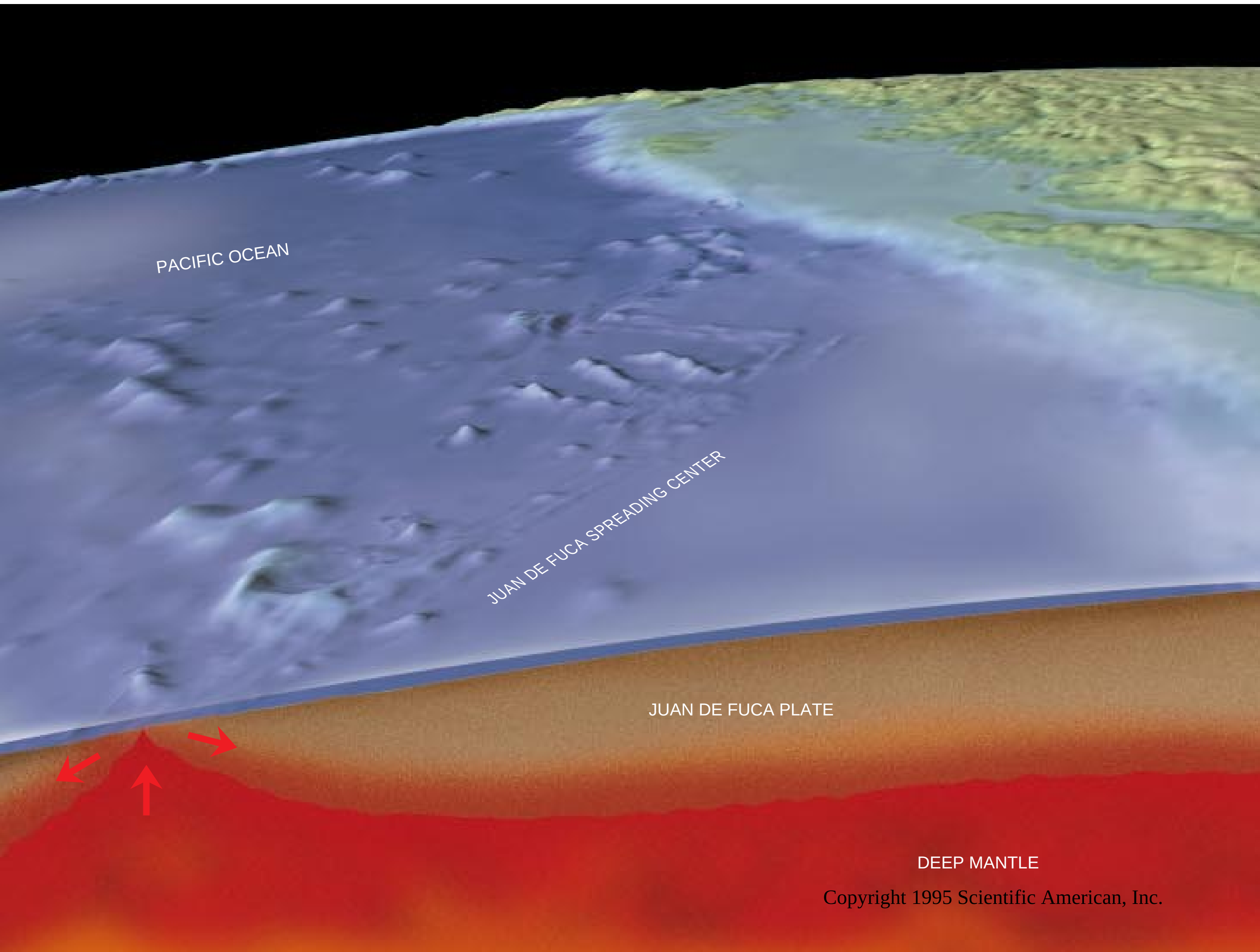
Giant Earthquakes of the Pacific Northwest

The danger of a very large earthquake striking the coast between northern California and British Columbia proves much greater than suspected

by Roy D. Hyndman

Few people question the possibility of a devastating earthquake once again hitting Los Angeles or San Francisco. The state of Alaska has also suffered some serious shaking, including, in 1964, one of the world's largest earthquakes. Until recently, however, many residents believed that the intervening territory from northernmost California to southern British Columbia (an area sometimes referred to as Cascadia) was a safer place to live. Seismologists had recognized that Vancouver and Seattle were not exactly sheltered—sizable earthquakes buffeted the region in 1946, 1949 and 1965—but no truly disastrous events had ever damaged these cities.

Yet views have changed drastically. Ten years ago Thomas H. Heaton of the U.S. Geological Survey and Garry C. Rog-



ers of the Geological Survey of Canada began warning that giant earthquakes could indeed strike this seemingly quieter stretch of coast. Initially, many scientists questioned the seriousness of the threat, but most doubters now realize that such earthquakes have happened in the past and will do so again. How could perceptions have shifted so quickly?

To understand the change in thinking requires some knowledge of the way seismologists estimate how and where powerful but infrequent earthquakes occur. For most active fault zones, the rate at which earthquakes take place decreases with increasing size in a systematic way, as was shown in the 1930s by Beno Gutenberg and Charles F. Richter. This regular pattern applies up to some maximum earthquake size—one that corresponds to a break of the entire fault zone from end to end. Using the Gutenberg-Richter relation, seismologists can gauge how often large earthquakes strike a given place even if no such events have ever been recorded. Engineers can then design buildings, dams and other structures accordingly.

In a few areas, this strategy fails. Sizable earthquakes can hit without small ones, presenting seismologists with a vexing problem: How can the danger from large earthquakes be reasonably defined? This difficulty applies to Cascadia, where one of the tectonic plates underlying the Pacific Ocean thrusts underneath the coast of western North America in a process termed subduction. Although regional seismic activity can be quite intense in some areas inland of this coast, no earthquakes of any size have been detected where most of the motion is seemingly focused—on the main thrust fault that separates the Juan de Fuca plate from the North American continent.

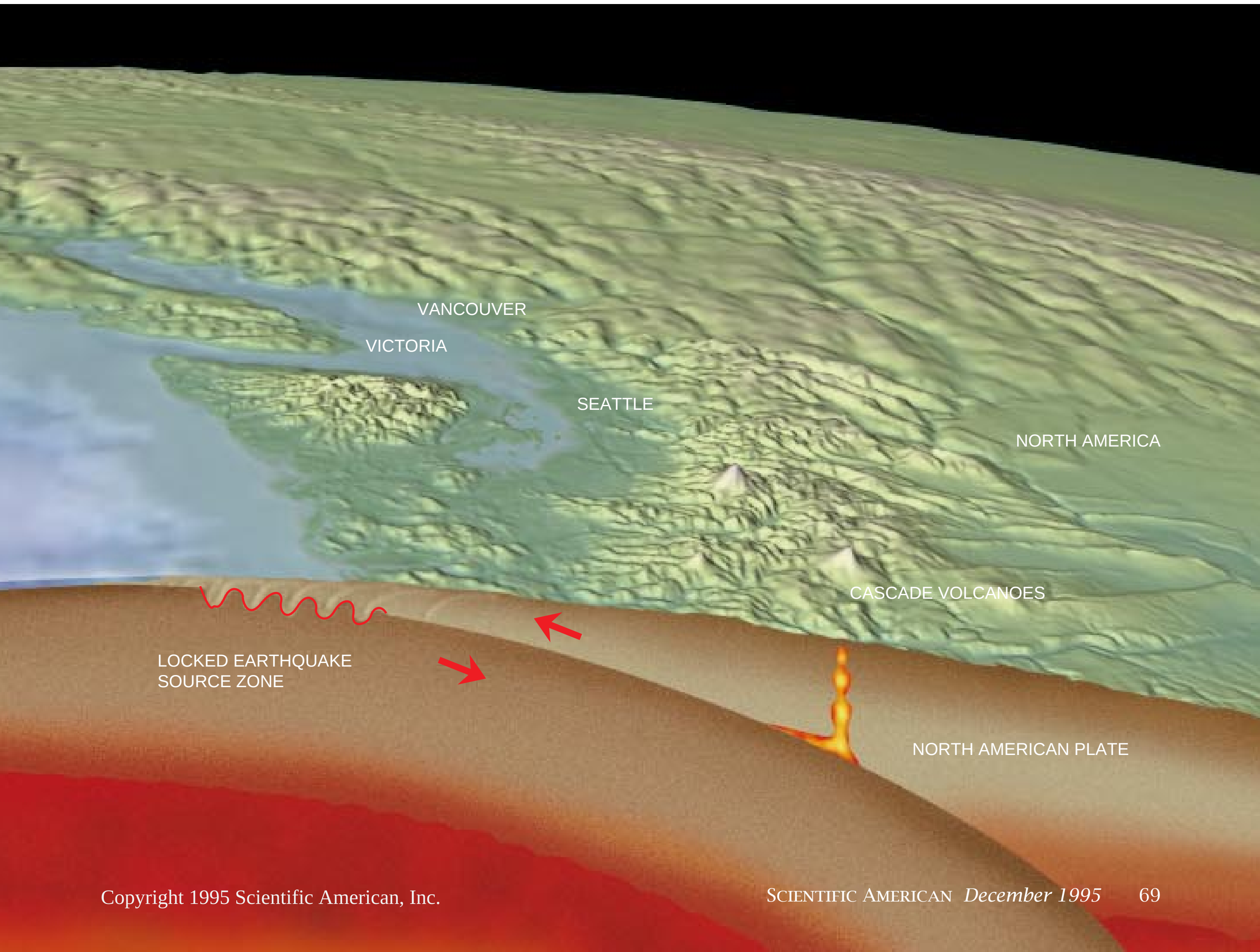
In global perspective, the lack of such thrust earthquakes is surprising. Most subduction zones have experienced great thrust events (defined as those having a Richter magnitude higher than 8) at some time. These earthquakes are especially concentrated around the rim of the Pacific Ocean in an vast band called the ring of fire—a name that comes from the lines of active volcanoes that lie landward of where the oceanic crust dives into the earth's mantle.

No Large Earthquakes?

There are several possible explanations for the absence of major subduction earthquakes. Although the Cascadia part of western North America has many of the characteristics of a subduc-

DIGITAL COMPOSITION BY WILLIAM HAXBY AND LAURIE GRACE

TECTONIC PLATE created at the Pacific's Juan de Fuca spreading center travels laterally (*arrows indicate motion*) before it dives below the western coast of North America. Part of the fault that separates the two tectonic plates remains locked, causing the continent near the coast to bend elastically as stress accumulates. When the fault finally releases this stored energy, a giant earthquake may ensue.



UPI/Bettmann

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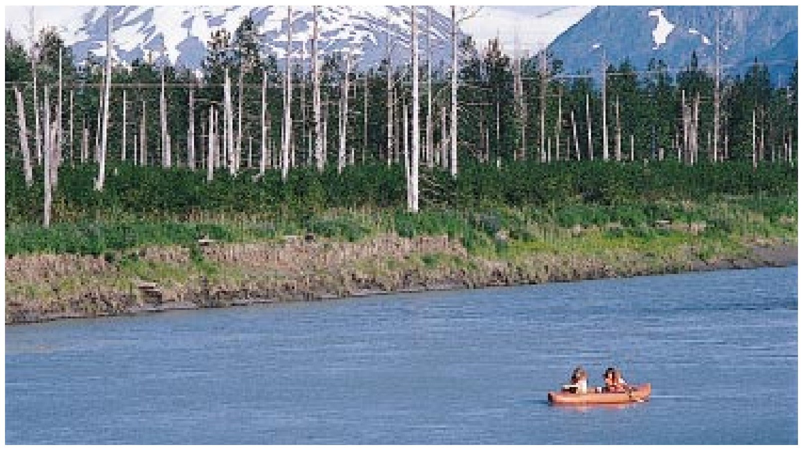


Third Eye Photo Alaska Stock

ALASKA suffered widespread devastation in 1964, when a giant thrust earthquake struck on Good Friday. Much of Anchorage (*top right*) was damaged by the ground motion, and coastal sites around Seward (*above*) were inundated by water and mud. The southern coast of Alaska still shows the effects of this great earthquake in the many trees killed when the ground subsided (*bottom right*), allowing saltwater to drown their roots.

tion zone, the Juan de Fuca plate may have stopped moving toward North America in geologically recent times. Twenty years ago, when geologists first debated this question, my colleague at the Pacific Geoscience Center Robin P. Riddihough and I wrote an article making the case that convergence and underthrusting are indeed continuing. The work of many researchers has since confirmed that the Juan de Fuca plate has not made a sudden stop. Persuasive evidence for continued motion comes from the study of sediments lying underwater at the base of the continental slope. These muds and sands were laid down in the deep sea as flat layers, but even the most recent deposits are found to be highly contorted. The North American continent, acting as a giant bulldozer blade, has scraped them off the oceanic crust and left them as crumpled evidence of continuing subduction.

Perhaps the most dramatic evidence for ongoing subduction came in 1980 with the volcanic eruption of Mount St. Helens in southwest Washington State. Scientists have recognized for many years that such volcanoes are a consequence of subduction. Some geologists had thought the Cascade volcanoes were dormant. But this volcanic cataclysm left little doubt that the Cascadia coast is indeed an active part of the ring of fire.

To reconcile the plates' convergence with the absence of thrust events, some scientists have supposed that the downward push below the coast involves a smooth, stable slide, not the jerky "stick-slip" behavior that generates earthquakes. The alternative explanation is that the fault between them is truly locked (the friction being large enough to hold the two plates firmly together), so that there is not enough movement to generate even small earthquakes. If the fault is freely sliding, the chance of large thrust earthquakes is slim. But if the fault is locked, the plate convergence must be accommodated by the silent but deadly buildup of strain in the rocks around the fault, the makings of a significant earthquake.

The lack of substantial earthquakes in the historical record might at first seem to favor the idea that the fault is slipping quietly. That interpretation, however, neglects the brevity of the record along this coast. Only a little more than 200 years ago did the explorers Juan Perez and James Cook first visit the region. The limited written history contrasts markedly with the span of Japanese records describing many large subduction earthquakes and the so-called harbor waves ("tsunamis") that usually resulted from them. That detailed archive extends back to the seventh century.

When Was the Last One?

To probe those times before Europeans arrived on these shores, researchers have sought traces of past earthquakes in the geologic record. They found some telltale evidence in sheltered inlets where salt marshes form between high and low tide. Excavations of these coastal marshes uncovered a remarkable record. Brian F. Atwater of the U.S. Geological Survey was first to show that distinct layers below the present marsh (spaced at successive depths of about a meter) contain peat that is made of the remains of vegetation identical to the flora now living in the intertidal zone. He concluded that each peat deposit constitutes a former marsh that was buried when the ground abruptly dropped with the release of strain in a sizable earthquake.

What makes his interpretation even more convincing is that many of the buried peat layers are covered by sand washed in by the huge tsunamis that rushed onto the subsided coast. Theoretical modeling as well as preserved geologic effects on the shoreline indicates that these waves attained heights of 10 meters on the open coast and much higher still in some confined inlets.

After the tsunamis dissipated, mud slowly filled the subsided region, and the marsh vegetation returned. Thus, the repeated sequences of peat, sand and mud clearly demonstrate that large earthquakes have plagued the region in the past. But how long ago were these prehistoric upheavals? The ages of the peat layers are difficult to determine precisely, but coastal fir trees have been found that were drowned by the ocean after the land abruptly subsided. By examining growth rings and measuring radiocarbon in these trees, researchers have estimated that they died in the last great earthquake, which hit the area about 300 years ago. Before that, similar events struck at irregular intervals of about 500 years.

This conclusion is also supported by unusual deposits found far out on the floor of the ocean. Scientists at the University of Oregon have sampled seafloor sediments in long core tubes and found fine-grained muds alternating with sandier layers. Mud is typical of the deep sea bottom; it accumulates from the slow, continuous rain of fine sediment settling from the ocean above. The sandier sediments, however, are strange to find far from shore. John Adams of the Geological Survey of Canada provided an explanation: energetic earthquakes could have triggered huge submarine landslides that carried coastal sediments down the continental slope and out onto the deep ocean floor.

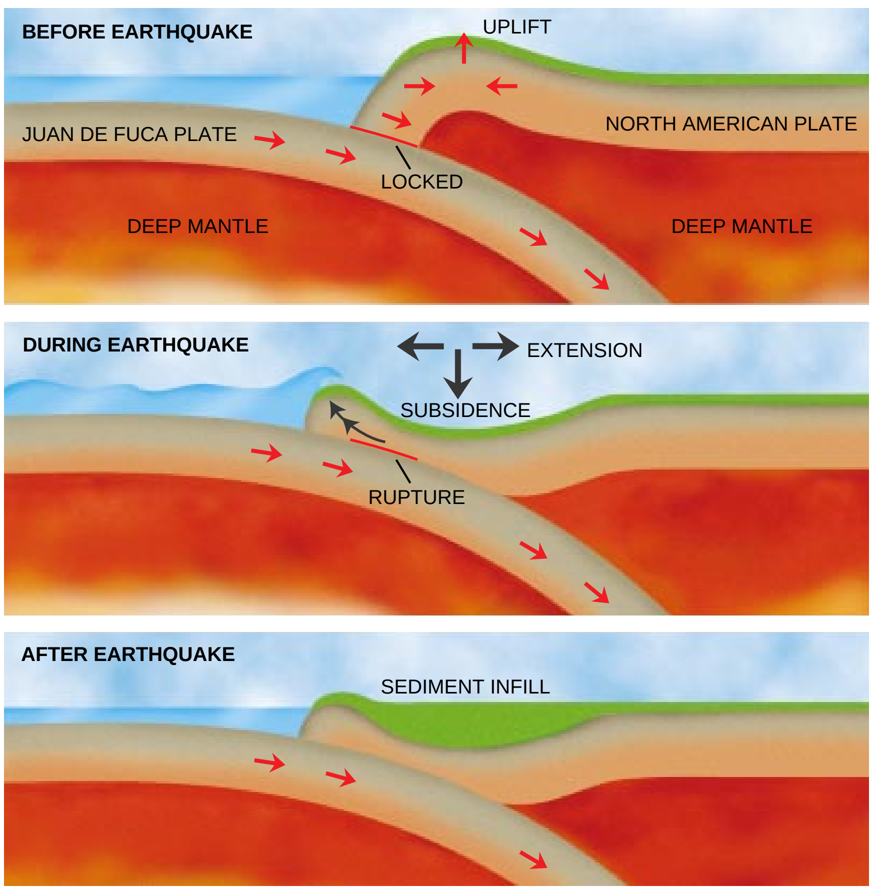
The timing of the events is hard to judge from the sediments, but a peculiar deposit found near the base of some of the cores gives an important clue. This layer contains volcanic ash from the eruption of the former Mount Mazama in Oregon (now known as Crater Lake). That colossal explosion—similar to the recent Mount St. Helens blast—happened 7,700 years ago. Assuming that the rain of mud onto the seafloor was steady, the chronology for these earthquakes proves similar to the results from coastal peat deposits. The most recent event happened about 300 years ago, and the 12 previous submarine landslides were separated by 300 to 900 years.

A clever strategy may pinpoint the time of the most recent earthquake even more precisely. Tsunamis generated by Cascadia earthquakes with magnitudes near 9 should be large enough to be noticed in Japan even after traveling across the Pacific Ocean. Recognizing this fact, Kenji Satake and his colleagues at the Geological Survey of Japan think they have found the written record: a two-meter-high tsunami that washed onto the coast of Honshu nearly 300 years ago. After correcting for the time the wave would have taken to travel to Japan (and the time zone change), Satake determined that the earthquake occurred along the North American coast on January 26, 1700, at about 9 P.M.

Remarkably, that detective work agrees with reports of a disaster preserved in the oral history of the original residents of British Columbia. My colleague Rogers found what may be a description of this event in the provincial archives in Victoria. Native tradition records that an earthquake struck Pachena Bay on the west coast of Vancouver Island one winter night; in the morning the village at the head of the bay was gone. Gary A. Carver of Humboldt State University uncovered a similar account in the unwritten lore of northernmost California. Thus, native stories, Japanese writings and sedimentary deposits all point to the inevitable conclusion that giant earthquakes do in fact haunt the Cascadia coast.

The Great Earthquake Cycle

Like all earthquakes, large subduction zone events prove complex when considered in detail. The basic process, however, follows the simple "elastic rebound" theory first developed for the notorious San Andreas fault in California. According to this concept, ongoing movement between two plates compresses and bends the crust as stress accumulates. Contrary to the illusion of the earth being made of rigid and solid rock, the contraction is nearly elastic. If not squeezed too much, the earth acts



LAURIE GRACE

FLEXING like a board bent over the edge of a table, the North American plate develops an inland bulge as its western margin is pulled downward by the oceanic slab (*top*). After an earthquake releases the stress, the bulge collapses (*middle*), forcing much of the coastal region to subside and fill with sediment (*bottom*).

Historical Precedents

The native Yurok people who occupied the coastal region personified natural powers such as earthquakes and thunder in their lore. This excerpt from an interview recorded by A. L. Kroeber in *Yurok Myths* describes what perhaps were relatively recent earthquakes:

> And from there [Earthquake and Thunder] went south.... They went south first and sank the ground.... Every little while there would be an earthquake, then another earthquake, and another earthquake.... And then the water would fill those [depressed] places.... "That is what human beings will thrive on," said Earthquake. "For they would have no subsistence if there were nothing for the creatures [of the sea] to live in. For that is where they will obtain what they will subsist on, when this prairie has become water, this stretch that was prairie: there will be ocean there."..."Yes, that is true. That is true. That is how they will subsist," said Thunder. "Now go north." Then they went north together and did the same: they kept sinking the ground. The earth would quake and quake and quake again. And the water was flowing all over.

EDWARD SHERIFF CURTIS *Courtesy of the American Museum of Natural History*

NOOTKA of Vancouver Island and other Native American tribes of the region were susceptible to tsunami disasters.

HOKUSAI *Bettmann Archive*

TSUNAMIS generated from giant earthquakes in western North America would be large enough to travel across the Pacific and strike Japan. The wave that washed over the island of Honshu in January 1700 may have had such a distant origin.

ROY D. HYNDMAN

BURIED PEAT (*brown layer at right*) lying below coastal marshes attests to a past earthquake. Such deposits formed when the surface of the land dropped suddenly, and tsunamis washed into the subsided region, burying the intertidal vegetation in sand. Mud then filled the remaining depression before plants once again established themselves on the new surface. A series of peat layers lie below.

like a gigantic piece of rubber. Eventually, however, the tectonic forces become so extreme that they exceed the hold of friction along the fault. The surface slips abruptly, and the elastic energy that was stored over many years radiates outward as ground-shaking earthquake waves. The fault then locks once more, and the cycle of tectonic stress buildup and release resumes.

Along the Cascadia subduction zone, the oceanic Juan de Fuca plate encroaches on North America by about 40 millimeters a year. This progress may seem slow, but it represents a considerable shortening—about 20 meters in a typical 500-year-long stretch between giant earthquakes. The motion is taken up by elastic shortening distributed across a swath several hundred kilometers wide. But the tectonic stresses cause more than just horizontal contraction—the ground moves vertically, too. As the oceanic plate dives under the coast, it drags the seaward nose of the continent downward and causes parts of the North American plate further inland to flex upward; this process mimics the bending of a long board over the edge of a table—as the front is forced down, a bulge forms behind. When a large earthquake breaks the locked fault, the seaward part of the continent springs back, and the bulge collapses. The abrupt rise of the outer continental shelf generates tsunamis, and the sudden fall of the "flexural bulge" centered near the coast causes the drop that buries intertidal salt marshes.

The position of the locked zone proves especially important because this surface becomes the source of seismic-wave energy when the fault eventually gives way in an earthquake. The landward limit of the earthquake source zone affects how closely the earthquake will impinge on the larger population centers; the seaward edge controls where tsunamis will develop. The total width of the source zone influences the seismic hazard because it sets the maximum size of the earthquake.

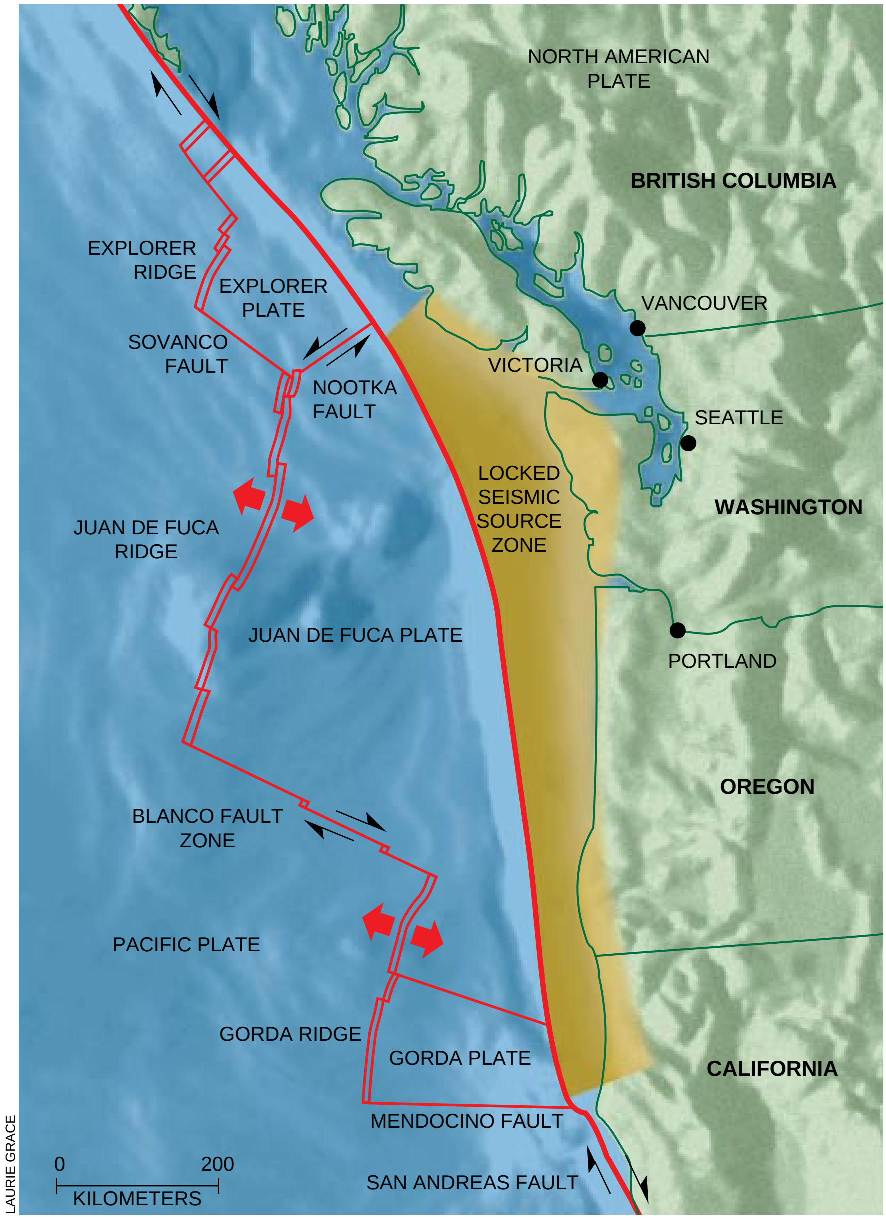
Scientists can determine the extent of the locked zone from the form of crustal deformation. If the locked zone is narrow, extending only a short distance down the inclined fault, the region of elastic bending will also be quite restricted. Conversely, if the locked zone runs appreciably farther down, the bending deformation will reach a long distance inland. Land surveying can thus help to map out the earthquake hazard. The rates of deformation are only a few millimeters a year, but they can be resolved with modern surveying techniques if the measurements are applied with exceptional care.

Watching the Strain Build Up

Several different kinds of observations repeated over time define how the Cascadia margin is currently deforming. Geophysicists can follow the horizontal shortening of the coastal region by measuring, for example, the distance between surveyors' benchmarks on mountaintops using a laser ranging device. This feat requires a good deal of care and plenty of clear sky (not common in the rainy West Coast mountains). Using this technique, James C. Savage and his colleagues at the U.S. Geological Survey first reported in 1981 that the crust near Seattle was shortening perpendicular to the coast. They concluded that strain was building toward an appreciable earthquake.

Some survey methods are sufficiently sensitive to vertical motion. The most simple of these, known as leveling, employs the same technique one sees being used along highways. Surveyors take sightings on calibrated rods to measure the difference in elevation between two places. By combining the measured offsets, surveyors can determine relative heights throughout a network of connected points spread over large distances. Repeated surveys after several years yield the uplift or subsidence of one position with respect to another. The Geodetic Survey Canada has, for instance, carried out several surveys of exceptional accuracy specifically to study earthquake-related uplift. One of these field experiments tracked back and forth across the width of Vancouver Island (about 100 kilometers each way) in a series of sightings, each of 100 meters or so. The complete circuit had a total vertical error limited to only one centimeter.

Another method makes use of tide gauges that track the level of the sea relative to coastal bedrock. The primary purpose of these devices is to monitor the ocean, but surprisingly, with gauges that have been recording for 20 years or more, it is possible to use the average



CONVERGING PLATES are locked together over a confined region of the thrust fault under the coast. The extent of this locked zone is limited on its western side because clays deposited on the surface of the downgoing oceanic crust help to lubricate the fault. To the east, the locked zone gradually fades to the point where the deeply buried fault slides freely because of elevated temperatures.

TRIMBLE

JAMES C. SAVAGE *U.S. Geological Survey*

DEFORMING CRUST changes shape extremely slowly, but careful measurements can track the subtle movements of the ground. Using a laser range finder between mountaintops (*top*), scientists were able to measure horizontal contraction in the region more than a decade ago, but modern instruments that use the Global Positioning System of satellites (*left*) have eased the task of conducting precision surveys.

level of the sea surface as a reference and to trace subtle vertical shifts of the land. The record must, of course, be long enough to smooth over tides and other oceanographic variations, such as El Niño, that can endure for years. One also needs to account for the steady global rise in sea level (of about two millimeters per year) and to correct for postglacial rebound, the slow but continuing rise of crust initially pushed downward under the weight of glaciers from the last ice age.

Yet a third way to detect vertical motion is by using gravity, a force that varies with the square of the distance from the center of the earth. Although it is impossible for people to sense the slight shifts in their weight when they change altitude, sensitive instruments can register these variations. By repeatedly measuring gravity at one spot every few years, geophysicists have been able to estimate the rate of coastal uplift.

During the past few years, the satellite-based Global Positioning System (GPS) has permitted scientists to measure distances and vertical offset between sites spaced hundreds of kilometers apart. Herb Dragert and Michael Schmidt of the Geological Survey of Canada have used GPS to show that every year coastal Victoria shifts nearly a centimeter closer to Penticton (a locale some 300 kilometers inland). GPS is accurate and inexpensive and in the future may prove the most effective technique for keeping track of the subtle bending and squeezing of the earth's crust that leads to earthquakes.

All these methods give similar results: the Cascadia margin currently rises by one to four millimeters a year, and it also contracts horizontally by several centimeters every year. This deformation—direct evidence that the crust is being squeezed between converging plates—registers the slow but relentless accumulation of strain that is building toward the next catastrophic release.

A Troublemaker Locked Up

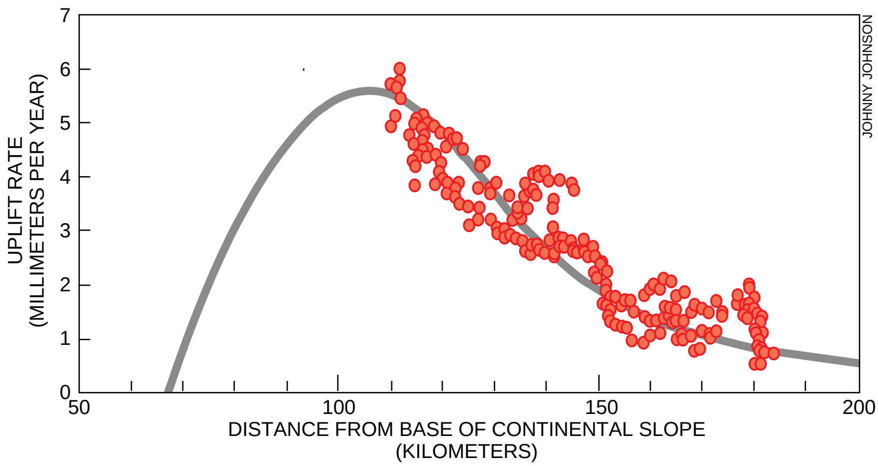
Because knowing the position of the locked part of a fault is so critical to defining earthquake risk, my colleagues at the Pacific Geoscience Center and I have tried to determine the extent of the locked zone by comparing survey measurements with mathematical models of the deformation. Fitting the observations to theory allowed us to map the width of the locked zone deep below the earth's surface. The actual situation is somewhat more complex than this simple conceptualization: at the deeper, landward boundary of the locked zone, there is a gradual transition between areas that are rigidly locked and those that are completely free-sliding.

The comparison between our data and models shows that for most of the Cascadia coast the locked zone is restricted to a swath 50 to 100 kilometers across that runs underneath the continental shelf. (It widens considerably only near the coast of northern Washington.) This surface represents a huge fault area with potential for enormous earthquakes. Yet, curiously, it is unusually narrow compared with other subduction zones.

Such differences prompted us to examine which attributes of the geology influence the width of the locked zone. Many factors may contribute, but temperature plays a dominant role. For example, the clay-rich sediments that blanket the oceanic plate may act to lubricate the seaward, "up-dip" edge of the fault; as the ooze becomes more deeply buried, however, the clays chemically alter into stronger minerals that prevent the fault from sliding. This change happens at a depth of 10 kilometers or so, where the temperature reaches about 150 degrees Celsius.

Temperature also appears to control the landward, "down-dip" limit of the locked zone. At moderate temperatures the rocks show normal frictional behavior. That is, the large initial resistance to motion drops to a lesser level once the fault begins to slip. So, once sliding starts, runaway release of the stored elastic energy—an earthquake—ensues. But lower in the crust, where the temperature exceeds about 350 degrees C, the rocks lining the fault surface should behave more like a viscous fluid—faster motion meets with increasing resistance. Hence, the deeper, hotter parts of the fault are apt to creep along slowly without generating any seismic waves.

How well do these temperature limits correspond to the actual boundaries of the locked zone? My colleagues and I have tried to provide the answer by using our computer models to calculate temperatures on the subduction thrust fault. The results of that work confirmed what we had surmised. The depth on the fault where the rocks reach 350 degrees C agrees well with the down-dip limit of the locked zone as determined from the measurements of deformation.



COASTAL UPLIFT in Cascadia is documented by repeated leveling surveys (*dots*). The data match theoretical predictions (*solid line*) for the bending of the North American plate and serve to locate the locked part of the subduction fault.

One important question remains: Does the locked zone that we have calculated truly correspond to the source area for large subduction earthquakes? We believe it does because the vertical drop we predict for a rupture of the locked zone matches what has been observed in the buried coastal marshes. Further support comes from our efforts to apply the same techniques to other subducting margins. My colleague Kelin Wang and I, along with Makoto Yamano of the University of Tokyo, have shown that the width of the present locked zone on the Nankai margin of southwest Japan corresponds well to the rupture areas of the magnitude 8 earthquakes that struck there in the 1940s. So we can be confident that our models for Cascadia are telling us about the kind of devastating earthquakes that will eventually strike along the North American coast.

When the Big One Hits

How intensely would the ground shake at the major West Coast cities during a giant subduction earthquake? The answer rests on the exact earthquake magnitude as well as on the position of the seismic source zone. The maximum magnitude that a Cascadia earthquake could achieve depends on just how far along the coast the fault releases. Simultaneous rupture of the entire stretch from British Columbia to California would be surprising because such extended breaks have been rare anywhere in the world. Yet some evidence points to a failure of this size having occurred during the Cascadia earthquake of 1700. If the total locked zone (an area of nearly 100,000 square kilometers) releases at once, a giant earthquake of magnitude 9 could result—much larger, for example, than the catastrophic San Francisco earthquake of 1906. There have been only two events of this size ever recorded: an earthquake along the coast of Chile in 1960 and the other in southern Alaska in 1964.

Seismologists can estimate the amount of ground motion that might come from such Cascadia earthquakes in two ways. One approach is to compare the situation along North America's western coast with earthquakes that have occurred elsewhere. The other method is to use rather complicated theoretical models of the seismic rupture area and slip displacement. Either way the conclusions are similar. The next great earthquake in Cascadia will generate extremely large seismic waves lasting for as long as several minutes. After the shaking ceases, most coastal sites will be one to two meters lower and five to 10 meters seaward of where they started.

Fortunately, the locked part of the fault that would generate such earthquakes lies primarily under the continental shelf and extends little, if at all, below the coast. Hence, Vancouver, Seattle and Portland (which sit 100 to 200 kilometers inland) are subject to less severe shaking than sites near the outer western coast. Nevertheless, the seismic energy from such violent earthquakes radiates for a considerable distance, so the danger to those cities is still substantial. U.S. and Canadian residents of this Pacific coastal region who had imagined they lived on quiet ground will indeed have to learn to accept the threat of a giant earthquake upheaval happening at any moment.

The Author

ROY D. HYNDMAN is a senior research scientist at the Pacific Geoscience Center of the Geological Survey of Canada; he is also an adjunct professor at the University of Victoria in British Columbia. After receiving a Ph.D. degree in geophysics from Australian National University in 1967, Hyndman split his research efforts between studies of the ocean floor and of continental interiors. In recent years, he has reconciled the two interests that had divided his attention by focusing on the boundary between land and sea, particularly in the area of subduction zones. Hyndman has participated in research cruises to all of the world's oceans. He is a fellow of the Royal Society of Canada and is president of the Canadian Geophysical Union.

Further Reading

SEISMIC POTENTIAL OF THE CASCADIA SUBDUCTION ZONE. Garry C. Rogers in *Nature,* Vol. 332, page 17; March 3, 1988.

CASCADIA SUBDUCTION ZONE: THE CALM BEFORE THE QUAKE? Thomas H. Heaton in *Nature,* Vol. 343, pages 511–512; February 8, 1990.

THERMAL CONSTRAINTS ON THE ZONE OF MAJOR THRUST EARTHQUAKE FAILURE: THE CASCADIA SUBDUCTION ZONE. R. B. Hyndman and K. Wang in *Journal of Geophysical Research (Solid Earth),* Vol. 98, No. 2, pages 2039–2060; February 10, 1993.

CURRENT DEFORMATION AND THE WIDTH OF THE SEISMOGENIC ZONE OF THE NORTHERN CASCADIA SUBDUCTION THRUST. H. Dragert et al. in *Journal of Geophysical Research (Solid Earth),* Vol. 99, No. 1, pages 653–668; January 10, 1994.

How Breast Milk Protects Newborns

Some of the molecules and cells in human milk actively help infants stave off infection

by Jack Newman

Doctors have long known that infants who are breast-fed contract fewer infections than do those who are given formula. Until fairly recently, most physicians presumed that breast-fed children fared better simply because milk supplied directly from the breast is free of bacteria. Formula, which must often be mixed with water and placed in bottles, can become contaminated easily. Yet even infants who receive sterilized formula suffer from more meningitis and infection of the gut, ear, respiratory tract and urinary tract than do breast-fed youngsters.

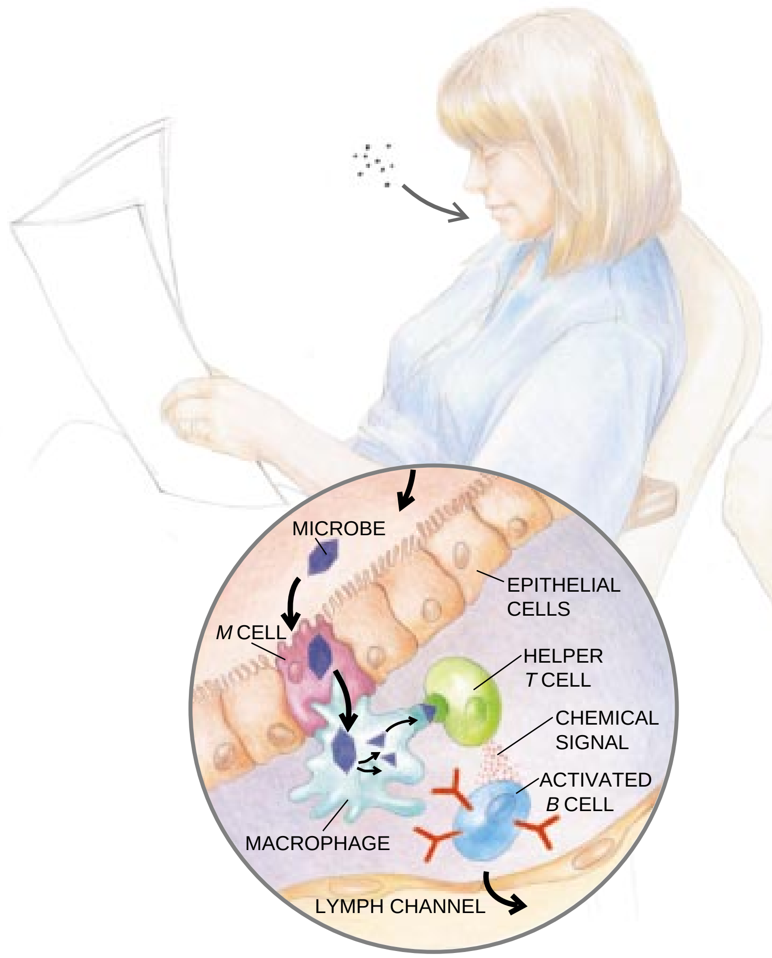
The reason, it turns out, is that mother's milk actively helps newborns avoid disease in a variety of ways. Such assistance is particularly beneficial during the first few months of life, when an infant often cannot mount an effective immune response against foreign organisms. And although it is not the norm in most industrial cultures, UNICEF and the World Health Organization both advise breast-feeding to "two years and beyond." Indeed, a child's immune response does not reach its full strength until age five or so.

All human babies receive some coverage in advance of birth. During pregnancy, the mother passes antibodies to her fetus through the placenta. These proteins circulate in the infant's blood for weeks to months after birth, neutralizing microbes or marking them for destruction by phagocytes—immune cells that consume and break down bacteria, viruses and cellular debris. But breast-fed infants gain extra protection from antibodies, other proteins and immune cells in human milk.

Once ingested, these molecules and cells help to prevent microorganisms from penetrating the body's tissues. Some of the molecules bind to microbes in the hollow space (lumen) of the gastrointestinal tract. In this way, they block microbes from attaching to and crossing through the mucosa—the layer of cells, also known as the epithelium, that lines the digestive tract and other body cavities. Other molecules lessen the supply of particular minerals and vitamins that harmful bacteria need to survive in the digestive tract. Certain immune cells in human milk are phagocytes that attack microbes directly. Another set produces chemicals that invigorate the infant's own immune response.

Breast Milk Antibodies

Antibodies, which are also called immunoglobulins, take five basic forms, denoted as IgG, IgA, IgM, IgD and IgE. All have been found in human milk, but by far the most abundant type is IgA, specifically the form known as secretory IgA, which is found in great amounts throughout the



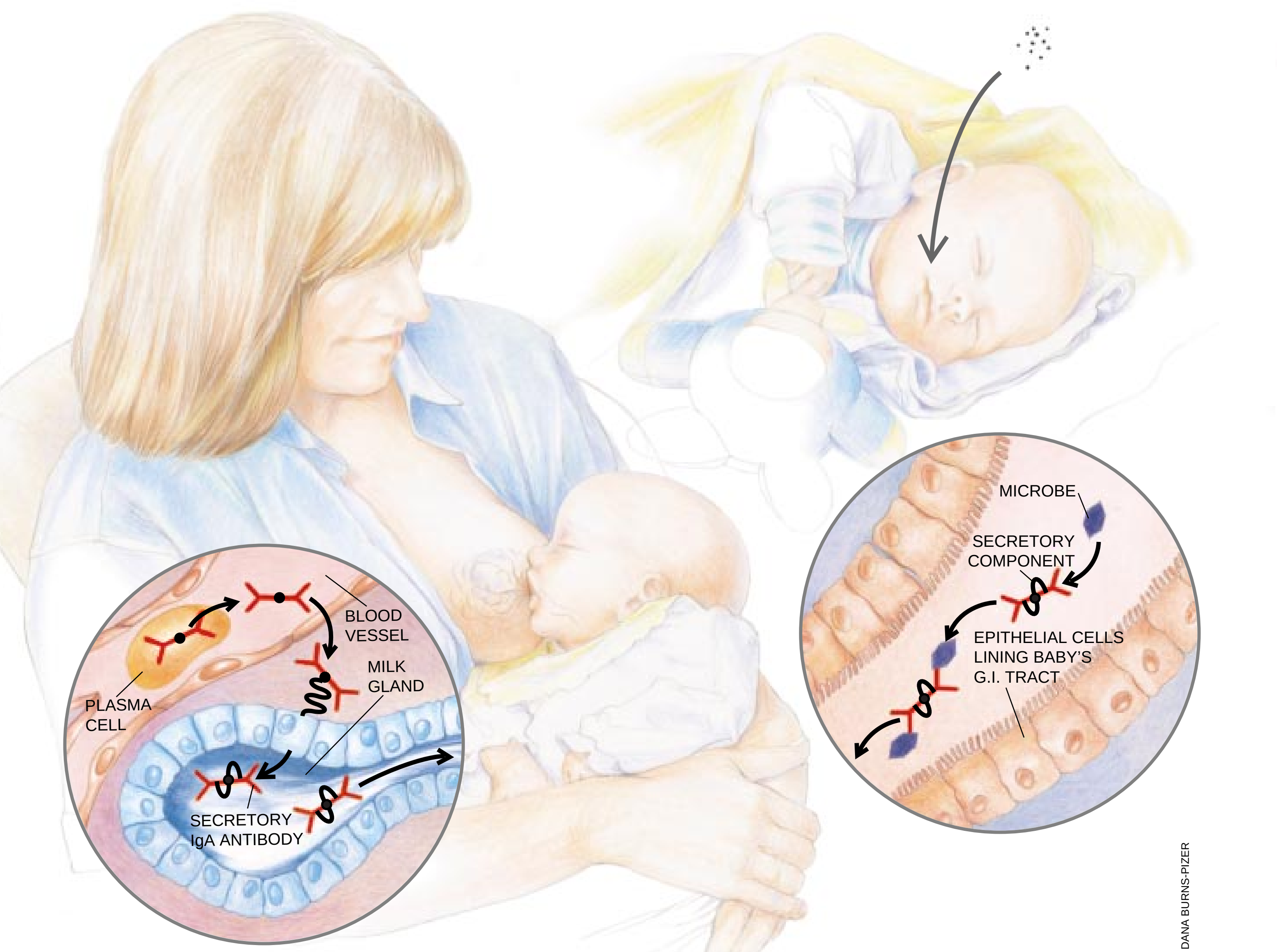
AFTER INGESTING A MICROBE (*left*), a new mother manufactures antibody molecules termed secretory IgA that enter breast milk (*center*) and help to protect the breast-fed baby from pathogens in its environment (*right*). More specifically, a microbe is taken up by the mother's *M* cells (*inset at left*)—specialized cells in the epithelial lining of the digestive tract—

gut and respiratory system of adults. These antibodies consist of two joined IgA molecules and a so-called secretory component that seems to shield the antibody molecules from being degraded by the gastric acid and digestive enzymes in the stomach and intestines. Infants who are bottle-fed have few means for battling ingested pathogens until they begin making secretory IgA on their own, often several weeks or even months after birth.

The secretory IgA molecules passed to the suckling child are helpful in ways that go beyond their ability to bind to microorganisms and keep them away from the body's tissues. First, the collection of antibodies transmitted to an infant is highly targeted against pathogens in that child's immediate surroundings. The mother synthesizes antibodies when she ingests, inhales or otherwise comes in contact with a disease-causing agent. Each antibody she makes is specific to that agent; that is, it binds to a single protein, or antigen, on the agent and will not waste time attacking irrelevant substances. Because the mother makes antibodies only to pathogens in her environment, the baby receives the protection it most needs—against the infectious agents it is most likely to encounter in the first weeks of life.

Second, the antibodies delivered to the infant ignore useful bacteria normally found in the gut. This flora serves to crowd out the growth of harmful organisms, thus providing another measure of resistance. Researchers do not yet know how the mother's immune system knows to make antibodies against only pathogenic and not normal bacteria, but whatever the process may be, it favors the establishment of "good bacteria" in a baby's gut.

Secretory IgA molecules further keep an infant from harm in that, unlike most other antibodies, they ward off disease without causing inflammation—a process in which various chemicals destroy microbes but potentially hurt healthy tissue. In an infant's developing gut, the mucosal membrane is extremely delicate, and an excess of these



and passed to immune cells known as macrophages. The macrophages break down the pathogen and display fragments of it (antigens) to other immune cells called helper *T* lymphocytes, which secrete chemicals that activate still other immune cells, *B* lymphocytes. The *B* cells, in turn, mature into so-called plasma cells that travel to epithelial tissues in the breast and release antibodies (*inset at center*). Some of these molecules enter the milk and are swallowed by the baby. In the infant's digestive tract (*inset at right*), the antibodies, which are protected from breakdown by a so-called secretory component, prevent microorganisms from penetrating the baby's gut.

Immune Benefits of Breast Milk at a Glance

Component	Action
White Blood Cells	
B lymphocytes	Give rise to antibodies targeted against specific microbes.
Macrophages	Kill microbes outright in the baby's gut, produce lysozyme and activate other components of the immune system.
Neutrophils	May act as phagocytes, injesting bacteria in baby's digestive system.
T lymphocytes	Kill infected cells directly or send out chemical messages to mobilize other defenses. They proliferate in the presence of organisms that cause serious illness in infants. They also manufacture compounds that can strengthen a child's own immune response.
Molecules	
Antibodies of secretory IgA class	Bind to microbes in baby's digestive tract and thereby prevent them from passing through walls of the gut into body's tissues.
B_{12} binding protein	Reduces amount of vitamin B_{12}, which bacteria need in order to grow.
Bifidus factor	Promotes growth of *Lactobacillus bifidus,* a harmless bacterium, in baby's gut. Growth of such nonpathogenic bacteria helps to crowd out dangerous varieties.
Fatty acids	Disrupt membranes surrounding certain viruses and destroy them.
Fibronectin	Increases antimicrobial activity of macrophages; helps to repair tissues that have been damaged by immune reactions in baby's gut.
Gamma-interferon	Enhances antimicrobial activity of immune cells.
Hormones and growth factors	Stimulate baby's digestive tract to mature more quickly. Once the initially "leaky" membranes lining the gut mature, infants become less vulnerable to microorganisms.
Lactoferrin	Binds to iron, a mineral many bacteria need to survive. By reducing the available amount of iron, lactoferrin thwarts growth of pathogenic bacteria.
Lysozyme	Kills bacteria by disrupting their cell walls.
Mucins	Adhere to bacteria and viruses, thus keeping such microorganisms from attaching to mucosal surfaces.
Oligosaccharides	Bind to microorganisms and bar them from attaching to mucosal surfaces.

chemicals can do considerable damage.

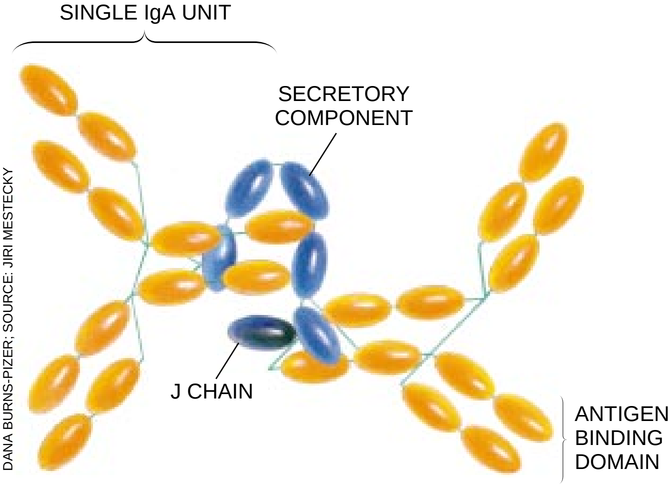
Interestingly, secretory IgA can probably protect mucosal surfaces other than those in the gut. In many countries, particularly in the Middle East, western South America and northern Africa, women put milk in their infants' eyes to treat infections there. I do not know if this remedy has ever been tested scientifically, but there are theoretical reasons to believe it would work. It probably does work at least some of the time, or the practice would have died out.

An Abundance of Helpful Molecules

Several molecules in human milk besides secretory IgA prevent microbes from attaching to mucosal surfaces. Oligosaccharides, which are simple chains of sugars, often contain domains that resemble the binding sites through which bacteria gain entry into the cells lining the intestinal tract. Thus, these sugars can intercept bacteria, forming harmless complexes that the baby excretes. In addition, human milk contains large molecules called mucins that include a great deal of protein and carbohydrate. They, too, are capable of adhering to bacteria and viruses and eliminating them from the body.

The molecules in milk have other valuable functions as well. Each molecule of a protein called lactoferrin, for example, can bind to two atoms of iron. Because many pathogenic bacteria thrive on iron, lactoferrin halts their spread by making iron unavailable. It is especially effective at stalling the proliferation of organisms that often cause serious illness in infants, including *Staphylococcus aureus.* Lactoferrin also disrupts the process by which bacteria digest carbohydrates, further limiting their growth. Similarly, B_{12} binding protein, as its name suggests, deprives microorganisms of vitamin B_{12}.

Bifidus factor, one of the oldest known disease-resistance factors in human milk, promotes the growth of a beneficial organism named *Lactobacillus bifidus.* Free fatty acids present in milk can damage the membranes of enveloped viruses, such as the chicken pox virus, which are packets of genetic material encased in protein shells. Interferon, found particularly in colostrum—the scant, sometimes yellowish milk a mother produces during the first few days after birth—also has strong antiviral activity. And fibronectin, present in large quantities in colostrum, can make certain phagocytes more aggressive so that they will ingest microbes even when the microbes have not been tagged by an antibody. Like secretory IgA, fibronectin minimizes inflammation; it also seems to aid in repairing tissue damaged by inflammation.



DANA BURNS-PIZER; SOURCE: JIRI MESTECKY

SECRETORY IgA ANTIBODY, depicted schematically, consists of two IgA molecules "glued" together by a protein fragment known as the J chain. The secretory element (*blue*) wraps around the joined molecules. The ellipses represent functional domains. Each of the four arms in such antibodies contains an antigen binding domain.

Cellular Defenses

As is true of defensive molecules, immune cells are abundant in human milk. They consist of white blood cells, or leukocytes, that fight infection themselves and activate other defense mechanisms. The most impressive amount is found in colostrum. Most of the cells are neutrophils, a type of phagocyte that normally circulates in the bloodstream. Some evidence suggests that neutrophils continue to act as phagocytes in the infant's gut. Yet they are less aggressive than blood neutrophils and virtually disappear from breast milk six weeks after birth. So perhaps they serve some other function, such as protecting the breast from infection.

The next most common milk leukocyte is the macrophage, which is phagocytic like neutrophils and performs a number of other protective functions. Macrophages make up some 40 percent of all the leukocytes in colostrum. They are far more active than milk neutrophils, and recent experiments suggest that they are more motile than are their counterparts in blood. Aside from being phagocytic, the macrophages in breast milk manufacture lysozyme, increasing its amount in the infant's gastrointestinal tract. Lysozyme is an enzyme that destroys bacteria by disrupting their cell walls.

In addition, macrophages in the digestive tract can rally lymphocytes into action against invaders. Lymphocytes constitute the remaining 10 percent of white cells in the milk. About 20 percent of these cells are *B* lymphocytes, which give rise to antibodies; the rest are *T* lymphocytes, which kill infected cells directly or send out chemical messages that mobilize still other components of the immune system. Milk lymphocytes seem to behave differently from blood lymphocytes. Those in milk, for example, proliferate in the presence of *Escherichia coli,* a bacterium that can cause life-threatening illness in babies, but they are far less responsive than blood lymphocytes to agents posing less threat to infants. Milk lymphocytes also manufacture several chemicals—including gamma-interferon, migration inhibition factor and monocyte chemotactic factor—that can strengthen an infant's own immune response.

Added Benefits

Several studies indicate that some factors in human milk may induce an infant's immune system to mature more quickly than it would were the child fed artificially. For example, breast-fed babies produce higher levels of antibodies in response to immunizations. Also, certain hormones in milk (such as cortisol) and smaller proteins (including epidermal growth factor, nerve growth factor, insulin-like growth factor and somatomedin C) act to close up the leaky mucosal lining of the newborn, making it relatively impermeable to unwanted pathogens and other potentially harmful agents. Indeed, animal studies have demonstrated that postnatal development of the intestine occurs faster in animals fed their mother's milk. And animals that also receive colostrum, containing the highest concentrations of epidermal growth factor, mature even more rapidly.

Other unknown compounds in human milk must stimulate a baby's own production of secretory IgA, lactoferrin and lysozyme. All three molecules are found in larger amounts in the urine of breast-fed babies than in that of bottle-fed babies. Yet breast-fed babies cannot absorb these molecules from human milk into their gut. It would appear that the molecules must be produced in the mucosa of the youngsters' urinary tract. In other words, it seems that breast-feeding induces local immunity in the urinary tract.

In support of this notion, recent clinical studies have demonstrated that the breast-fed infant has a lower risk of acquiring urinary tract infections. Finally, some evidence also suggests that an unknown factor in human milk may cause breast-fed infants to produce more fibronectin on their own than do bottle-fed babies.

All things considered, breast milk is truly a fascinating fluid that supplies infants with far more than nutrition. It protects them against infection until they can protect themselves.

The Author

JACK NEWMAN founded the breast-feeding clinic at the Hospital for Sick Children in Toronto in 1984 and serves as its director. He has more recently established similar clinics at Doctors Hospital and St. Michael's Hospital, both in Toronto. Newman received his medical degree in 1970 from the University of Toronto, where he is now an assistant professor. He completed his postgraduate training in New Zealand and Canada. As a consultant for UNICEF, he has worked with pediatricians in Africa. He has also practiced in New Zealand and in Central and South America.

Further Reading

MUCOSAL IMMUNITY: THE IMMUNOLOGY OF BREAST MILK. H. B. Slade and S. A. Schwartz in *Journal of Allergy and Clinical Immunology,* Vol. 80, No. 3, pages 348–356; September 1987.

IMMUNOLOGY OF MILK AND THE NEONATE. Edited by J. Mestecky et al. Plenum Press, 1991.

BREASTFEEDING AND HEALTH IN THE 1980'S: A GLOBAL EPIDEMIOLOGIC REVIEW. Allan S. Cunningham in *Journal of Pediatrics,* Vol. 118, No. 5, pages 659–666; May 1991.

THE IMMUNE SYSTEM OF HUMAN MILK: ANTIMICROBIAL, ANTIINFLAMMATORY AND IMMUNOMODULATING PROPERTIES. A. S. Goldman in *Pediatric Infectious Disease Journal,* Vol. 12, No. 8, pages 664–671; August 1993.

HOST-RESISTANCE FACTORS AND IMMUNOLOGIC SIGNIFICANCE OF HUMAN MILK. In *Breastfeeding: A Guide for the Medical Profession,* by Ruth A. Lawrence. Mosby Year Book, 1994.

The Puzzle of Conscious Experience

Neuroscientists and others are at last plumbing one of the most profound mysteries of existence. But knowledge of the brain alone may not get them to the bottom of it

by David J. Chalmers

Conscious experience is at once the most familiar thing in the world and the most mysterious. There is nothing we know about more directly than consciousness, but it is extraordinarily hard to reconcile it with everything else we know. Why does it exist? What does it do? How could it possibly arise from neural processes in the brain? These questions are among the most intriguing in all of science.

From an objective viewpoint, the brain is relatively comprehensible. When you look at this page, there is a whir of processing: photons strike your retina, electrical signals are passed up your optic nerve and between different areas of your brain, and eventually you might respond with a smile, a perplexed frown or a remark. But there is also a subjective aspect. When you look at the page, you are conscious of it, directly experiencing the images and words as part of your private, mental life. You have vivid impressions of colored flowers and vibrant sky. At the same time, you may be feeling some emotions and forming some thoughts. Together such experiences make up consciousness: the subjective, inner life of the mind.

For many years, consciousness was shunned by researchers studying the brain and the mind. The prevailing view was that science, which depends on objectivity, could not accommodate something as subjective as consciousness. The behaviorist movement in psychology, dominant earlier in this century, concentrated on external behavior and disallowed any talk of internal mental processes. Later, the rise of cognitive science focused attention on processes inside the head. Still, consciousness remained off-limits, fit only for late-night discussion over drinks.

Over the past several years, however, an increasing number of neuroscientists, psychologists and philosophers have been rejecting the idea that consciousness cannot be studied and are attempting to delve into its secrets. As might be expected of a field so new, there is a tangle of diverse and conflicting theories, often using basic concepts in incompatible ways. To help unsnarl the tangle, philosophical reasoning is vital.

The myriad views within the field range from reductionist theories, according to which consciousness can be explained by the standard methods of neuroscience and psychology, to the position of the so-called mysterians, who say we will never understand consciousness at all. I believe that on close analysis both of these views can be seen to be mistaken and that the truth lies somewhere in the middle.

Against reductionism I will argue that the tools of neuroscience cannot provide a full account of conscious experience, although they have much to offer. Against mysterianism I will hold that consciousness might be explained by a new kind of theory. The full details of such a theory are still out of reach, but careful reasoning and some educated inferences can reveal something of its general nature. For example, it will probably involve new fundamental laws, and the concept of information may play a central role. These faint glimmerings suggest that a theory of consciousness may have startling consequences for our view of the universe and of ourselves.

The Hard Problem

Researchers use the word "consciousness" in many different ways. To clarify the issues, we first have to separate the problems that are often clustered together under the name. For this purpose, I find it useful to distinguish between the "easy problems" and the "hard problem" of consciousness. The easy problems are by no means trivial—they are actually as challenging as most in psychology and biology—but it is with the hard problem that the central mystery lies.

The easy problems of consciousness include the following: How can a human subject discriminate sensory stimuli and react to them appropriately? How does the brain integrate information from many different sources and use this information to control behavior? How is it that subjects can verbalize their internal states? Although all these questions are associated with consciousness, they all concern the objective mechanisms of the cognitive system. Consequently, we have every reason to expect that continued work in cognitive psychology and neuroscience will answer them.

The hard problem, in contrast, is the question of how physical processes in the brain give rise to subjective experience. This puzzle involves the inner aspect of thought and perception: the way things feel for the subject. When we see, for example, we experience visual sensations, such as that of vivid blue. Or think of the ineffable sound of a distant oboe, the agony of an intense pain, the sparkle of happiness or the meditative quality of a moment lost in thought. All are part of what I am calling consciousness. It is these phenomena that pose the real mystery of the mind.

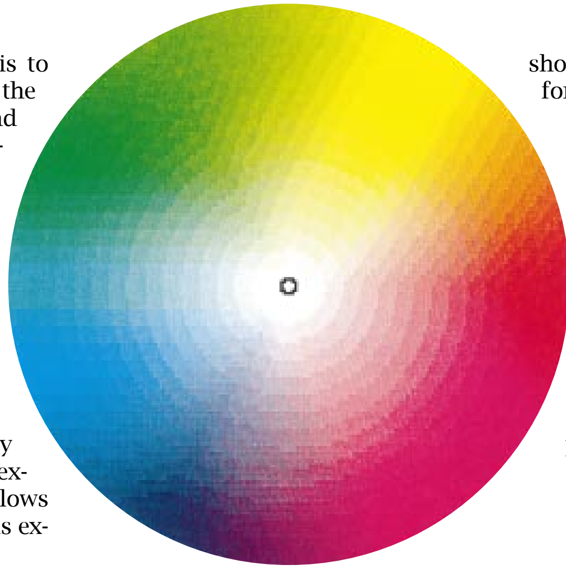
To illustrate the distinction, consider a thought experiment devised by the Australian philosopher Frank Jackson. Suppose that Mary, a neuroscientist in the 23rd century, is the world's leading expert on the brain processes responsible for color vision. But Mary has lived her whole life in a black-and-white room and has never seen any other col-

ISOLATED NEUROSCIENTIST in a black-and-white room knows everything about how the brain processes colors but does not know what it is like to see them. This scenario suggests that knowledge of the brain does not yield complete knowledge of conscious experience.

BLACK-AND-WHITE PHOTOGRAPH BY DAN WAGNER; DIGITAL COMPOSITION BY TOM DRAPER DESIGN ors. She knows everything there is to know about physical processes in the brain—its biology, structure and function. This understanding enables her to grasp everything there is to know about the easy problems: how the brain discriminates stimuli, integrates information and produces verbal reports. From her knowledge of color vision, she knows the way color names correspond with wavelengths on the light spectrum. But there is still something crucial about color vision that Mary does not know: what it is like to experience a color such as red. It follows that there are facts about conscious experience that cannot be deduced from physical facts about the functioning of the brain.

Indeed, nobody knows why these physical processes are accompanied by conscious experience at all. Why is it that when our brains process light of a certain wavelength, we have an experience of deep purple? Why do we have any experience at all? Could not an unconscious automaton have performed the same tasks just as well? These are questions that we would like a theory of consciousness to answer.

I am not denying that consciousness arises from the brain. We know, for example, that the subjective experience of vision is closely linked to processes in the visual cortex. It is the link itself that perplexes, however. Remarkably, subjective experience seems to emerge from a physical process. But we have no idea how or why this is.



COLOR WHEEL arranges hues so that ones experienced as similar are closest. Nearby colors also correspond to similar perceptual representations in the brain.

Is Neuroscience Enough?

Given the flurry of recent work on consciousness in neuroscience and psychology, one might think this mystery is starting to be cleared up. On closer examination, however, it turns out that almost all the current work addresses only the easy problems of consciousness. The confidence of the reductionist view comes from the progress on the easy problems, but none of this makes any difference where the hard problem is concerned.

Consider the hypothesis put forward by neurobiologists Francis Crick of the Salk Institute for Biological Studies in San Diego and Christof Koch of the California Institute of Technology. They suggest that consciousness may arise from certain oscillations in the cerebral cortex, which become synchronized as neurons fire 40 times per second. Crick and Koch believe the phenomenon might explain how different attributes of a single perceived object (its color and shape, for example), which are processed in different parts of the brain, are merged into a coherent whole. In this theory, two pieces of information become bound together precisely when they are represented by synchronized neural firings.

The hypothesis could conceivably elucidate one of the easy problems about how information is integrated in the brain. But why should synchronized oscillations give rise to a visual experience, no matter how much integration is taking place? This question involves the hard problem, about which the theory has nothing to offer. Indeed, Crick and Koch are agnostic about whether the hard problem can be solved by science at all [*see box on pages 84 and 85*].

The same kind of critique could be applied to almost all the recent work on consciousness. In his 1991 book *Consciousness Explained,* philosopher Daniel C. Dennett laid out a sophisticated theory of how numerous independent processes in the brain combine to produce a coherent response to a perceived event. The theory might do much to explain how we produce verbal reports on our internal states, but it tells us very little about why there should be a subjective experience behind these reports. Like other reductionist theories, Dennett's is a theory of the easy problems.

The critical common trait among these easy problems is that they all concern how a cognitive or behavioral function is performed. All are ultimately questions about how the brain carries out some task—how it discriminates stimuli, integrates information, produces reports and so on. Once neurobiology specifies appropriate neural mechanisms, showing how the functions are performed, the easy problems are solved.

The hard problem of consciousness, in contrast, goes beyond problems about how functions are performed. Even if every behavioral and cognitive function related to consciousness were explained, there would still remain a further mystery: Why is the performance of these functions accompanied by conscious experience? It is this additional conundrum that makes the hard problem hard.

The Explanatory Gap

Some have suggested that to solve the hard problem, we need to bring in new tools of physical explanation: nonlinear dynamics, say, or new discoveries in neuroscience, or quantum mechanics. But these ideas suffer from exactly the same difficulty. Consider a proposal from Stuart R. Hameroff of the University of Arizona and Roger Penrose of the University of Oxford. They hold that consciousness arises from quantum-physical processes taking place in microtubules, which are protein structures inside neurons. It is possible (if not likely) that such a hypothesis will lead to an explanation of how the brain makes decisions or even how it proves mathematical theorems, as Hameroff and Penrose suggest. But even if it does, the theory is silent about how these processes might give rise to conscious experience. Indeed, the same problem arises with any theory of consciousness based only on physical processing.

The trouble is that physical theories are best suited to explaining why systems have a certain physical structure and how they perform various functions. Most problems in science have this form; to explain life, for example, we need to describe how a physical system can reproduce, adapt and metabolize. But consciousness is a different sort of problem entirely, as it goes beyond the explanation of structure and function.

Of course, neuroscience is not irrelevant to the study of consciousness. For one, it may be able to reveal the nature of the neural correlate of consciousness—the brain processes most directly associated with conscious experience. It may even give a detailed correspondence between specific processes in the brain and related components of experience. But until we know why these processes give rise to conscious experience at all, we will not have crossed what philosopher Joseph Levine has called the explanatory gap between physical processes and consciousness. Making that leap will demand a new kind of theory.

A True Theory of Everything

In searching for an alternative, a key observation is that not all entities in science are explained in terms of more basic entities. In physics, for example, space-time, mass and charge (among other things) are regarded as fundamental features of the world, as they are not reducible to anything simpler. Despite this irreducibility, detailed and useful theories relate these entities to one another in terms of fundamental laws. Together these features and laws explain a great variety of complex and subtle phenomena.

It is widely believed that physics provides a complete catalogue of the universe's fundamental features and laws. As physicist Steven Weinberg puts it in his 1992 book *Dreams of a Final Theory,* the goal of physics is a "theory of everything" from which all there is to know about the universe can be derived. But Weinberg concedes that there is a problem with consciousness. Despite the power of physical theory, the existence of consciousness does not seem to be derivable from physical laws. He defends physics by arguing that it might eventually explain what he calls the objective correlates of consciousness (that is, the neural correlates), but of course to do this is not to explain consciousness itself. If the existence of consciousness cannot be derived from physical laws, a theory of physics is not a true theory of everything. So a final theory must contain an additional fundamental component.

Toward this end, I propose that conscious experience be considered a fundamental feature, irreducible to anything more basic. The idea may seem strange at first, but consistency seems to demand it. In the 19th century it turned out that electromagnetic phenomena could not be explained in terms of previously known principles. As a consequence, scientists introduced electromagnetic charge as a new fundamental entity and studied the associated fundamental laws. Similar reasoning should apply to consciousness. If existing fundamental theories cannot encompass it, then something new is required.

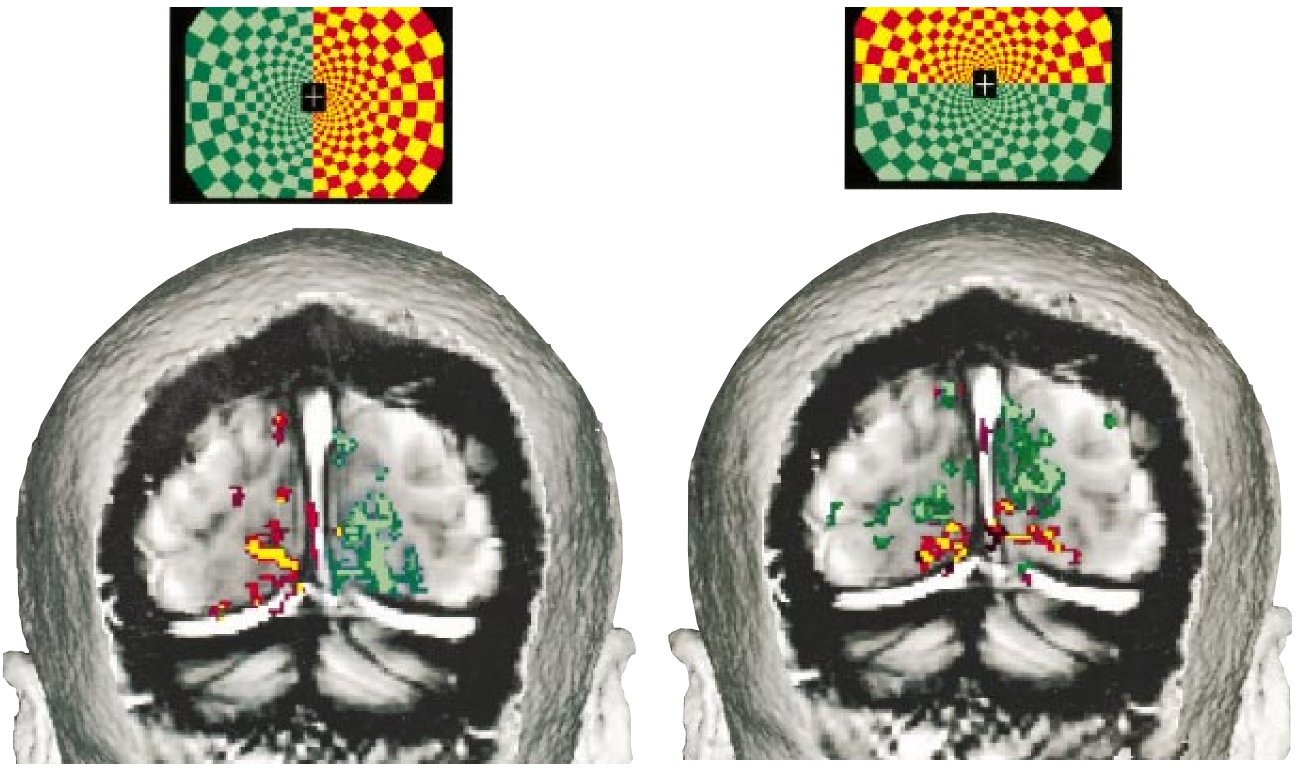
Where there is a fundamental property, there are fundamental laws. In this case, the laws must relate experience to elements of physical theory. These laws will almost certainly not interfere with those of the physical world; it seems that the latter form a closed system in their own right. Rather the laws will serve as a bridge, specifying how experience depends on underlying physical processes. It is this bridge that will cross the explanatory gap.

Thus, a complete theory will have two components: physical laws, telling us about the behavior of physical systems from the infinitesimal to the cosmological, and what we might call psychophysical laws, telling us how some of those systems are associated with conscious experience. These two components will constitute a true theory of everything.

Searching for a Theory

Supposing for the moment that they exist, how might we uncover such psychophysical laws? The greatest hindrance in this pursuit will be a lack of data. As I have described it, consciousness is subjective, so there is no direct way to monitor it in others. But this difficulty is an obstacle, not a dead end. For a start, each one of us has access to our own experiences, a rich trove that can be used to formulate theories. We can also plausibly rely on indirect information, such as subjects' descriptions of their experiences. Philosophical arguments and thought experiments also have a role to play. Such methods have limitations, but they give us more than enough to get started.

These theories will not be conclusive-



UNIVERSITY OF PITTSBURGH

BLOOD FLOW variations in the visual cortex demonstrate how a subject's brain responds to a pattern being viewed. The colors in this image show the cortical activity corresponding to the subject's view of either half of the pattern. The experiment illuminates a neural correlate of visual experience; such experiences may be the basis of consciousness.

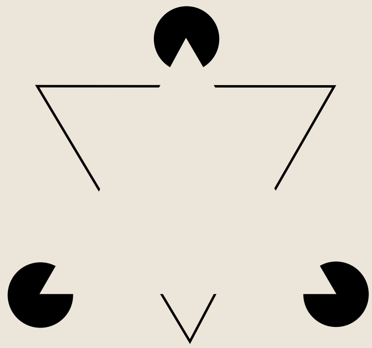
Why Neuroscience May Be Able to Explain Consciousness

by Francis Crick and Christof Koch

We believe that at the moment the best approach to the problem of explaining consciousness is to concentrate on finding what is known as the neural correlates of consciousness—the processes in the brain that are most directly responsible for consciousness. By locating the neurons in the cerebral cortex that correlate best with consciousness, and figuring out how they link to neurons elsewhere in the brain, we may come across key insights into what David J. Chalmers calls the hard problem: a full accounting of the manner in which subjective experience arises from these cerebral processes.

We commend Chalmers for boldly recognizing and focusing on the hard problem at this early stage, although we are not as enthusiastic about some of his thought experiments. As we see it, the hard problem can be broken down into several questions: Why do we experience anything at all? What leads to a particular conscious experience (such as the blueness of blue)? Why are some aspects of subjective experience impossible to convey to other people (in other words, why are they private)? We believe we have an answer to the last problem and a suggestion about the first two, revolving around a phenomenon known as explicit neuronal representation.

What does "explicit" mean in this context? Perhaps the best way to define it is with an example. In response to the image of a face, say, ganglion cells fire all over the retina, much like the pixels on a television screen, to generate an implicit representation of the face. At the same time, they can also respond to a great many other features in the image, such as shadows, lines, uneven lighting and so on. In contrast, some neurons high in the hierarchy of the visual cortex respond mainly to the face or even to the face viewed at a particular angle. Such neurons help the brain represent the face in an explicit manner. Their loss, resulting from a stroke or some other brain injury, leads to prosopagnosia, an individual's inability to recognize familiar faces consciously—even his or her own, although the person can still identify a face as a face. Similarly, damage to other parts of the visual cortex can cause someone to lose the ability to experience color, while still seeing in shades of black and white, even though there is no defect in the color receptors in the eye.



KANIZSA TRIANGLE stimulates neurons that code explicitly for such illusory contours.

At each stage, visual information is reencoded, typically in a semihierarchical manner. Retinal ganglion cells respond to a spot of light. Neurons in the primary visual cortex are most adept at responding to lines or edges; neurons higher up might prefer a moving contour. Still higher are those that respond to faces and other familiar objects. On top are those that project to pre-motor and motor structures in the brain, where they fire the neurons that initiate such actions as speaking or avoiding an oncoming automobile.

Chalmers believes, as we do, that the subjective aspects of an experience must relate closely to the firing of the neurons corresponding to those aspects (the neural correlates). He describes a well-known thought experiment, constructed around a hypothetical neuroscientist, Mary, who specializes in color per-

ly testable, so they will inevitably be more speculative than those of more conventional scientific disciplines. Nevertheless, there is no reason they should not be strongly constrained to account accurately for our own first-person experiences, as well as the evidence from subjects' reports. If we find a theory that fits the data better than any other theory of equal simplicity, we will have good reason to accept it. Right now we do not have even a single theory that fits the data, so worries about testability are premature.

We might start by looking for high-level bridging laws, connecting physical processes to experience at an everyday level. The basic contour of such a law might be gleaned from the observation that when we are conscious of something, we are generally able to act on it and speak about it—which are objective, physical functions. Conversely, when some information is directly available for action and speech, it is generally conscious. Thus, consciousness correlates well with what we might call "awareness": the process by which information in the brain is made globally available to motor processes such as speech and bodily action.

The notion may seem trivial. But as defined here, awareness is objective and physical, whereas consciousness is not. Some refinements to the definition of awareness are needed, in order to extend the concept to animals and infants, which cannot speak. But at least in familiar cases, it is possible to see the rough outlines of a psychophysical law: where there is awareness, there is consciousness, and vice versa.

To take this line of reasoning a step further, consider the structure present in the conscious experience. The experience of a field of vision, for example, is a constantly changing mosaic of colors, shapes and patterns and as such has a detailed geometric structure. The fact that we can describe this structure, reach out in the direction of many of its components and perform other actions that depend on it suggests that the structure corresponds directly to that of the information made available in the brain through the neural processes of awareness.

Similarly, our experiences of color have an intrinsic three-dimensional structure that is mirrored in the structure of information processes in the brain's visual cortex. This structure is illustrated in the color wheels and charts used by artists. Colors are arranged in a systematic pattern—red to green on one axis, blue to yellow on another, and black to white on a third. Colors that are close to one another on a color wheel are experienced as similar [*see illustration on page 82*]. It is extremely likely that they also correspond to similar perceptual representations in the brain, as part of a system of complex three-dimensional coding among neurons that is not yet fully understood. We can recast the underlying concept as a principle of structural coherence: the structure of conscious experience is mirrored by the structure of information in awareness, and vice versa.

Another candidate for a psychophysical law is a principle of organizational invariance. It holds that physical systems with the same abstract organization will give rise to the same kind of conscious experience, no matter what they are made of. For example, if the ception but has never seen a color. We believe the reason Mary does not know what it is like to see a color, however, is that she has never had an explicit neural representation of a color in her brain, only of the words and ideas associated with colors.

In order to describe a subjective visual experience, the information has to be transmitted to the motor output stage of the brain, where it becomes available for verbalization or other actions. This transmission always involves reencoding the information, so that the explicit information expressed by the motor neurons is related, but not identical, to the explicit information expressed by the firing of the neurons associated with color experience, at some level in the visual hierarchy.

It is not possible, then, to convey with words and ideas the exact nature of a subjective experience. It is possible, however, to convey a difference between subjective experiences—to distinguish between red and orange, for example. This is possible because a difference in a high-level visual cortical area will still be associated with a difference in the motor stages. The implication is that we can never explain to other people the nature of any conscious experience, only its relation to other ones.

The other two questions, concerning why we have conscious experiences and what leads to specific ones, appear more difficult. Chalmers proposes that they require the introduction of "experience" as a fundamental new feature of the world, relating to the ability of an organism to process information. But which types of neuronal information produce consciousness? And what makes a certain type of information correspond to the blueness of blue, rather than the greenness of green? Such problems seem as difficult as any in the study of consciousness.

We prefer an alternative approach, involving the concept of "meaning." In what sense can neurons that explicitly code for a face be said to convey the meaning of a face to the rest of the brain? Such a property must relate to the cell's projective field—its pattern of synaptic connections to neurons that code explicitly for related concepts. Ultimately, these connections extend to the motor output. For example, neurons responding to a certain face might be connected to ones expressing the name of the person whose face it is and to others for her voice, memories involving her and so on. Such associations among neurons must be behaviorally useful—in other words, consistent with feedback from the body and the external world.

Meaning derives from the linkages among these representations with others spread throughout the cortical system in a vast associational network, similar to a dictionary or a relational database. The more diverse these connections, the richer the meaning. If, as in our previous example of prosopagnosia, the synaptic output of such face neurons were blocked, the cells would still respond to the person's face, but there would be no associated meaning and, therefore, much less experience. A face would be seen but not recognized as such.

Of course, groups of neurons can take on new functions, allowing brains to learn new categories (including faces) and associate new categories with existing ones. Certain primitive associations, such as pain, are to some extent inborn but subsequently refined in life.

Information may indeed be the key concept, as Chalmers suspects. Greater certainty will require consideration of highly parallel streams of information, linked—as are neurons—in complex networks. It would be useful to try to determine what features a neural network (or some other such computational embodiment) must have to generate meaning. It is possible that such exercises will suggest the neural basis of meaning. The hard problem of consciousness may then appear in an entirely new light. It might even disappear.

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precise interactions between our neurons could be duplicated with silicon chips, the same conscious experience would arise. The idea is somewhat controversial, but I believe it is strongly supported by thought experiments describing the gradual replacement of neurons by silicon chips [*see box on next page*]. The remarkable implication is that consciousness might someday be achieved in machines.

Information: Physical and Experiential

The ultimate goal of a theory of consciousness is a simple and elegant set of fundamental laws, analogous to the fundamental laws of physics. The principles described above are unlikely to be fundamental, however. Rather they seem to be high-level psychophysical laws, analogous to macroscopic principles in physics such as those of thermodynamics or kinematics. What might the underlying fundamental laws be? No one knows, but I don't mind speculating.

I suggest that the primary psychophysical laws may centrally involve the concept of information. The abstract notion of information, as put forward in the 1940s by Claude E. Shannon of the Massachusetts Institute of Technology, is that of a set of separate states with a basic structure of similarities and differences between them. We can think of a 10-bit binary code as an information state, for example. Such information states can be embodied in the physical world. This happens whenever they correspond to physical states (voltages, say); the differences between them can be transmitted along some pathway, such as a telephone line.

We can also find information embodied in conscious experience. The pattern of color patches in a visual field, for example, can be seen as analogous to that of the pixels covering a display screen. Intriguingly, it turns out that we find the same information states embedded in conscious experience and in underlying physical processes in the brain. The three-dimensional encoding of color spaces, for example, suggests that the information state in a color experience corresponds directly to an information state in the brain. We might even regard the two states as distinct aspects of a single information state, which is simultaneously embodied in both physical processing and conscious experience.

A natural hypothesis ensues. Perhaps information, or at least some information, has two basic aspects: a physical one and an experiential one. This hypothesis has the status of a fundamental principle that might underlie the relation between physical processes and experience. Wherever we find conscious experience, it exists as one aspect of an information state, the other aspect of which is embedded in a physical process in the brain. This proposal needs to be fleshed out to make a satisfying theory. But it fits nicely with the principles mentioned earlier—systems with the same organization will embody the same information, for example—and it could explain numerous features of our conscious experience.

The idea is at least compatible with several others, such as physicist John A. Wheeler's suggestion that information is fundamental to the physics of the universe. The laws of physics might

Dancing Qualia in a Synthetic Brain

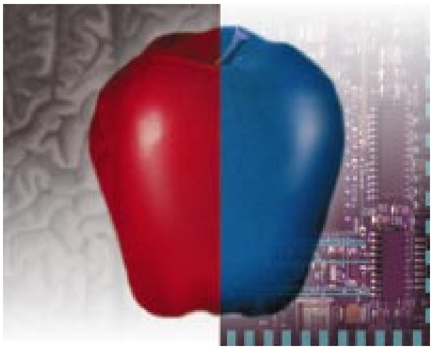
Whether consciousness could arise in a complex, synthetic system is a question many people find intrinsically fascinating. Although it may be decades or even centuries before such a system is built, a simple thought experiment offers strong evidence that an artificial brain, if organized appropriately, would indeed have precisely the same kind of conscious experiences as a human being.

Consider a silicon-based system in which the chips are organized and function in the same way as the neurons in your brain. That is, each chip in the silicon system does exactly what its natural analogue does and is interconnected to surrounding elements in precisely the same way. Thus, the behavior exhibited by the artificial system will be exactly the same as yours. The crucial question is: Will it be conscious in the same way that you are?

Let us assume, for the purpose of argument, that it would not be. (Here we use a reasoning technique known as reductio ad absurdum, in which the opposite hypothesis is assumed and then shown to lead to an untenable conclusion.) That is, it either has different experiences—an experience of blue, say, when you are seeing red—or no experience at all. We will consider the first case; the reasoning proceeds similarly in both cases.

Because chips and neurons have the same function, they are interchangeable, with the proper interfacing. Chips therefore can replace neurons, producing a continuum of cases in which a successively larger proportion of neurons are replaced by chips. Along this continuum, the conscious experience of the system will also change. For example, we might replace all the neurons in your visual cortex with an identically organized version made of silicon. The resulting brain, with an artificial visual cortex, will have a different conscious experience from the original: where you had previously seen red, you may now experience purple (or perhaps a faded pink, in the case where the wholly silicon system has no experience at all).

Both visual cortices are then attached to your brain, through a two-position switch. With the switch in one mode, you use the natural visual cortex; in the other, the artificial cortex is activated. When the switch is flipped, your experience changes from red to purple, or vice versa. When the switch is flipped repeatedly, your experiences "dance" between the two different conscious states (red and purple), known as qualia.



TOM DRAPER DESIGN

IN THOUGHT EXPERIMENT, an apple might flash from red to blue.

Because your brain's organization has not changed, however, there can be no behavioral change when the switch is thrown. Therefore, when asked about what you are seeing, you will say that nothing has changed. You will hold that you are seeing red and have seen nothing but red—even though the two colors are dancing before your eyes. This conclusion is so unreasonable that it is best taken as a reductio ad absurdum of the original assumption—that an artificial system with identical organization and functioning has a different conscious experience from that of a neural brain. Retraction of the assumption establishes the opposite: that systems with the same organization have the same conscious experience. —*D.J.C.*

ultimately be cast in informational terms, in which case we would have a satisfying congruence between the constructs in both physical and psychophysical laws. It may even be that a theory of physics and a theory of consciousness could eventually be consolidated into a single grander theory of information.

A potential problem is posed by the ubiquity of information. Even a thermostat embodies some information, for example, but is it conscious? There are at least two possible responses. First, we could constrain the fundamental laws so that only some information has an experiential aspect, perhaps depending on how it is physically processed. Second, we might bite the bullet and allow that all information has an experiential aspect—where there is complex information processing, there is complex experience, and where there is simple information processing, there is simple experience. If this is so, then even a thermostat might have experiences, although they would be much simpler than even a basic color experience, and there would certainly be no accompanying emotions or thoughts. This seems odd at first, but if experience is truly fundamental, we might expect it to be widespread. In any case, the choice between these alternatives should depend on which can be integrated into the most powerful theory.

Of course, such ideas may be all wrong. On the other hand, they might evolve into a more powerful proposal that predicts the precise structure of our conscious experience from physical processes in our brains. If this project succeeds, we will have good reason to accept the theory. If it fails, other avenues will be pursued, and alternative fundamental theories may be developed. In this way, we may one day resolve the greatest mystery of the mind.

The Author

DAVID J. CHALMERS studied mathematics at Adelaide University and as a Rhodes Scholar at the University of Oxford, but a fascination with consciousness led him into philosophy and cognitive science. He has a Ph.D. in these fields from Indiana University and is currently in the department of philosophy at the University of California, Santa Cruz. Chalmers has published numerous articles on artificial intelligence and the philosophy of mind. His book *The Conscious Mind,* which elaborates many of the ideas in this article, is forthcoming from Oxford University Press.

Further Reading

ABSENT QUALIA, FADING QUALIA, DANCING QUALIA. David J. Chalmers in *Conscious Experience.* Edited by Thomas Metzinger. Ferdinand Schöningh, 1995.

EXPLAINING CONSCIOUSNESS: THE "HARD PROBLEM." Special issue of *Journal of Consciousness Studies,* Vol. 2, No. 3; Autumn 1995.

THE NATURE OF CONSCIOUSNESS: PHILOSOPHICAL AND SCIENTIFIC DEBATES. Edited by Ned Block, Owen Flanagan and Güven Güzeldere. MIT Press (in press).

Confidential Communication on the Internet

Cryptography gives people the ability to authenticate the identity of their correspondents, the first step in establishing trust

by Thomas Beth

MICHAEL GOODMAN

"Be on your guard against the wolf," the mother goat said. "If he gets in, he'll eat you up, skin and bones. The villain often disguises himself, but you'll know him right away by his gruff voice and his black feet."

—from *The Wolf and the Seven Young Kids,* by the Brothers Grimm

The well-meaning goat tried to protect her children by using what a computer-security expert would call an access-control mechanism: let no one in unless he displays a fine voice and white paws. This method is, in principle, very effective because it checks for the physical characteristics of those who are authorized to enter. In the fairy tale, its fatal flaw was the meager information required. To distinguish between a goat and a wolf is easy if you can see the whole body, but the kids were programmed only for paw color and voice.

Computers transfer so much money and valuable information that their communications make an extraordinarily tempting target for criminals. Yet people trying to protect their data and transmissions apply less caution than the goats do: they attempt to distinguish between friend and foe using a mere sequence of symbols sent by a correspondent over a network.

The relative anonymity that networks now offer, combined with the increasing capability of machines connected to them, is frightening to governments, which foresee an accelerating wave of digital crime. Many nations are responding with draconian cures that may be at least as bad as the ills they seek to ward off. My colleagues and I believe, however, that we have found a path between the dangers of state control over the keys to information and a free field for organized crime. We simply had to work a little harder to find it.

Anyone communicating via computer needs a security system that ensures three essential requirements: confidentiality, authentication and trust. Even the supposedly simple routine of withdrawing money from a bank's automated cash machine involves a communication based on trust. This system currently operates in a strictly one-sided fashion: the machine makes sure the person who inserted the card is its legitimate owner by asking for a secret password, but the cardholder must blindly trust that the machine has not been tampered with. Although this classic authoritarian model may have been appropriate once, today it is naive to suppose that none of the machines involved in a communication have been manipulated.

So long as both communication partners are monitored by a common institution, the electronic equivalent of a central ticket booth may provide authentication and confidentiality. This principle underlies the Kerberos protocol in the Athena system of the Massachusetts Institute of Technology [see "Secure Distributed Computing," by Jeffrey I. Schiller; SCIENTIFIC AMERICAN, November 1994].

It would be absurd, however, to employ the same method for the millions of users of the Internet. First, it is practi-

CHAIN OF CERTIFICATION in the author's scheme extends from local authorities who vouch for an individual's identity and probity up through regional, national and supranational authorities (represented here by different names and seals), each vouching for those below it. Digital signatures prevent tampering; anyone who recognizes one signature in the chain can be assured that a signed document is valid.

cally impossible to build such an enormous central file server and operate it continuously. Second, such a concentration of sensitive data would encourage even the most difficult criminal attacks.

Moreover, the use of secret passwords to verify the identity of a person at a terminal is insecure on open networks. Programs that surreptitiously record the combination of passwords and user names for later misuse have become known as packet sniffers. They have been implicated in dozens of major break-ins throughout the U.S. and Europe. An Internet user should not be required to type in a password or reveal any personal characteristics that someone else could copy. Instead users should be asked to provide answers that depend on their knowledge of some secret without revealing it.

In 1986 my colleagues and I at the Institute for Informatics at the University of Karlsruhe began to address this problem. Although funding for our initial project was cut, we have since succeeded in developing a network-security system we call SELANE (secure local-area network). The name is also an allusion to the Greek moon goddess, Selene, who moves as an equal partner between her siblings, Eos and Helios, in the open sky—just as both parties to an electronic transaction must be equal.

SELANE is compatible with almost every commercial and academic network. We have also created a "smart" card that can carry out the necessary calculations securely for each user. SELANE is currently in use at our university, where it provides secure access to the departmental network.

Shared Secret Keys

Modern cryptology is based on the notion that all digital texts are merely chains of bits, which can be interpreted as numbers. Hence, encryption is simply a matter of applying an appropriate mathematical function to change an intelligible string of numbers into pseudogibberish that can be read only by someone who knows the function and the proper key.

The first problem for network security is confidentiality. How can Alice and Bob (as cryptographers like to call the partners in a communication) safely exchange a private sequence of bits over a wire that can be tapped? At the very least, they must be able to exchange a key that can be used to encrypt or decrypt subsequent messages. In the 1970s Martin E. Hellman of Stanford University and his students Whitfield Diffie and Ralph Merkle developed a method that enabled Alice and Bob to obtain the same string of bits without sending either the bits or the information needed for their reconstruction through the wire [*see box below*].

Hellman, Diffie and Merkle employed what are known as one-way functions, which are easy to calculate but practically impossible to reverse. Knowing the result of applying a one-way function to a number leaves no clue to the number itself. The class of one-way functions we use relies on a technique called modular exponentiation. Modular exponentiation preserves two important relations among the scrambled numbers. First, it is commutative, which means that multiple exponentiations can be done in any order on a string of data without changing the results. Second, it is homomorphic: if two numbers add up to a third, then multiplying their exponentiated versions will yield the exponentiation of the third number.

To exchange a key with Bob according to the Diffie-Hellman protocol, Alice takes a publicly known number, applies her one-way function—exponentiation to a secret power that only she knows—and sends the result via public channels to Bob. Because exponentiation is a one-way function, an eavesdropper cannot extract her secret from the combination of the public bit sequence and its exponentiated version. Bob, meanwhile, applies his secret exponent to the same publicly known number and sends the result to Alice.

Alice and Bob then apply their one-way functions to the number received from the other. Because the combination of the two functions yields the same result regardless of which is applied first, both partners will end up with the same string of bits, known to no one else. They can then use the string as the "key" for a function that encrypts and decrypts the information they want to exchange. A third party who has monitored the exchanges will be unable to determine the key or Alice and Bob's secret functions.

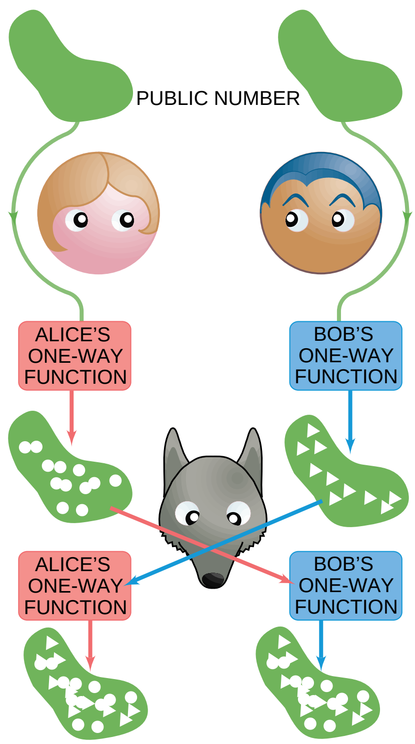
Passport Instead of Password

The second problem is authentication: Bob must be able to verify that it is really Alice who sent him a message. There is no central authority, however, that can vouch for the identity of every single user of the Internet. While thinking about this problem, we were reminded of an access-control system with similar demands that is used successfully worldwide on a daily basis:

One-Way Functions Foil Eavesdroppers

A technique known as the Diffie-Hellman key exchange enables two correspondents to communicate securely over an insecure channel. The exchange relies on a kind of one-way function (a numerical transformation that is straightforward to perform but impossible to undo) termed modular exponentiation. To encrypt a message, one raises a constant (say, 3) to the power of the number representing the message in digital form and then takes the remainder after division by a large prime number. To encrypt the number 66, for example, one might calculate the remainder of 3^{66} divided by, say, 127. (In actuality, the prime number would be much larger—perhaps 300 digits long.)

Bob and Alice apply their exponentiations in sequence to a known string of bits (*top*); Alice performs her operation first in one case, Bob in the other. The order does not influence the final result, but the exponentiation scrambles the bits so that an interloper will be unable to determine either the exponents that Bob and Alice are using or the final bit sequence they share—which can then serve as an encryption key for future transactions. —*T.B.*



MICHAEL GOODMAN

SKIDATA COMPUTER

CRYPTOGRAPHIC WATCH developed by Skidata Computer in Austria contains a short-range transmitter and receiver and a microcomputer.

passports. The passport photograph and signature form a connection with the owner that is further verified by the government insignia and the stamp and signature of the issuing office. The most important feature is that everyone can verify the validity of a passport without asking the issuing authority.

In 1984 Taher ElGamal, then at Stanford University, devised a digital-signature scheme that could be used to verify the sender of a message and to make sure its contents had not been altered. Everyone who wants to sign documents selects a permanent, secret bit string as a private signature and publishes an exponentially distorted version of those bits as a public signature. Signing a particular document proceeds as follows:

- Generate a "one-time stamp" (a digital equivalent of a serial number).
- Run the stamp through a one-way exponential function to get a distorted version.
- Formulate and solve an equation that relates the numerical values of the message being sent, the personal secret bit string, the stamp and the distorted version of the stamp.
- Transmit the message.
- Append a signature consisting of the distorted stamp and the solution to the equation.

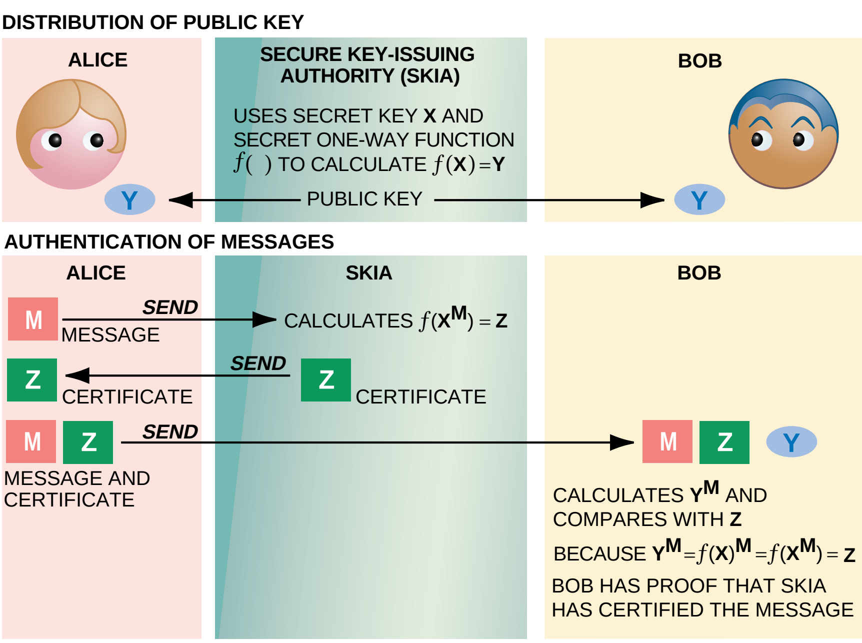
Everyone who knows the signer's public signature (the exponentially distorted version of the secret bit string) can check that the numbers in the signature were indeed generated from the private string and the message in question. During the past 10 years, numerous variations of ElGamal's basic scheme have been constructed.

Armed with this unforgeable process, we conceived a scheme that would establish a secure key-issuing authority (SKIA), in the place of a passport-issuing authority, for every local computer network. Before issuing the first ID, the SKIA adopts its own signature keys, a secret one and a distorted, public version. Anyone who wishes to check the IDs issued by the SKIA saves a copy of the public key, just as every foreign immigration office keeps a sample of an American passport.

The SKIA issues a token (a tamper-resistant chip embedded in a credit card or specially designed watch) to every person, terminal or computer on its network. This token can be used in any subsequent transaction. When Alice asks the SKIA for an ID, it gives her a token whose memory contains a readable message—"The holder of this card, Alice Wunderkind, is a professor of computer science at the University of Karlsruhe"—and an ElGamal-type signature based on the message.

To convince Bob that her ID is valid, Alice instructs her chip card to give him the message and the distorted one-time stamp from the signature. Bob uses these values, along with the SKIA's public key, to compute a distorted image of the rest of the signature—which the token does not disclose. To ensure that the ID is valid, Bob can engage in a challenge-response sequence with the token, in effect asking it questions that it can answer only if it actually contains the secret part of the signature.

My colleagues Fritz Bauspiess, Christoph Günther and Hans-Joachim Knobloch and I have designed a protocol that merges the authentication and verification with the subsequent key ex-



MICHAEL GOODMAN

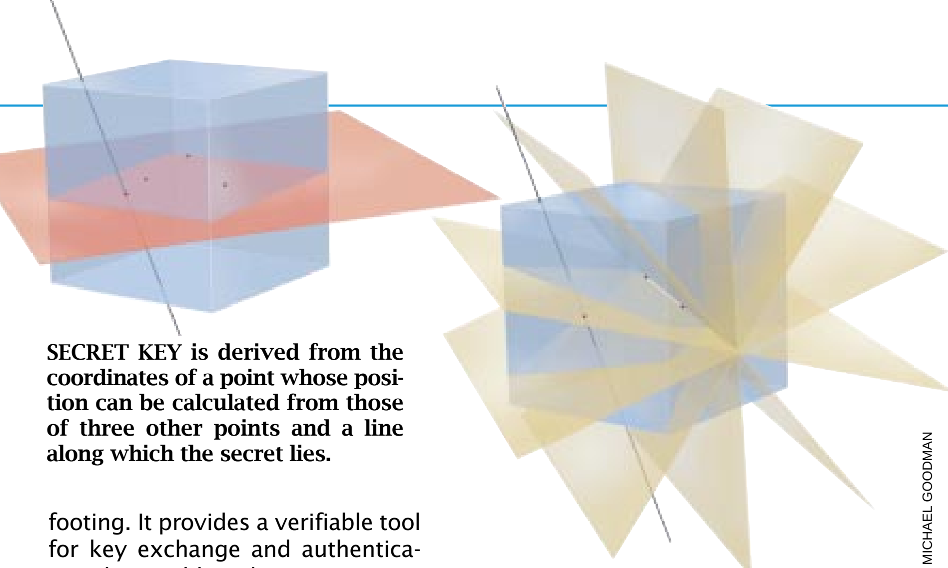
AUTHENTICATION PROTOCOL relies on a secret bit sequence known only to the certifying authority and a series of exponentiations. The authority makes available only a distorted image of its secret, but it is still possible to verify that it has signed a given document.

When Wiretapping Is Needed

The cryptographic techniques that I and my colleagues have been developing may offer a solution to the growing conflict between individuals who want to keep their messages secret and law-enforcement agencies that would like to be able to decode evidence of crimes. Fearing that wiretapping could soon yield nothing but gibberish, the U.S. government has restricted the export of encoding equipment. It has also begun pushing a "secure" telephone system using an encryption chip known as Clipper, whose keys would be held in escrow by government agencies and turned over to law-enforcement officials on request. The details of this system are secret.

This plan hardly inspires confidence. First, it is not clear that keys will be adequately safeguarded—especially when law-enforcement agencies from several countries are involved. Second, there is no way for outsiders to determine whether there are additional decryption methods that require no judicial intervention.

In contrast, the methods we have developed for SELANE can be used as the basis for a fair cryptosystem that would put users and government code breakers on an even



SECRET KEY is derived from the coordinates of a point whose position can be calculated from those of three other points and a line along which the secret lies.

KNOWLEDGE of the three points can be split among several deputies so that none alone can deduce the secret point—because an infinite number of possible planes can pass through the two points that are given to each deputy.

MICHAEL GOODMAN

footing. It provides a verifiable tool for key exchange and authentication that could work in conjunction with either the Clipper chip or more robust encryption devices. To strengthen people's confidence in the system, one could construct digital keys that would require the cooperation of several different agencies for wiretapping.

Understanding how this kind of safeguard could be achieved requires imagining the bit sequence making up a key not as one number but as three or more. Gustavus J. Simmons of Sandia National Laboratories, for instance, came up with the idea of using three parts of a secret key as integer coordinates of a point in a three-dimensional space.

All the secret number sequences that might be used are chosen from coordinates that lie on a universally agreed-on line. (Because so many points are on the line, even this "restricted" set is large enough to be secure.) To split the information about the secret point, a plane that passes through the point is selected, and three random points on it are chosen. These points can be used to reconstruct the plane and calculate its intersection with the line.

Each of the committee members receives the coordinates of two of the points. As soon as two members come together, they can determine the secret point. Thanks to SELANE, however, they can also assure themselves that they have been given accurate coordinates without actually finding the secret (and thereby compromising the associated key). If they give exponentially distorted versions of their points to their fellows, the mathematical relation that holds between those points and a distorted image of the line also exists between the real points and the line along which the secret point lies.

This principle can be generalized to a committee of any size, with arbitrary authorized subsets of members. Shared responsibility of this kind would also considerably complicate any attempt at a breach of secrecy by the use of violence, blackmail or bribery. I believe the business world would welcome such a system, particularly as an alternative to government-imposed escrow. And governments may welcome it as an alternative to the dissemination of unregulated strong cryptography that is taking place even as this article is being written. —*T.B.*

change. This protocol can be executed in a fraction of a second by a chip on a smart card. If their IDs are in order, both partners finish their initial exchange with a common key for encoding subsequent communications. If authentication fails, however, each receives a different, useless bit sequence.

Chain of Confidentiality

In principle, this authentication method depends on Bob's knowledge of—and trust in—Alice's home SKIA. Anyone who wanted to verify the digital IDs of faculty or staff at a German university, for example, would have to know the signature of the SKIA of every university's computer center.

In international data traffic, this method becomes impractical. Hence, SKIAs must legitimize themselves by procuring an ID from a superior SKIA. A central ID distribution station might be established to serve all German universities. It would certify the trustworthiness of each university's SKIA, which could certify internal SKIAs. This scheme can be extended to any number of levels. For example, a German central station can legitimize itself using the digital ID of a European ID distribution center, which, in turn, is legitimized by a worldwide organization. To verify an ID, one would need to know—and trust—only the digital signatures of a few top-level certifying authorities.

The same hierarchical structure could serve as well for corporate employees and affiliates of other institutions. In a future we hope to bring about, SELANE's principles would allow people to transact business over a network with as much confidence as they would have dealing face-to-face.

The Author

THOMAS BETH is director of the European Institute for System Security, which he helped to found in 1988. He is also professor of computer science at the University of Karlsruhe, where he has worked since 1985. He received his undergraduate degree in mathematics from the University of Göttingen and a doctorate in mathematics and in computer science and engineering from the University of Erlangen. This article was adapted from one by Beth in the May issue of *Spektrum der Wissenschaft,* the German edition of *Scientific American.*

Further Reading

A PUBLIC KEY CRYPTOSYSTEM AND A SIGNATURE SCHEME BASED ON DISCRETE LOGARITHMS. Taher ElGamal in *IEEE Transactions on Information Theory,* Vol. 31, No. 4, pages 469–472; July 1985.

EFFICIENT ZERO-KNOWLEDGE IDENTIFICATION SCHEME FOR SMART CARDS. T. Beth in *Advances in Cryptology: EUROCRYPT '88.* Edited by Christoph Günther. Springer-Verlag, 1988.

CONTEMPORARY CRYPTOLOGY: THE SCIENCE OF INFORMATION INTEGRITY. Gustavus J. Simmons. IEEE Press, 1992.

PUBLIC-KEY CRYPTOGRAPHY: STATE OF THE ART AND FUTURE DIRECTIONS. Edited by T. Beth, M. Frisch and G. J. Simmons. Springer-Verlag, 1992.

KEEPING SECRETS A PERSONAL MATTER OR THE EXPONENTIAL SECURITY SYSTEM. T. Beth in *Cryptography and Coding III.* Edited by M. J. Ganley. Oxford University Press, 1993.

RFC 1824: THE EXPONENTIAL SECURITY SYSTEM TESS. H. Danisch in European Institute for System Security World Wide Web site at http://avalon.ira.uka.de/eiss/indexe.html

Fighting Future Wars

U.S. military planners hope to rely on improved versions of the technologies tested in the Gulf War to help fight the next Saddam Hussein. They may be preparing for the wrong conflict

by Gary Stix, *staff writer*

George Patton, Dwight Eisenhower and Colin Powell all came to Fort Leavenworth on the Kansas bluffs overlooking the Missouri River to learn about the tactics and weaponry they would need in battle. This past May a new generation of military leaders peered into Sun workstations at this former Indian-fighting post to discern the future of warfare. On their screens, a North Korean force rolled across the demilitarized zone; short-range ballistic missiles carrying chemical weapons hit their mark in South Korean cities. U.S. and South Korean army divisions, with support from U.S. Marines and a French and a British brigade, slowly drove the invading troops back.

One of the U.S. units, a division called a mobile strike force, pretended to mimic the digital fighting force of the future. Pictures of the battlefield, supplied by ground, airborne and satellite sensors, provided a field commander with a sweeping view of the disputed territory, even at night. This "God's-eye" battlefield perspective helped to cement a victory.

The hostilities were what is known in Department of Defense parlance as a "Desert Storm equivalent"—a standoff against a "rogue state," an Iran or an Iraq or a North Korea. For the Pentagon, rogues are the most likely new enemy, the nuclear pretenders that pose the real menace in the post-cold-war world. According to the Clinton administration's 1993 "bottom-up review," the document that assesses the current military force structure, the U.S. should be prepared to fight two Desert Storm equivalents almost simultaneously.

But the young officers may be getting the wrong perspective from the images on those color screens. The classic rogue power relying on heavy-handed, Soviet-style fighting techniques may be an endangered species. Policy experts, technical gurus and defense contractors have begun to study a range of other potential threats, from a newly hatched superpower to a regional power with dramatically altered fighting tactics, to legions of mercenary hackers that bring down banks and stock exchanges with computer viruses and other malevolent software. The vast array of scenarios is a measure of the speculative turn that has gripped the military-planning establishment. Without the tangible presence of a superpower, new menaces can emerge from any quarter. At the same time, the most pressing drain on military resources is created by the Bosnias and the Haitis, the smaller-scale conflicts and crises that often turn contemporary soldiering into glorified police work.

The American military's high-tech expertise was honed

BATTLEGROUND CIRCA 2020 may replace massed troops and armor with networks of intelligent mines and unpiloted drones that can perform reconnaissance and launch or plant weapons. Highly dispersed special forces may scout for targets and evaluate battle damage. Remotely fired missiles may become the main instrument for destroying enemy targets.

over decades of cold war with the Soviet Union. During the 1980s, the Soviets put forward the notion that military forces should be able to detect an enemy and destroy it from a distance. As radar-laden surveillance aircraft and intelligent antitank missiles became more pivotal in the contest, however, the U.S. acquired a clear advantage. "If the key to future warfare would be the rapid processing of electronically acquired information, how could a society that was virtually incapable of manufacturing a simple personal computer keep up in the technological race?" writes Eliot A. Cohen of the Paul H. Nitze School of Advanced International Studies at Johns Hopkins University.

Replaying Desert Storm

World War III never came, but the Gulf War did. The U.S. armed forces held up the victory over Iraq as proof of the validity of their technophilic approach to fighting, involving intelligence from air and space and the use of stealth fighters and laser-guided bombs. (No matter that, notwithstanding the domination of the air, the coalition forces missed destroying installations involved in the Iraqi nuclear weapons program and mobile missile launchers.) Much of the subsequent effort of military leaders has gone toward burnishing the accomplishments of the Gulf. The army's war games, such as the exercise at Fort Leavenworth, have been oriented toward improving the digital layout of the battlefield—in essence, fighting a more efficient Gulf War.

A coterie of defense analysts, both inside and outside the Pentagon, have nonetheless begun to explore concepts of high-tech war that move beyond a replay of Desert Storm. The inspiration for some of this soul-searching comes from the Pentagon's Office of Net Assessment, a future-oriented planning office headed by Andrew Marshall, a former cold-war strategist.

One reason for a reassessment is that, within a few decades, the threat to the U.S. may come not from a small rogue regional power but instead from what has come to be known as a "peer competitor": in essence, a new superpower, such as China, a resurgent Russia or perhaps even India. In any future conflict, the U.S. and its allies may not have a monopoly, or even a strategic advantage, in the arena of advanced technology. Furthermore, regional powers have learned their own lessons from the Gulf War and are looking for ways to use and counter precision-guided weapons, computers and space-based communications.

Andrew F. Krepenevich, Jr., a former army colonel who collaborated with Marshall, now directs the Defense Budget Project, a think tank in Washington, D.C., that continues to examine radical changes in the character of warfare. He

BARRY ROSS

SIKORSKY AIRCRAFT

JOHN T. BARR *Gamma Liaison*

points to articles in Third World technical journals that talk about the Gulf War as the example of what to avoid when confronting an "extraregional superpower," a code phrase for the U.S. or any large industrial state. In a paper published after the Gulf conflict, V. K. Nair, a retired Indian military officer, outlined how a developing nation could have countered "ill-conceived adventurism" by the U.S. by crippling naval forces with land- or submarine-based nonnuclear missiles. "The possibility of the loss of one or more aircraft carriers would be a totally unacceptable risk in terms of economic and personnel losses for the United States," he wrote.

In world arms markets, an advanced weapons stockpile is available virtually for the asking. Short-range ballistic missiles and, in particular, information technologies have become commodities. Unlike nuclear weapons systems that often arose from secret work at national laboratories, Krepenevich points out that information systems have come from commercial companies. Although the U.S. and the Soviet Union largely succeeded in preventing access to the technologies needed to fabricate nuclear weapons, they would now be incapable of doing so for the memory chips or microprocessors that are the brains of "smart" weaponry.

A Real No-Man's-Land

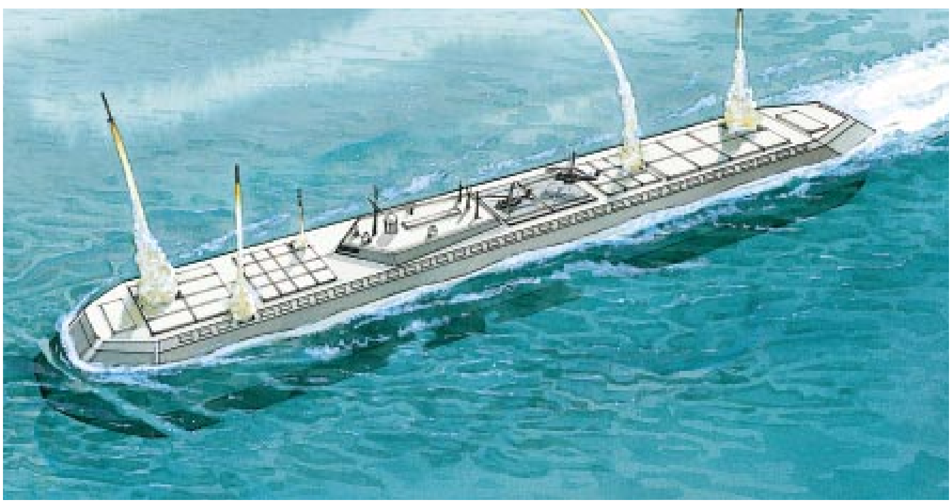
Think tanks and strategists have begun to ponder what it will mean to fight in the 21st century. Many of their speculations on what is often called a "revolution in military affairs" seek a way to fight another large power without resorting to nuclear weapons or to find the means to stay far enough away from an adversary to avoid a nuclear menace or chemical or biological armaments. Future war, in fact, may let former nuclear war planners retread a few of the scenarios conceived for a face-off with the Soviets. It might rely on nuclear-weapons delivery vehicles—cruise or other long-range missiles—armed with conventional warheads.

The lethality and precision of the weaponry, and the ability to detect an enemy virtually anywhere, suggest it will become all quiet on every front—the idea of close engagement, still a fixture of the Gulf War, will fade. Michael Mazaar of the Center for Strategic and International Studies describes "disengaged" conflict, a war fought from a distance that proceeds without a massing of troops and weapons. Missiles fired from hundreds or thousands of miles away, or even from the continental U.S., might converge on a single location or several strategic targets at once.

In this long-term scenario, aircraft carriers, tanks, fighters and bombers may cease to have a primary role in the postmodern theater of war. Most U.S. forces might be stationed at home. During the first stages of a conflict, long-range missiles would destroy air defenses or other key infrastructure. Later, inexpensive staging platforms would be needed to field large numbers of missiles, weapons systems far less expensive than the submarines and aircraft carriers now used. Some analysts have even toyed with the notion of a missile-laden Boeing 747 or a subsurface tug carrying a barge crammed with projectiles.

The navy, in fact, has begun to consider building an arsenal ship, which might be a tankerlike vessel loaded with hundreds of vertically launched cruise missiles or other projectiles. The arsenal ship, which would be partially submerged to avoid detection, is estimated to cost less than a fifth of the purchase price of a $4.5-billion aircraft carrier. Instead of a crew numbering in the thousands, it might need fewer than 50 people.

Big changes would occur in land warfare as well. At least in the early stages of a conflict, in a step toward the science-fiction fantasy of robotic warfare, most human soldiers might be kept well away from the battlefield. The reconnaissance and targeting role will increasingly be taken over by unpiloted aircraft, highly novel versions of those flown during Desert Storm and in Bosnia. Tiny, low-cost sensors in the air or on the ground might be deployed by



BARRY ROSS

ARSENAL SHIP (*left*), with a design perhaps based on that of commercial tankers, could carry hundreds of missiles. The semisubmersible vessel might one day play a strategic role—deploying weapons to their targets—that now is filled by the airplanes on a carrier (*right*).

AW&ST *Gamma Liaison*

PERSONAL COMPUTERS versus mainframe? Unmanned aerial vehicles, such as the six-foot-diameter rotary-motor-powered prototype tested by Sikorsky Aircraft (*left*) or the stealthy drone manufactured by Lockheed Martin and Boeing (*middle*), are in development. They could gradually take over some of the functions of large surveillance aircraft, such as the U.S. Army's joint surveillance target-attack radar system (*right*).

the hundreds or thousands, forming a network that could beam a composite image of an unfolding skirmish.

Electronic intelligence today depends heavily on large aircraft filled with sensors—the air force's advanced warning and control system (AWACS) or the army's joint surveillance target-attack radar system (JSTARS). Precisely because the battle view supplied would become ever more crucial, an AWACS or a JSTARS would be increasingly vulnerable: if shot down, it could cause an electronically illuminated battlefield to go dark. Safety in numbers may be the answer. A research group at the Massachusetts Institute of Technology's Lincoln Laboratory has contemplated building drones smaller than a model airplane. Eventually, large numbers of these minute craft could collectively act as battle surveyors. Sikorsky Aircraft has fashioned a flying-saucerlike vehicle, powered by rotary motors, that could act as a scout or drop mines or sensors. "If you have 1,000 unmanned aerial vehicles, you can afford to lose 100," says Martin C. Libicki of the National Defense University.

At least in theory, land-based weapons could also become smart, numerous and relatively cheap. Lethal robots may look less like the Terminator than like a mine. Military contractor Textron Systems Division, for example, already has a "wide area mine" that uses sensors to detect a tank or helicopter and then launches projectiles at it.

The few manned units sent to the battlefield would consist of dispersed special operations units that could perform reconnaissance missions or determine battle damage. Contingents spread out over the landscape might ride in stealthy attack helicopters or commercially purchased Jeeps, the chassis only lightly armed but crammed full of sensors and communications and jamming gear. Toward the latter stages of a conflict, more conventional armored and infantry forces would arrive; combat might still end by occupying territory.

Future war might become a contest for domination of space, as both sides try to deploy and preserve communications and surveillance satellites. Concocting lasers or weapons that employ the kinetic energy of a high-impact collision to kill satellites might give aging Strategic Defense Initiative scientists a chance to dust off old research papers. Single-stage-to-orbit launch vehicles might be needed to place a network of satellites over a battle area.

The most important changes may relate not to the technology but to the way these systems transform military organization—and the pace at which decisions are made. "The real innovation may be the ability to integrate sensors and weapons to coordinate forces effectively," says Andrew Marshall of the Office of Net Assessment. In the year 2020 the panoramic image of battle that emerges from the mesh of sensors may make military commanders more into split-second air-traffic controllers than deliberative strategists and tacticians. The same commander may order weapons strikes from air, land or sea—or maybe even space. In some cases, targeting information may be beamed directly from a satellite or an unmanned aerial vehicle to a soldier in the field.

War by Wire

Debate on high-tech fighting culminates in the question of whether information technologies—a computer virus, for one—could make conventional military hardware obsolete and whether they would make possible a virtual invasion of the continental U.S. A battle of the bits would be fought by destroying an enemy's information assets, its financial, electrical, telecommunications and air-traffic-control networks. Direct strikes at the military would not be ruled out: cracking a government computer is already a not infrequent hacker rite of passage. In addition, more than 95 percent of military communications travel over public networks.

Daniel T. Kuehl is a professor of military strategy at the National Defense University, who earlier in his career worked for the Strategic Air Command planning where to aim nuclear weapons at the Soviet Union. He now teaches at the School of Information Warfare and Strategy, established two years ago at this graduate military school. The program offers courses in cyber-war similar to those that have recently sprouted throughout the military. It joins a number of offices in the Pentagon and the various services that bear the name "information warfare."

Kuehl's students will return to the armed forces and other government posts to help defend against attacks on

ASSOCIATED PRESS

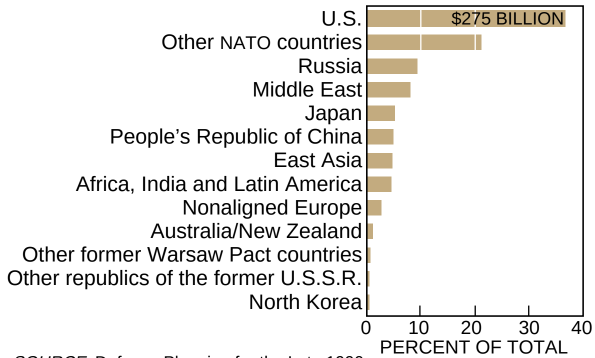
A Faster, Cheaper, Smaller Military?

Defense budgets have dropped somewhat in inflation-adjusted dollars from their cold-war average of $300 billion. Nevertheless, with expenditures totaling about $260 billion for the current fiscal year, the U.S. spends more on defense than every prospective enemy and neutral country combined. "We could probably cut defense spending by $35 billion and still remain the world's preeminent military power," notes Lawrence Korb, a senior fellow at the Brookings Institution and a former assistant secretary of defense in the Reagan administration. (The chart below conveys an idea of the magnitude of U.S. spending for 1993.)

A war that emphasizes precision-guided missiles and commercially procured information and transport technologies might cost less to fight than one that relies on large weapons systems, a Seawolf submarine and an F-22 fighter. Moreover, readying military forces to fight two almost simultaneous Desert Storm–like conflicts may prove an unnecessary extravagance in an era of budget tightening. The Defense Budget Project, an independent research organization, has recommended that preparing to fight only one regional conflict may be a means to free up funding to experiment with new technologies—an arsenal ship or networks of unmanned aerial vehicles.

But the track record on embracing wholly new types of warfare is not particularly good. In 1978, more than a decade before the end of the cold war, physicist Philip Morrison and political scientist Paul F. Walker wrote a book on military spending that suggested that a relatively inexpensive national defense could be built around precision munitions, thereby forgoing vulnerable weapons platforms such as the aircraft carrier. Budgets, they asserted, could be cut by 40 percent. Their ideas, of course, have remained no more than academic treatise. "We want to say warfare is changing, but not ours," Morrison remarks today.

GLOBAL MILITARY EXPENDITURES IN 1993



SOURCE: Defense Planning for the Late 1990s, *by Michael O'Hanlon (Brookings Institution, 1995)*

Scenarios for future wars, in fact, could simply become a means of preserving the status quo. "Is the Pentagon's Revolution in Military Affairs a scam?" writes Steven Aftergood of the Federation of American Scientists. "Could it be just another, more seductive way of packaging military programs to help sustain defense budgets at a time when the long-standing military justification for existing structures and programs has diminished sharply?"

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information resources. "How do you know you're under attack and who did it?" Kuehl asks his classes. Other points for discussion: Does the military have any responsibility for defending the stock market against malicious attack? Should a nation declare war when a major financial system is brought down through electronic means? Should it respond with conventional or nuclear weapons? When is victory achieved in such a conflict? Should the U.S. engage in offensive information maneuvers to destroy or muddle databases an enemy uses to choose targets?

Tofflerian Wave Theory

These questions often get mixed with a large helping of popular sociology. The School of Information Warfare and Strategy may be the first graduate program to frame a course of study around the ideas of mass-market authors Alvin and Heidi Toffler, perhaps best known these days as consultants to Speaker of the House Newt Gingrich. The Tofflers have had a pervasive influence on the military. In a monograph entitled "Envisioning Future Warfare," recently retired army Chief of Staff General Gordon Sullivan cites Alvin Toffler in 10 of 38 references.

At the school of information warfare, the world becomes segmented by the Tofflers' "wave" theory, the notion that society—and war itself—is passing into a postindustrial information age that follows a "second wave" industrial era characterized by the use of tanks and bombers and a "first wave" agrarian economy that employed muskets and spears. "As the Third Wave war-form takes shape, a new breed of 'knowledge warriors' has begun to emerge—intellectuals in and out of uniform dedicated to the idea that knowledge can win, or prevent, wars," the Tofflers write earnestly in *War and Anti-War.*

Elite corps of knowledge warrior-hackers may not be able completely to replace conventional divisions of 20,000 armed grunts. John I. Alger, dean of the information warfare school, lapses into Tofflerese to explain why. "Most of the world still has second-wave armies, and we still have to concern ourselves with physical destruction as a threat to the U.S.," he says.

This vision of wars to come may emerge from reading too many futuristic treatises. Not everyone in the defense establishment warms to embracing the new fighting methods so quickly. The military still treasures its aircraft carriers and fighter planes. Reticence may also stem from a fear that the new technologies may not work as expected. Two sides lobbing missiles at each other may revive an apocalyptic form of trench warfare in which each side bloodies the other but fails to achieve victory. "It may be a long-range equivalent of 1914," says Daniel Gouré of the Center for Strategic and International Studies in reference to the World War I stalemate.

And flooding more information to soldiers may not give them a better grasp of an unfolding battle. The U.S. military has wrestled with the travails of the information age since the Vietnam War. Instead of streamlining the management of war, the expanding communications infrastructure in Southeast Asia led to a burgeoning of support personnel. Five percent of all troops there—a unit larger than a division—handled communications. In his 1985 book, *Command in War,* historian Martin van Creveld of the Hebrew University in Israel notes that "the communications establishment made possible by the revolution in technology, and necessary in order to deal with the consequences of specialization and complexity, had itself turned into a major source of both specialization and complexity. The cure was part of the disease."

Things have not necessarily changed. The U.S. Army has stated its intention of using high technology to decrease the size of its forces. But this past August, in a war game that deployed armored units to test digital communications systems, soldiers found they had more work—time spent putting information into computers or connecting one system to another, according to a report in the independent newsletter *Inside the Army.* After the exercise, an officer offered the opinion that the targeting efficiency of a new tank, the M1A2, might improve fighting capability more than advanced digital communications could.

In another war game in 1994, a digital battalion became confused when a nonautomated opponent lit fires to fool, or "spoof," infrared sensors deployed by the high-tech forces. What is more, the digital soldiers performed no better than other units that had fought the same opponent without advanced equipment.

Issues of cost and technical feasibility also pervade the debate over the naval arsenal ship. The new vessel might not be such a bargain. It has to travel with other ships for protection. An electronic message posted on the Internet lampooned the idea: "One low-tech incoming, and we could double the national debt," a suggestion of what might happen to an arsenal ship if targeted by an inexpensive missile.


LAWRENCE LIVERMORE NATIONAL LABORATORY

SNIPER TRACKER, developed by Lawrence Livermore National Laboratory, determines the location from which an automatic rifle (*background photograph*) fires. On the tracking screen, the cross in the rectangle at the bottom left shows the firing point. Each series of colored squares represents the track of a bullet.

Low-Intensity Conflict

If the military is looking for the nature of war in the next century, it may be looking in the wrong place. By some accounts, the generals have yet to learn the lessons—or adapt their war-fighting methods—to the type of conflict that has predominated since World War II. This argument represents a broadside on the school of military thinking associated with Carl von Clausewitz, the Prussian army officer whose writings on war are often distilled to the cliché that war is a continuation of politics by other means. This intersecting notion of politics and armed conflict can be linked to the idea that the modern state and its armies are the only legitimate purveyor of organized violence. Anyone else taking up arms is either an outlaw or a bandit.

A number of military historians have declared the Clausewitzian world of states fighting states to be effectively dead. In his book *The Transformation of War*—published, in a grim irony, on the day the ground offensive of the Gulf War was launched in 1991—van Creveld argues that the terms of modern warfare and the costs of advanced weapons systems are making traditional combat ever less likely. In a nuclear era, all sides must exercise restraint or risk mutual annihilation. This measure of self-control, van Creveld believes, also extends to the use of chemical and biological arms. Few nations would dare to unleash them against an enemy, for fear that the retaliation, by the attacked state or one of its more powerful allies, might be a nuclear strike. (Unfortunately, chemical and biological weapons might still become the inexpensive weapons of choice among terrorists, who would not be constrained by this vulnerability.)

In a world populated by nuclear weapons and their cousins, war has not gone away but simply shifted to another arena. Van Creveld maintains that most conflicts—Somalia, Rwanda and even Bosnia—do not involve state against state and that these wars take place largely without deploying advanced weaponry. Of the 100 or so wars fought since World War II, more than 80 have been characterized as low-intensity conflicts, many of which are civil wars or ethnic hostilities. They are often engendered over scarcity of resources [see "Environmental Change and Violent Conflict," by Thomas F. Homer-Dixon, Jeffrey H. Boutwell and George W. Rathjens; SCIENTIFIC AMERICAN, February 1993]. Low-level struggles, despite the modest sound of the name, often attain genocidal levels of bloodshed. The Nigerian civil war claimed the lives of more than one million people from 1967 to 1970, and turmoil between Hindus and Muslims in India took a toll of one million from 1947 to 1949. The neat categorizations on the nature of warfare set out in the Clausewitzian universe have been completely lost in the strife.

Peacekeeping has therefore become the order of the day. Unfortunately, that order flummoxes many in a military elite that has spent decades preparing to stop waves of Soviet tanks from rolling across across the West German border. These officers, too, still experience lingering effects of a post-Vietnam syndrome, that soldiers should leave the barracks only to protect clear-cut threats to the national interest. In a 1993 U.S. Army manual this type of quasi-police activity is relegated to a chapter with the Orwellian title "Operations Other Than War."

The various service branches do train for what is reduced to the inevitable acronym "OOTW." The army, for one, has set up a peacekeeping institute at its Army War College in Carlisle, Pa. But the military and Congress have a decidedly ambivalent relationship to these types of conflicts. Chairman of the Joint Chiefs of Staff General John Shalikashvili commented last year: "My fear is we're becoming mesmerized by operations other than war, and we'll take our mind off what we're all about, [which is] to fight and win our nation's wars."

Nevertheless, the military has devoted some effort to devising weapons and tactics more appropriate to the next Somalia than the B-2 bomber and the Trident submarine are. The army, the Department of Energy, the Advanced Research Projects Agency and other research institutes have labored on technologies that would minimize the bloodshed, or at least the public-relations sting, of these nasty and brutish affairs.

Lawrence Livermore National Laboratory has devised an infrared sensing system, called Lifeguard, that could be used by peacekeepers or even police to detect the precise location from which a sniper's bullets originate. The Advanced Research Projects Agency has equipped U.S. soldiers on a peacekeeping mission in Macedonia with a combination rescue-radio and satellite-location receiver that beeps when a soldier or vehicle gets within 500 meters of the Serbian border. (Crossing the bor-

SCOTT PETERSON *Gamma Liaison*

"TECHNICALS," pickup trucks with automatic weapons, have been used by clans in Somalia to terrorize the streets of the capital city of Mogadishu. They are a product of a deadly indigenous cottage industry.

der inadvertently could cause an international incident.)

A set of unusual technologies has begun to contribute to peacekeeping. "Nonlethal" weapons are intended to stun or immobilize but spare their victims. A chemical that makes a street slippery or sticky, rendering it impassable to traffic and passersby, may deflect public condemnation. "Rather than shooting a 14-year-old boy, you stop him with sticky glue," says Andrew J. Bacevich of the Nitze School at Johns Hopkins. "You can do an operation without having the media lambaste you for inhumane and cruel treatment."

U.S. marines dispersed a mix of sticky foam, concertina wire and small, pointed objects that look like jacks to hold off crowds of Somalis during the withdrawal of U.N. peacekeeping troops in early March, says Charles S. Heal, the marine officer who coordinated the use of these weapons. The troops had a five-minute respite before the Somalis put down planks and used a number of other ploys that enabled them to traverse the barrier.

Threats of force were perhaps as effective in Mogadishu. Training a visible laser used to illuminate targets on trespassers who made their way onto a runway kept loyalists to warlord Mohammed Farah Aidid outside the airport perimeter. "The guys had seen enough Schwarzenegger movies to know it worked," says Anthony Fainberg of the recently disbanded Office of Technology Assessment.

The nonlethals are subject to the same dynamics as other weapons technologies—any armament engenders countermeasures. "Sand spread on the stickum-coated pavement would presumably stick (what else?) and provide a sandpaper surface on which one could walk or drive," writes Richard L. Garwin, an IBM fellow and a longtime adviser on defense technologies and arms control. "Before sand could be spread, attaching a pad of newspaper on the sole…would allow one step per page—enough to cross a small region of stickum-covered pavement at high speed."

Nonlethals also bear a taint of deadliness and may prove inhumane. "The grime from hell," as Garwin calls one hypothetical weapon, a thin layer of paint that can be sprayed onto an aggressor's windshield to obscure vision, could certainly cause a fatal loss of vehicle control. An international ban was recently approved on lasers that permanently blind victims, a type of weapon classified as nonlethal.

Low-Tech Retaliation

Soldiers armed with weapons that do not kill face a fundamental dilemma in fighting a war. "To paraphrase Clausewitz," van Creveld says, "those who think war can be waged without bloodshed should be wary of an opponent coming along and cutting off their heads." While the West concocts kinder and gentler weapons, determined irregular fighters in the Third World (or elsewhere) may fail to observe a protocol that avoids deaths. The quintessential postindustrial war machine is a Somali "technical," a pickup truck with an automatic weapon mounted in the back.

Moreover, a Somali warlord or his ilk may not have to gain an ultimate strategic advantage to win. He may indulge in the subtleties of information warfare and global public relations by manipulating the power of satellite news broadcasting to influence an event without recourse to superior weaponry. The impact of television imagery of a dead U.S. soldier being dragged through the streets of Mogadishu most likely contributed to the U.S. decision to call off a hunt to track down Aidid and to set a date for a withdrawal of its troops.

A tribal leader, meanwhile, may conduct information warfare with technologies that predate Thomas Edison. Aidid's followers in Somalia reportedly communicated U.S. troop activity at the Somali airport to their peers by beating wooden sticks on oil barrels. To avoid detection, Aidid shunned use of the telephone altogether.

Messages encoded as drumbeats will leave suites of infrared sensors undisturbed. Technological sophistication, a prerequisite for strategic dominance in a regional theater of war, may thus founder in the chaos of a Saigon or a Mogadishu. "We're getting a lot of clever ideas about how to fight a Gulf War more efficiently," remarks Libicki of the National Defense University. "But we rarely get anything about how to fight a Vietnam more efficiently."

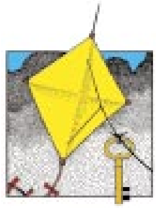
The disparity between war as a technological tour de force and the realities of low-level conflict have yet to be reconciled by the leaders of large standing armies. Precision bombing may achieve some success in Bosnia. But decisions to proceed with air strikes become muddied when U.N. troops are chained as hostages to Serb military targets. War at a distance—the vision put forth by the seers of future conflict—may quickly erode in the ambiguities of OOTW. Peacekeeping may confound the complex stratagems of nuclear planners, who have defined the nature of warfare for the past half century. The fragile cold-war balance of power has given way to a fog of peacetime.

Further Reading

THE TRANSFORMATION OF WAR. Martin van Creveld. Free Press, 1991.

MONITORING EMERGING MILITARY TECHNOLOGIES. Steven Aftergood in *Federation of American Scientists Public Interest Report,* Vol. 48, No. 1, pages 1–14; January–February 1995.

THE MESH AND THE NET: SPECULATIONS ON ARMED CONFLICT IN A TIME OF FREE SILICON. Martin C. Libicki. Available on the World Wide Web at http://www.ndu.edu/ndu/inss/macnair/mcnair28/m028cont.html



THE AMATEUR SCIENTIST conducted by Shawn Carlson

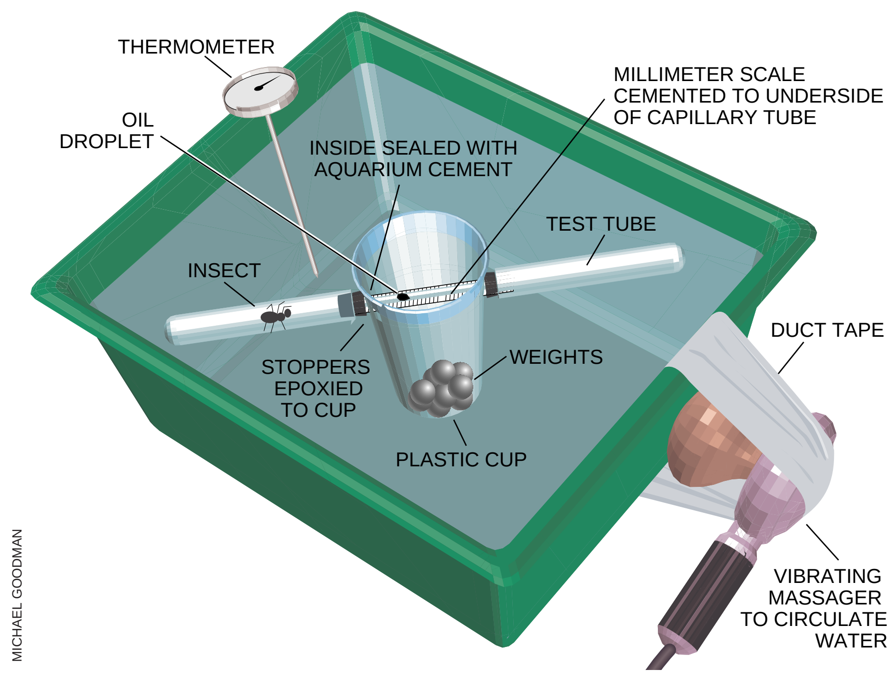
Measuring the Metabolism of Small Organisms

Metabolism is basic to life. Everything that breathes combines chemical energy stored in its tissues with oxygen contained in the atmosphere to liberate energy to grow, move and reproduce. Despite long-running efforts, biologists have so far surveyed only the basics of metabolism. Life is so diverse that discoveries await anyone who ventures carefully into these deep waters. Of course, few amateurs can grapple with the many technical and ethical complexities involved in experimenting on large or warm-blooded animals. Fortunately, most of the earth's 10 million or so species are quite small and cold-blooded. Indeed, insects offer myriad opportunities for amateur exploration.

It is actually quite simple to measure the metabolism of an insect. When an organism is enclosed in an airtight container, its respiration removes oxygen molecules from the air and releases carbon dioxide. Often fewer molecules are added to the air than are removed. The resulting loss causes the pressure inside the container to fall.

That pressure drop is key to measuring metabolism, and it can easily be observed using a device called a Warburg apparatus [*see illustration below*]. The instrument consists of two stoppered test tubes connected by a capillary tube. A tiny droplet of oil (or soap) in the capillary tube moves in response to pressure differences between the test tubes. Therefore, as the respiration of an insect in one of the test tubes causes a decrease in pressure in that tube, the oil drop will slip toward it. You can witness this movement if you warm one test tube with your hand. That makes the air inside expand and push the droplet to the cooler test tube. To quantify the movement of the droplet, photocopy a ruler with millimeter gradations and tape the copy to the capillary tube.

As the warming with your hand demonstrates, the device is sensitive to small temperature differences between the test tubes. The best way to ensure equal temperatures is to submerge the tubes in a large basin of water. To keep them below the surface, attach them to the sides of the plastic cup. Weigh the cup down with sand, pebbles or a fistful of spare change. The cup also permits you to view the oil in the capillary tube in dry air. To reduce further the effects of temperature gradients, set the water moving slowly with a handheld body massager.



***INSECT RESPIRATION** can be calculated by knowing the air pressure, the water temperature and the distance covered by an oil droplet in the capillary tube.*

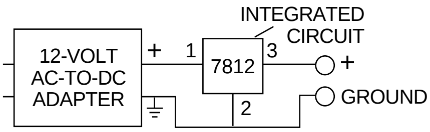
If you know the air pressure, the water temperature and the distance the oil drop moves, you can determine the number of molecules the insect respires. The box on the opposite page lists the exact relations.

The next step is to find the ratio of carbon dioxide produced to oxygen consumed. Called the respiratory quotient, it represents a fundamental measure of metabolism. It tells you what biological fuel the organism is burning. If it is converting sugar, the ratio is 1; for fat, about 0.70; for protein, about 0.80; for alcohol, about 0.67. For most creatures, the quotient ranges from 0.72 to 0.97, because organisms metabolize several kinds of energy sources simultaneously.

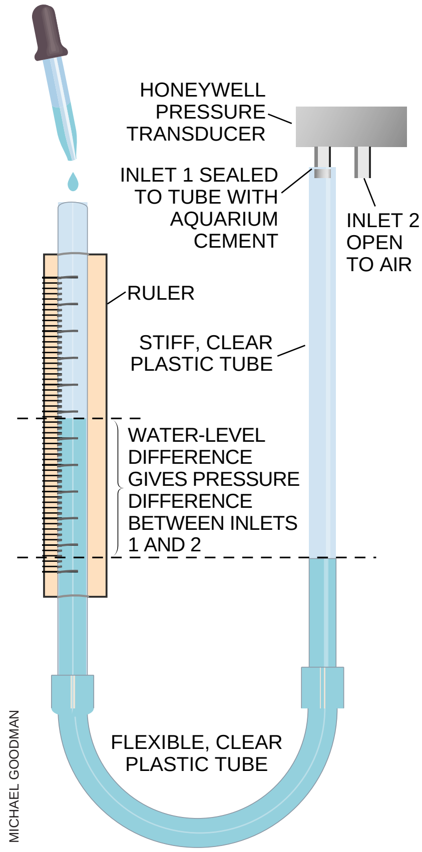
To measure the respiratory quotient, you will need some sodium hydroxide ($NaOH$), which absorbs carbon dioxide from the air. Purchase this compound in solid form from any chemical supply house; check your Yellow Pages. But watch out—sodium hydroxide is caustic and will burn skin and eyes if not handled properly. Rubber gloves and safety goggles should be worn.

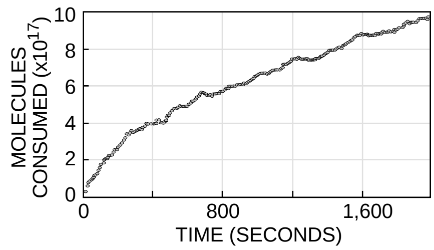
Before conducting trials, you will need to clear all the carbon dioxide out of the test tubes. Place several grams of NaOH in just one test tube. The toe of a nylon stocking makes an excellent pouch to hold the chemical; ball the nylon up on the open side to prevent the insect from touching the NaOH. Measure how long it takes for the droplet to stop moving, that is, for the NaOH to remove the carbon dioxide from the air. Make sure to wait at least that long before you start each trial. You will want the system to come to equilibrium quickly, so use a lot of NaOH. (Alert readers may wonder about water vapor, which NaOH also absorbs; for technical reasons, it will not affect the measurements.)

Now you are ready to begin the experiments. First, place both the wrapped NaOH and the creature inside one test tube and just NaOH in the other. Measure how long it takes for the droplet to move at least five times the smallest distance marked on your scale. Then run a second trial for exactly the same length of time, but with only the organ-



CALIBRATION of the Honeywell transducer relies on a difference of water level in the two stiff tubes **(right).** ***The transducer itself is powered by a type 7812 chip*** **(above).** ***To clear any drops that get trapped, insert a wire into the tubes.***





BEETLE BREATHS recorded over time indicate, by dips in the plotted curve, that the insect "exhales" about once every seven minutes. (Data were taken without NaOH.)

ism. The box lists the equations needed to obtain the respiratory quotient. Note that your results will be valid only if the organism is in the same physical state in both trials (not calm in one and agitated in the other, for example), if the NaOH removes all the carbon dioxide from the air before that trial begins and if both trials are run for exactly the same length of time.

With an investment of about $100, you can collect professional-quality data suitable for publication in a research journal. You will need to buy an electronic differential pressure transducer, a device that converts pressure differences into voltages that can be measured with a voltmeter. I used a Honeywell model (No. 163PC01D36) that registers pressure differences as small as 0.0003 percent of one atmosphere. (For more information about this sensor, call the Honeywell Corporation at 1-800-537-6945.)

The power-supply circuit for the device could not be simpler. It consists of an AC-to-DC adapter wired to a type 7812 integrated-circuit chip. Its voltage drifts a bit, causing the transducer's output to wander about 10 millivolts, but that should not pose much of a problem.

You will need to calibrate the transducer with a manometer—a clear, U-shaped plastic tube with some water inside [*see illustration above*]. I made mine out of two thin, stiff tubes I found in the garden department of a hardware store. Aquarium pet stores also stock similar kinds of tubes. I joined the pieces by inserting each into opposite ends of a six-inch-long flexible acrylic tube. The difference in height in the water column on either side of the U is a direct measure of the pressure. You can plot the output voltage against that difference, in inches (to match the standard units that pressure transducers made in the U.S. use).

The transducer has two inlets that permit easy connection to the rubber stoppers of each test tube in the Warburg apparatus. I used this setup to measure the respiratory quotient of a beetle, which I found to be 0.701, averaged over several breaths. Of course, you can also measure the metabolism of other living things: mushrooms, seeds, bread mold, to name a few.

For more information and suggestions for additional experiments, send $2 to the Society for Amateur Scientists, 4951 D Clairemont Square, Suite 179, San Diego, CA 92117, or download the information free from http://www.thesphere.com/SAS/ or on Scientific American's *area on America Online. Special thanks are due John Lighton, professor of biology at the University of Nevada, for his assistance in preparing this column.*

Calculating Respiration

The number of molecules the organism respires, or ΔN, is equal to $9.655 \times 10^{16}\ PA\Delta L/T$. Here P is the atmospheric pressure in centimeters of mercury (if you do not have a barometer, call your local weather service whenever you conduct a trial), A is the cross-sectional area of the inside of the capillary tube in square millimeters, ΔL is the distance the droplet moves in millimeters, and T is the temperature of the water bath in kelvins. To convert Celsius to kelvins, add 273.15 degrees. The numerical constant is my own derivation from the physics involved.

Figuring the respiratory quotient—the ratio of carbon dioxide molecules released to the number of oxygen molecules consumed—is not much more difficult. It equals

$$\frac{\Delta N_{O+NaOH} - \Delta N_O}{\Delta N_{O+NaOH} + \Delta N_O} = \frac{\Delta L_{O+NaOH} - \Delta L_O}{\Delta L_{O+NaOH} + \Delta L_O}$$

where ΔN_O is the number of molecules removed by just the organism, and ΔN_{O+NaOH} is the number of molecules removed when both the organism and the NaOH are in the test tube.

As is the case for ΔN, the subscripts denote the conditions of the trial: either with the organism alone or with the organism and the NaOH. Note that you do not need to know the atmospheric pressure, temperature or area of the capillary tube if you are looking solely for the respiratory quotient.

If you use the differential pressure transducer, the equations are slightly different. The value of ΔN equals $1.804 \times 10^{19}\ V\Delta P/T$, where V is the volume in cubic centimeters of the test tube containing the organism (allow for the volume taken up by the insect and the NaOH), ΔP is the pressure change in inches of water, and T is the temperature of the water bath in kelvins. The respiratory quotient then equals $(\Delta P_{O+NaOH} - \Delta P_O)/(\Delta P_{O+NaOH} + \Delta P_O)$, where ΔP_{O+NaOH} is the pressure change measured with both the organism and the NaOH in the test tube, and ΔP_O is the pressure change measured when the organism is by itself.

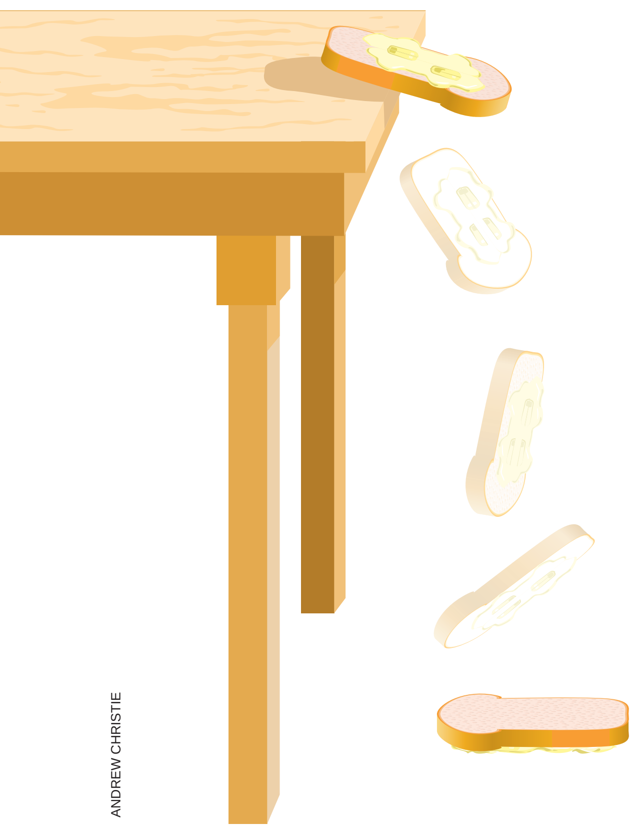
The Anthropomurphic Principle

I've never had a piece of toast
Particularly long and wide,
But fell upon the sanded floor,
And always on the buttered side.

So wrote the poet James Payn in parody of Thomas Moore's lines about a gazelle in "The Fire Worshippers." The event Payn describes is the archetypal instance of Murphy's Law, which states that if anything can go wrong, it will. A captain in the U.S. Air Force—no prizes for guessing his surname—made the observation during the late 1940s. His law has many variations and extensions, such as "Even if it can't possibly go wrong, it still will." The prediction appears under many names other than Murphy. And in 1991 the British Broadcasting Corporation's television series *QED* nearly disproved it.

The show's host tossed toast into the air 300 times under various conditions and found that it was not prone to land buttered face down. Indeed, the results were statistically indistinguishable from chance. There the matter might have rested were it not for Robert Matthews, a British journalist with a mathematical streak. Writing in the *European Journal of Physics,* he has recently described two problems with *QED*'s experiments. First, Murphy's Law by nature may conspire to falsify any experiments aimed at testing it. Second, toast is not normally hurled into the air during breakfast but most often knocked sideways off the edge of a table. *QED*'s experiments should have mimicked this same motion.

Before we proceed, it is important to note that butter makes up no more than 10 percent of the total weight of a typical piece of toast. Most of this added mass is absorbed into the middle of the bread. So the topping has little effect on the dynamics of flying toast. Its effect on the aerodynamics of the toast—resulting from changes in surface viscosity—is even more negligible. Further, Matthews traces Murphy's Law to a simpler asymmetry: because the top surface of toast is buttered, that same surface remains on top when the toast is nudged over the edge of a table.



ANDREW CHRISTIE

As the toast falls toward the ground, it rotates at an angular velocity determined by the degree by which its center of mass hung over the table's edge as it began its descent. Might it be the case that the height of a normal table and the earth's gravitational force conspire to create a predominance of rotations through an odd multiple of 180 degrees? The short answer, according to Matthews's calculations, is that they do. Indeed, a rotation that flips the toast over once for a butter-down landing is by far the most common.

Before considering the underlying reasons for this unhappy coincidence, we would do well to summarize Matthews's mathematical arguments. The illustration in the box on page 106 shows the initial configuration of the toast and the main variables involved, together with some key formulas derived from Newton's laws of motion. The main conclusion is that the toast cannot land butter up unless the "critical overhang parameter"—the fraction of the toast that hangs over the edge just before it falls, relative to half the width of the toast—is at least 6 percent. Experiment shows that for bread this value is 2 percent and for toast, 1.5 percent. Both are far too small for the bread or toast to rotate through at least 360 degrees on its way to the floor. Because the rotation is provably at least 180 degrees, a butter-down landing is the inevitable result.

Matthews's case makes a number of assumptions, one being that the toast does not bounce when it hits the ground. The typical outcome is, after all, a splat, not a boing. Another guess is that the toast slides slowly over the table's edge so that it detaches at the critical overhang value. No real difficulties here, either. Unless the horizontal velocity imparted to the toast as it goes off the edge is at least 1.6 meters per second—a fairly hefty wallop—it has no serious effect on the fall. So if you notice toast sliding off your table, you could bat it firmly with your hand. The strategy might not save your toast, but it should avoid buttering the carpet.

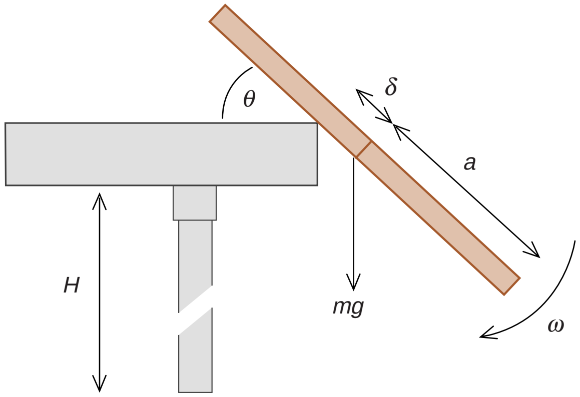
This analysis is all very well, but it suggests that Murphy's Law is merely a coincidence, a strange case of "murphic resonance" resulting from the arbitrary values human culture assigns to tables and toast, in conjunction with the equally arbitrary value of the earth's gravitational field. In fact, as Matthews demonstrates, nothing could be further from the truth. Murphy's Law, as embodied in twirling toast, is a deep consequence of the fundamental constants of nature. Any universe that contains creatures remotely like us will necessarily inflict Murphy's Law on its inhabitants—at least if they eat toast and sit at tables.

The precise argument is technical and convoluted, but its outlines are simple. The key piece of information comes from William H. Press of Harvard University, who put forth in 1980 that the height of an organism that walks on two legs is limited by the gravitational field in which it lives. Compared with quadrupeds, bipeds are intrinsically unstable. Their center of mass need only stray outside their "footprint" for them to topple over. Quadrupeds have a much larger region of stability; it is no acci-

The Murphodynamics of Toast

Define the critical overhang parameter—the initial portion of the toast that hangs over the table divided by half the width of the toast—as η. Then Newton's laws of motion lead to the relation $\omega^2 = (6g/a)(\eta/(1+3\eta^2))\sin\theta$, as long as the toast is pivoting about the edge of the table. The toast begins to slip when its weight exceeds the frictional force at the table's edge. The rotation rate at that instant is the rate at which the toast will thereafter rotate during its drop.

Simple estimates show that the toast will flip through at least 180 degrees on the way to the floor. To land butter side up, it must therefore rotate at least 360 degrees. We know how fast the toast is rotating, and H, together with g, tells us how long it will take until the toast hits the floor. For tables and toast of conventional dimensions, Matthews shows that the toast rotates at least 360 degrees only when the critical overhang parameter is greater than 0.06. The critical overhang occurs when the toast first detaches itself and begins to fall freely.



g = acceleration from gravity
m = mass of the toast
a = half-width of the toast
δ = initial overhang
θ = angle of rotation
ω = angular velocity of rotation
H = height of the table

dent that giraffes are taller than humans.

The maximum height for a biped is one at which, were the organism to fall, damage to its head would likely cause death. It is reasonable to assume that the height of a table used by such an intelligent biped would be about half its own height. On the earth, a table must be some 10 feet high for Murphy's Law to be violated, so we would have to be nearly 20 feet tall to escape the unfortunate consequences of murphic resonance. The real question is: Might some race of aliens on some distant planet be murphically immune?

To find out, Matthews models an alien as a cylinder of polymer topped with a headlike sphere. I will call such an organism a polymorph. Death occurs if the chemical bonds in a polymer layer shear. Matthews determines that the height of a viable polymorph is at most $(3nq/f)^{1/2}\mu^2 A^{-1/6}(\alpha/\alpha_G)^{1/4}a_0$. In this equation, n is the number of atoms in a plane across which any breakage takes place (typically about 100); q equals 3.10^{-3}, a constant related to polymers; f is the fraction of kinetic energy that goes into breaking the polymer bonds; μ is the radius of polymeric atoms in units of the Bohr radius; A is the atomic mass of polymer material; α equals the electronic fine structure constant $e^2/(2h\varepsilon_0 c)$, where e is the charge on the electron, h is Planck's constant, ε_0 is the permittivity of free space, and c is the speed of light; α_G is the gravitational fine structure constant $2\pi G m_p{}^2/hc$, where G is the gravitational constant, and m_p is the mass of the proton; and a_0 is the Bohr radius.

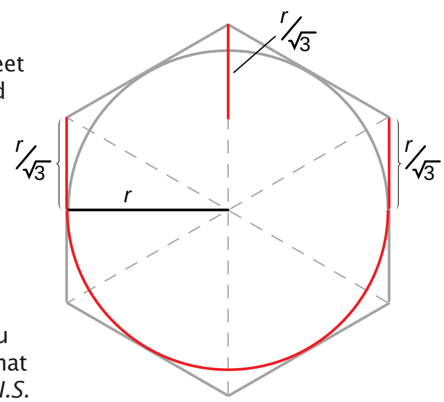
Plugging in the relevant values for our universe, we find that the maximum safe height for a polymurph is nine feet and eight inches. (The tallest recorded human being, by the way, is a certain Robert Wadlow, who measured eight feet and 11 inches tall.) This is far short of the 20 feet needed to avoid buttering the kitchen floor. Interestingly, this upper limit on polymurph height does not depend on which planet the alien inhabits. The reason is that the balance between internal gravitational forces and electrostatic and electron degeneracy effects required to keep the polymurph from falling apart relates the planet's gravity to more fundamental constants. Thus, we find that Murphy's Law is not coincidence at all but the consequence of some profound "anthropomurphic" principle: any universe built along conventional lines that contains intelligent polymurphs will conform to Murphy's Law. Matthews concludes that "according to Einstein, God is subtle, but He is not malicious. That may be so, but His influence on falling toast clearly leaves much to be desired."

Feedback

Several readers wrote or sent e-mail to point out that Sherlock Holmes could have saved some extra time in his search for the Ghastleigh Goat ("The Great Drain Robbery," September) by digging a disconnected ditch. Geoffrey L. Phillips of Briarcliff Manor, N.Y., put the case eloquently.

"The question was not to find the shortest single trench; it was to find the minimal amount of digging. Instead of digging distances AB and CD—a length of 200 feet—you should have dug only 58 feet from B toward A, and 58 feet from C toward D. Then a single third trench of 58 feet—midway between the two but farther from the center—would have completed the digging, the total distance being $(\sqrt{3}+\pi)r$" (*red lines*).

My solution yielded a trench $(2+\pi)r$ in length. Phillips's approach opens up a whole new set of questions. In particular, can you do better with two trenches? And what about three or more? —*I.S.*



The Scientific American Young Readers Book Awards

by Philip and Phylis Morrison

The "Wonders" column will pause this month so that we can present our traditional December reviews of young people's books. We have always used this occasion to single out those works that blend style and substance in some particularly deft alchemy. This year we have formalized our judgment by bestowing a new badge of merit—the Scientific American Young Readers Book Award—on the most outstanding of the many hundreds of these books that have crossed our doorstep over the preceding 12 months. The winners are reviewed below. We invite authors, publishers, parents and young people in particular to tell us of current books they wish to honor.

Peoples

MOON AND OTTER AND FROG, by Laura Simms. Illustrated by Clifford Brycelea. Hyperion Books for Children, 1995 ($14.95). **WHY THE SUN AND MOON LIVE IN THE SKY.** Retold and illustrated by Niki Daly. Lothrop, Lee & Shepard Books, 1995 ($15). **THE STORY OF THE MILKY WAY: A CHEROKEE TALE,** by Joseph Bruchac and Gayle Ross. Paintings by Virginia A. Stroud. Dial Books for Young Readers, 1995 ($14.99). **THE FIFTH AND FINAL SUN: AN ANCIENT AZTEC MYTH OF THE SUN'S ORIGIN.** Retold and illustrated by C. Shana Greger. Houghton Mifflin Company, 1994 ($14.95).

Most peoples have contrived to draw order out of the sky above. We receive these eye- and ear-catching tales through authors and artists who have colored them—what colors!—and shaped them to suit our times. Even so, a unity of observation, inference and expression links these chains of imagination, even as we wonder at the diversity of settings and societies. All four of these books can delight the youngest readers, even the read-to, by the glow of the images and by the bittersweet strangeness of the accounts.

Long ago, say the Modoc people of the Pacific Northwest, Moon was lonely, if bright, over the waters. He saw a possible companion in his own reflection. Moon visited Earth in the white buckskin and silver beads of a Modoc warrior. He learned that it was Otter's white face that had shone from the waves, while Otter had thought Moon a white-faced otter in the sky. How Moon chose a Frog wife, ugly but clever and loving, her silver comb still seen in the full moon, is a recognizable story of character. Laura Simms's text is songlike, the paintings luminous and strange.

In an audacious and successful gamble, Niki Daly, a Cape Town artist, has set a witty West African myth in the playful style of a Renaissance comedy. Sun is a young dandy and a roamer, a smiling, rayed disk for his head. His wife, Moon, her head a silvery crescent, reclines in their stylish drawing room. Dazzled by Sea's endless song and dance, Sun grandly invites her and all her teeming family to visit. The outcome is as expected: Sea floods everything away. Ever since, Sun and Moon have dwelt in the sky, but apart. Moon can no longer abide her foolhardy mate and lives among her children, the stars.

When the Cherokee still lived in the Smoky Mountains, they told of old days before the sky had stars. Over the long winter, people lived on bread made from cornmeal. Someone was robbing the stores: a huge, shining spirit dog. The people lay in wait and rose up all at once to beat drums and shake rattles, THUM THUM SHISSH SHISSH. As the dog fled to the sky, his mouth too full of stolen white meal, he left his track, the Milky Way, aglow across the newly starry sky. Virginia A. Stroud is a Chero-kee-Creek by birth and deftly evokes the look of those people, their sky and woods.

The strangest of these stories is a complex myth of a war-beset empire, drawn from Nahua manuscripts of the 16th century and from old glyphs. Once there was no sun; the Evening Star alone lit the sky dimly for the giants who lived on Earth. One after another the warring gods contended to outdo one another. The Goddess of the Water became the Fourth Sun as an act of mercy; Earth became so fair that Man and Woman were created to enjoy it. But that sun, too, like its predecessors, was extinguished in tears by divine insults. Finally, the Fifth Sun was made, not in pride and conflict, but in humility by the least among the gods. Sun and Moon remain, given motion by the sacrifices of the gods themselves. Intricate illustrations gloss this wild, hopeful story.

BUFFALO GALS: WOMEN OF THE OLD WEST, by Brandon Marie Miller. Illustrated with toned period photographs. Lerner Publications Company, 1995 ($18.95).

A striking, brief account of the women who went to win the West is given real punch by many period photographs, mostly over the 50 years starting about 1840. Here are the toilsome strings of covered wagons, dinners fixed at the wagon wheel, posed heroines, sod shanties and tar-paper shacks and, yes, plenty of headstones. Here are teachers and taxidermists, dressmakers, homesteaders, compositors, rodeo riders, actresses and a missionary riding sidesaddle. Army wives faced endless moving from fort to fort. There are documents, too, of temperance and suffrage movements established by women. The first state to include voting rights for women was Wyoming, and it was the West that led. Eleven of the 18 states that were last to join the Union—all of them in the West—had guaranteed women's suffrage by 1914. Not one of the first 30 states had done so.

The Native Americans and the Hispanic people already on the land lost out to the legions of emigrants. White women in general were more peaceable than their men. "If women could go into your Congress... justice would soon be done to the Indians," wrote a Paiute author and lecturer named Sarah Winnemucca, a national figure in the 1880s.

The book ends with an arresting photograph: two shadowy daredevil women in wide skirts kicking high in their dance on a narrow rock shelf far above the Yosemite Valley, two Buffalo Gals at sunset.

THE RULES OF BASEBALL: AN ANECDOTAL LOOK AT THE RULES OF BASEBALL AND HOW THEY CAME TO BE, by David Nemec. Lyons & Burford, 1994 (31 West 21st Street, New York, NY 10010) ($24.95; paperbound, $16.95).

Laws grow out of a great number of recorded events and decisions. Here we find out about the legal regulations not of courts but of diamonds. The rules of baseball are cited in full, on close to 40 fine-print pages, from field layout to instructions for scorers (this book is an official publication of Major League Baseball). The first couple of hundred pages recount informally how these grand rules grew over the course of 150 years.

The game we recognize as baseball arose out of manager Alexander Cartwright's codification in 1846; although he wrote the rules, his Knicks lost the first game under them to the New York Nine in Hoboken, 23–1! Rules are not enough; you have to get more runs.

This cheerful, colloquial little book is an ideal wintertime companion for logical young readers, who know that spring will come. Among the sharper factual hits: Home plate was at first a real round plate, squared off in 1869. A bunt was long called a baby hit; your reviewers dare to conjecture that the current word arises from an allusion to the baby's bunting. Six-foot-tall pitcher Stu Miller received a harsh ruling, called a balk, when he was literally blown off the mound in San Francisco's windswept Candlestick Park during the 1961 All-Star game. Two runs scored, but in a happy ending, Miller won his game anyhow, for the wind blew hard on both teams. Fans well know that "time and chance happeneth to them all."

What debates will rage around this volume!

Technology and Physical Science

ROUND BUILDINGS, SQUARE BUILDINGS, & BUILDINGS THAT WIGGLE LIKE A FISH, by Philip M. Isaacson. With photographs by the author. Alfred A. Knopf, 1988 (second printing, 1995) ($22).

About 100 pages are here, wider than they are high. A few bear only a color photograph of some building old or new; most divide the page between a picture and 100-odd words of text. This artist shows us by example what he writes as precept: "All beautiful buildings, indeed all beautiful things, have a magical feeling about them...called harmony." In a dozen spare chapters he shows us the special qualities of walls thick and thin, of light and color, of pathways and doorways, of roofs, domes and ceilings, of the building's bones, of settings and more.

The village Church of San Francisco de Asis at Ranchos de Taos was built long ago by local builders, who brought an ancient craft to the Spanish priest's design. The buttressed walls of smoothed clay over the adobe make a form that "might have risen from the desert and been carved by the wind." At John F. Kennedy Airport, the designers of the TWA terminal smoothed it, too, in shapes of concrete that flow like the wind. In Stow-on-the-Wold, England, a simple painted wooden door gleams bright red in its plain gray stone wall. Behind that door is housed the fire brigade; all harmony?

Like the Parthenon, the Pantheon of Rome is shown here more than once. Its big eye open to sun and rain overhead casts a dazzling circle into the square-coffered dome. Deep in the Canyon de Chelly we see the ruin of a dwelling abandoned six centuries ago, at the foot of a cliff so high that it becomes the sandstone illusion of a sky. There are simpler, straight-line wooden buildings, too. Three are shown on one spread: an old paper mill in Topsham, Maine, of painted clapboard; fishermen's shacks of cedar shingles on a rocky offshore island in the Gulf of Maine; and a resort structure at Sea Ranch in California, its redwood dyed black by the insistent sun and sea. This "simple style that we find all over America" may come from the good carpenters who built them, like the old ones in Maine, or from a distinguished design firm, as in the California example of 1966. The feeling is common, "honest and proud," another strain of harmony.

Isaacson is an attorney in Lewiston, Maine, "an architectural fanatic and an incorrigible photographer" and a gifted critic whose own harmony of eye, word and lens has made a book hard to match or to forget, brief and easy enough for young browsers, deep and satisfying.

IN MARCONI'S FOOTSTEPS: EARLY RADIO, by Peter R. Jensen. Kangaroo Press, Australia, 1994 (In the U.S.: Seven Hills Book Distributors, 49 Central Avenue, Cincinnati, Ohio 45202) (US$39.50 plus $3.50 postage).

Reflective young Guglielmo Marconi looks elegantly sidewise at you from the first picture. The next photograph shows the hilltop country villa outside Bologna where he grew up. His Scottish-Irish mother, Annie, was as firmly supportive as his wealthy Italian father was disdainful of their dreamy youngest child, who sought his way in science after failing admission to a naval officer's career. In 1894 the gifted physicist Heinrich Hertz died prematurely. Reading the obituary during a holiday in the Italian Alps, 20-year-old Marconi first learned of Hertz's 1887 laboratory demonstration of the electromagnetic waves predicted by James Clerk Maxwell years before. Obsessed with the idea of using the Hertzian waves for long-range communication, Marconi came back to Villa Grifone, and his mother set aside two large rooms for his work.

Many others were treading the same irregular path. But the skeptical senior Marconi began to support the work seriously once Guglielmo had managed to send messages over the hill behind the villa, a full mile. Family British connections were drawn upon; nowhere else could be so favorable as that flourishing, far-flung and maritime empire. In June 1896 a first English patent application had been lodged; by March 1899 the English Channel was spanned, and in December 1901 the three dots of the Morse letter "S" were picked up by Marconi across the ocean in Newfoundland from the high masts of his powerful transmitter in the west of Cornwall. By 1904 the Marconi firm had its equipment on 124 vessels and 69 shore stations. In 1912 wireless saved those 700 persons who had reached the lifeboats of the sinking *Titanic,* including one of the two very young Marconi officers who had kept sending their SOS calls until seawater stopped the generators.

In this uncommonly intimate history, we share a personal pilgrimage through the photographs of locales the author has painstakingly revisited: old factories, isolated lighthouses and radio towers and museums. Jensen is an Australian architect, long a keen radio amateur, who still fires up his portable transceiver at many of the places he visits. Half the book sets out in detail how Jensen and his friends have built working replicas of the marine radio of Marconi's days, the high-voltage coil of very fine wire potted in wax, the curious detectors, the entire intricate system of brass and mahogany accessories. It is late Victorian electrical engineering at its best, lovingly rebuilt from the junk boxes, garage sales, plumbing suppliers and old cinemas of Sydney.

Marconi, a systems engineer like the brothers Wright, had a profound feeling for the whole. He improved the Hertzian scheme in every element, guided by intuition and insightful trial and error, long before the physical basis for his apparatus was known in detail. Jensen plausibly suggests that the first transatlantic contact may even have depended on the harmonics of the spark transmitter in Cornwall reaching the untuned receiver overseas, more signal coming by short wave than by the nominal frequency near one megahertz! Plainly a careful test and reenactment should mark the centenary of that first radioed "S," in 2001, aided by the devoted radio amateurs (and the television producers) of our well-linked world.

THE KLUTZ BOOK OF MAGNETIC MAGIC, by Paul Doherty and John Cassidy. Klutz Press, Palo Alto, Calif., 1994 (spiralbound, $11.95, with magnet kit).

A clever kid named Albert Einstein remembered all his life his first encounter with a magnetic compass; something hidden, he thought, is within things. Not just for Einsteins—they are too few to make a market—but for all curious girls and boys, this book offers essential magnetic experience, wrapped in tricks and games and neat writing.

Five ceramic doughnut magnets, a magnetic pill to fill each hole, and a steel cover page to act as game target and storage space supply the experience of a force field (the steady pull of gravity being too ubiquitous to make its equivalent nature clear). An empty air space houses a strong push or a strong pull between your magnets, and the instabilities that result from combining magnets are set forth for many a kid to exploit as magic. Item: the vapor coin. Using a special coin, you can cause a quarter to fall through a wooden tabletop, once you nourish "a fine clear-eyed ability to tell enormous lies" and some modest hand skill.

There are a score more of such fun setups, such as the much simpler air pudding and the basic coin-in-ear. Teacherly adults—your reviewers admit to a controlled but chronic case of pedantry—will admire even more the straight physics dished out in witty and flippant guise: a marvelous north-seeking banana, magnetic boats, shishkebabbing rings bouncily floating on a pencil, and lots of surprising jumps and pop-ups. The special coin supplied is a real mint-condition Brazilian 50-centavos piece; if you want to know how it is special, think it over, or buy the book.

FLY THE HOT ONES, by Steven Lindblom. Houghton Mifflin Company, 1991 (paperbound, $6.95).

The half-angelic skill of airplane pilot holds appeal to many who will never become adepts and irresistibly beckons others. This book, newly in paperback (1995), is an informal set of conversations with an articulate pilot who has happily flown his choice of eight aircraft, large ones and small, old designs and new. The aircraft here, he thinks, are all extremes, "pushing the envelope" in one way or another. Never mind that one is a Piper J-3 Cub and another a P-51D Mustang. They all have the same basic controls. As he flew the Cub, "small, old-fashioned, and slow," made of steel tubing and fabric, he heard again in memory the voice of his first instructor as she screamed at him so many times when landing, "You can't stretch a glide." Still can't.

The Quicksilver Sport Ultralight has a high, red-cloth-covered wing, held on a jungle gym of clipped tubing and taut wires, and a snowmobile engine up front. It is superb engineering close to a minimum, ready to take off after an 80-foot run. What is it like to fly an ultralight? Imagine telling your little brother. First sit him down in an aluminum lawn chair. "Next you walk... behind it...begin making engine noises, then lift it into the air and race about the yard, banking the chair and its passenger from side to side as you turn." In real life, nothing but fresh air in front of you, you fly for half an hour all around the patch and up to 2,000 feet high. When the tank nears empty, you touch down easily on the grass that you can see slipping backward below your legs.

Now wearing the G suit required of the pilot of the F-16 Fighting Falcon U.S.A.F. jet fighter, aloft and "flying by wire," everyone has to try one or two of its celebrated tricks. Level off, pull back on the stick and "punch on the afterburner." Five jolts mark each stage as it comes on, until for a few seconds you are rising straight up! "Held up by the sheer power of the engine," the airplane loses airspeed down to 350 knots. High time to level off and ease the throttle back to "Max Conserve cruise."

Each airplane is presented in a color photograph page, and a number of interesting detail photographs and diagrams add understanding. What is reviewed is only the half of it; a dozen pages report this pilot's flight in each of the airplanes he flew.

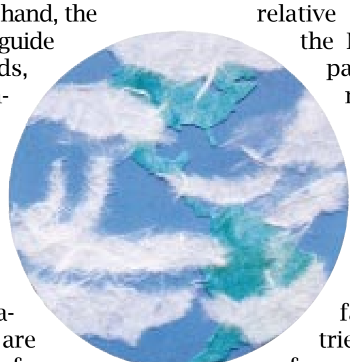
IMAGINING THE UNIVERSE: A VISUAL JOURNEY, by Edward Packard. Perigee Books, Berkley Publishing Group, 1994 (paperbound, $15). **LOOKING DOWN,** by Steve Jenkins. Houghton Mifflin Company, 1995 ($14.95). **EARTH FROM SPACE.** Text by Amy Leventer and Geoffrey Seltzer. National Audubon Society Pocket Guide, Alfred A. Knopf, 1995 (paperbound, $7.99).

In these disciplined, black-and-white computer images, Edward Packard's fancy opens with a view of this round earth nestled into the bowl of Candlestick Park. Accepting the change of scale implied, the reader embarks on a journey past the orbits of the planets on a map of the surrounding territory. The whole earth will not quite carry the orbit of Mars at this model scale.

Then shrink the earth from ballpark size down to baseball. Now the orbit of Uranus maps out across the Golden Gate, and Pluto lies 20 miles to sea. The stars are still much too far; a map of the entire world would not be big enough. Shrink once more, the earth to a grain of sand. Now we can fit in the stars we know. But to get the Milky Way on paper, the *sun* must be shrunk down to sand-grain size. That map reaches our Local Cluster, but no farther. To show the true realm of the galaxies, the solar system as a whole must be scaled down to a bit of sand. We move across page after page of pure black, the author's signal of uncertainty. He begins the voyage again, now inward. We expand a baseball first to the size of the ballpark and then to the size of the earth's solar orbit. A proton becomes a half-inch mark on home plate.

A final chapter voyages in time to cosmic past and future. Now the scale is fixed by thinking of an arrow in very slow, steady motion, a mile every million years, an atom's diameter each second, as it flies toward and past the ballpark. The arrow is now over home plate. It began its journey when the hot cosmic gas first expanded, corresponding to a starting point beyond the geosynchronous satellites. It will exhaust the expected lifetime of our sun just as it again leaves the earth. This is a fresh way to introduce cosmic scale, with models that do not depend on the iteration of numerical factors but rather on mappings that are visualizable, if not always very natural.

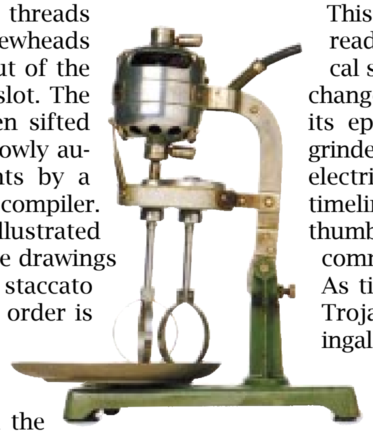
Steve Jenkins gives us an astronaut's-eye view as he comes to the earth under perfect control. In colorful full-page collages, we begin with a view of the earth and its moon seen beyond some asteroid, then arrive in a dozen or so excitingly closer steps, to find a ladybug through a magnifier in the hand of a kneeling boy in his front yard within a town on the East Coast of the U.S. Wide open to younger readers, this visual book needs only the two words of the title as text for the entire journey, and only three lines more to close.



About the size of your hand, the *Earth from Space* pocket guide offers about 80 spreads, each a page of geographical text with guide map and a false-color picture taken from space orbit. See cities by day and night, canyons and rivers, deserts and snowy peaks, atolls, lakes and seascapes, glaciers and polar ice. All are here, and well indexed, from the Adrar Plateau to Zimbabwe's Great Dyke. The book has wider views, too, of individual continents and of the whole earth to help young geographers. Essays of a few pages review some major topics, such as plate tectonics and the water cycle. The pictures are not large ones, but a better bargain of a compilation is not to be found.

SIZES: THE ILLUSTRATED ENCYCLOPEDIA, by John Lord. HarperCollins Publishers, 1995 (paperbound, $15).

Things here means mainly items you can buy, described along with their commercial attributes. Dinosaurs rate a few lines, stars half a page, wind forces two pages, but 18 pages and many diagrams catalogue screws—their sizes, threads and all the novel screwheads that have evolved out of the simple screwdriver slot. The information has been sifted out of a pile of narrowly authoritative documents by a tireless and cheerful compiler. The 350 pages are illustrated mostly by simple line drawings and silhouettes. The staccato pace of alphabetical order is relieved by a few thoughtful essays on topics such as time, the meter and the history of U.S. weights and measures; the text is written well enough to earn the edified browser's trust.



Want to buy a thimble? A medium thimble goes as size 10 in the U.S. and in France, but not everywhere. (A ring fitted to the same finger would be a size 5 in the U.S.) Recognize a category 3 hurricane? Choose an oar to fit your rowboat, or a hitch to suit your trailer. Learn the notes reached by singers from soprano to bass. Lay out a proper place for badminton, baseball, basketball, skeet, soccer, softball, shuffleboard or tennis. Grasp the dozen meanings for "ton." Among canned whole ripe olives, the supercolossal grade must run fewer than 33 to the pound. Six terms for relative hotness of peppers in the Nahuatl tongue accompany the table of hotness measured in Scoville units, alas, without conversion factors.

This is a book full of lasting utility, lots of fun for good readers and their classrooms. (A very few matter-of-fact sexually related entries may be rather frank for young readers.)

SMITHSONIAN VISUAL TIMELINE OF INVENTIONS, by Richard Platt. Dorling Kindersley, 1994 ($16.95).

Across about 55 large pages march some 400 photographs of widely differing sizes and scales, most in color, presented as sharply cutout images against a white ground, rather like butterflies pinned in a museum case. Indeed, these pictures are mainly from the museums of science where the objects are held.

The first half of the book runs from 600,000 B.C.E. up to 1780, the latter half on to the 1990s, with a page of "future trends." Each photograph, from hand ax to Game Boy, is keyed to a date, and the six or eight photographs on a page are set into four rows by broad topic. This disciplined style aids the reader to appreciate the logical structure of technological change; one look at a page and its epoch is suggested. Hand grinders for grain must precede electric eggbeaters. A parallel timeline at page bottom shows thumbnail sketches and brief comment on world context. As time goes by, you see the Trojan Horse, Florence Nightingale and Martin Luther King, Jr., among 100 other tiny images, chosen with clear sympathy for the historical underdog.

So rich a diet is to be sampled, and not gobbled down. The first printed book page is here, if shown very small: the frontispiece to the *Diamond Sutra,* block-printed in 868 C.E. There are some welcome novelties, such as the Indian origin of sugar refining, the Chinese pioneering of many innovations, including the wheelbarrow, paper, printing, gunpowder and the canal lock. The first parachutist is not forgotten, nor the aspirin chemists, nor the invention of the cathode-ray tube. Credit for the magnetic compass is here shared between China and Arabia. The foreword makes quite clear that ascribing inventions is no simple or firm matter. This book is an asset for families, classrooms and libraries.

Living Things

POND LAKE RIVER SEA, by Maryjo Koch. HarperCollins Publishers, 1994 ($28).

This watery book immerses you. Every one of six dozen page spreads is an inviting watercolor over a wide range, profound or joking, dazzlingly evocative of nature or styled in allusion. There is always a fresh, hand-lettered text. Few books are so single a work of art.

Its topic is life in the waters. A second theme is what people have made of what they found therein—their myths, food and science. The author's perspective is in part direct; many of the images show that she has watched what she paints. Some topics are didactic, telling you a string of wonders from the books, and a little is Maryjo Koch's opinion, never hidden.

Fifteen lines of text describe Louisiana crayfish and Atlantic lobsters as Cajun cooking and as cheap and monotonous fare for the convicts of 19th-century Maine. The facing page has a beautifully painted external view of a dissected lobster, not red but dark as seawater, the parts of one side neatly arrayed and labeled. A sentence about hunter and hunted winds around a marvelous image of a flounder, shown against a ground of myriad sand grains red, black, yellow and gray. The oval creature is both obscured and plain.

A dozen squares of color present convincing renderings of magnified skin and scales, from gray shark to blue-dotted coral trout. The text adds more: crystalline platelets of guanine reflect to provide "the flashy silver appearance of the archetypical fish," sometimes creating "a magical interplay of hues" by optical interference. "Fish, like artists, know that black and white stripes make a strong statement," and Koch paints a dozen disparate fish of that knowing sort.

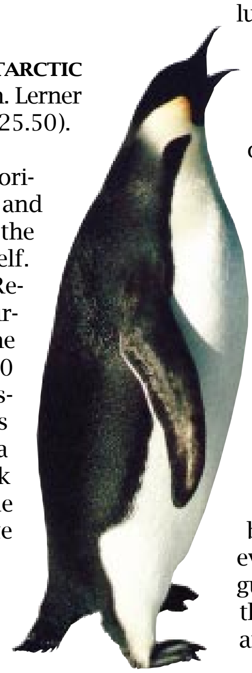
The fortunate reader might be any young person with the skill to read it, the patience to read slowly and the desire to think about it all, probably 12 years or older.

SCIENCE ON THE ICE: AN ANTARCTIC JOURNAL, by Rebecca L. Johnson. Lerner Publications Company, 1995 ($25.50).

In snow sunlit to the far horizon, a stout copper stake and an American flag mark the very spot of the South Pole itself. A newcomer, such as writer Rebecca L. Johnson, is properly surprised to see a long, straight line of such copper stakes, about 30 feet apart, running out some distance from the one that bears the flag. In fact, every spring a new stake is driven in to mark the new Pole position. The Pole hardly moves, but that icy, white landscape is drifting as a whole.

It takes three hours to fly the 900 miles from the big U.S. base at McMurdo Station on the sea ice up to the high polar plateau. The American-operated Amundsen-Scott South Pole Station is home to only 20 brave people during the six isolated months of night, but during summer sunshine 100 men and women, scientists and supporting staff, crowd south to work. Life-giving power and heat come from jet fuel. A thousand tons is flown in annually, and a year's supply is stored in big rubber bladders. On hand is a year's supply of food, too. One walk-in refrigerator keeps the "freshies," fruit and vegetables. "Unlike most refrigerators, though, this one is heated." This station is celebrated the Pole around for the good food served in its warm, cozy, cheerful galley, while outside the wind blows steady and strong, even on a summer day at a mild –50 degrees Fahrenheit.

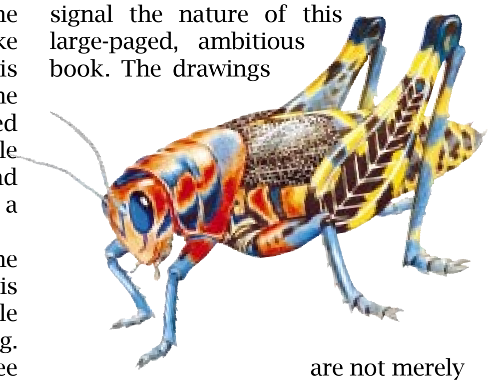
The Pole's people survey the ice, the atmosphere and beyond. High above is the ozone hole. In the sky, stars circle forever without ever rising or setting. Snow and ice, dry, thin and dust-free air, the colorful aurora, cosmic radiation and infrared from the deep skies—for these the Pole offers unique opportunities. Nine of the author's 10 chapters report in lively words and her own photographs what she saw and did as she went in red down parka and white "bunny boots" far around coastal McMurdo, with the busy biologists and geologists who sample, map, count, measure, track and come to admire all they study. Hers is a modern adventure, full of tracked vehicles, helicopters and radio. "On cloudy days, we had to use batteries if we wanted music"; no solar power for the Walkman. But cold batteries lack power. "Our solution was to heat them up carefully in a frying pan."



Yet these light-hearted people dare not ignore the constant risks of a frozen and dangerous world in which they are trained, equipped and linked in teams to survive. The challenge of the environment and its superbly adapted wildlife—the codfish with antifreeze blood, the offshore Weddell seals that all winter long gnaw breathing holes through a layer of ice yards thick, the rich sea-bottom life below the ice, even crowds of little penguins in black tie—inform this knowing story, open to any good reader.

BIG BUGS, by Jerry Booth. Illustrated by Edith Allgood. Harcourt Brace & Company, 1994 (paperbound, $14.95). **INSECTS,** by Laurence Mound and Stephen Brooks. Dorling Kindersley, 1995 (pocket edition, $5.95).

The bugs are indeed drawn big, a dozen of them shown eight or 10 inches long, mostly in black-and-white. Those portrayed include a little black ant and housefly, field cricket and June beetle. The specific names signal the nature of this large-paged, ambitious book. The drawings



are not merely for visual effect; each is flanked by a few big spreads that generally but effectively describe common related forms and outline physiology, behavior, habitat and life cycle, assisted by many color drawings and diagrams.

The book's higher aim is action. Nearly every text treatment includes some task of observation, craft or husbandry, intended for kids in the upper primary grades who may be hooked on bugs.

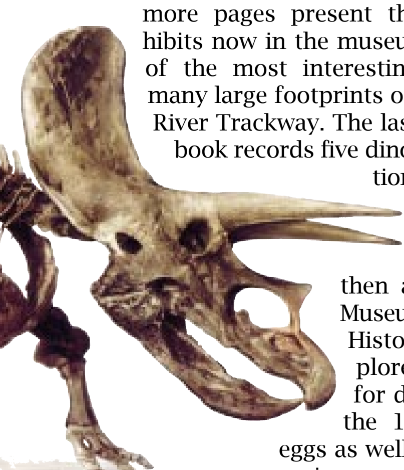
You can cut out colorful face masks and play giant hornet or Jerusalem cricket with long antennae. Most unusual, not to say "gross" in classroom vernacular, is a serious page on eating insects. You can buy a cupful of live crickets at the pet shop and follow the recipes given to prepare crunchy Cajun crickets or "chocolate chirpies." Cookbook references are included. A still more challenging task detailed here is beelining, the old countryman's craft for following nectar-collecting honeybees and bumblebees back to their homes. This seems a long and delicate task for kids, here encouraged not to rob the nest but to study its dwellers.

The second book—it is five inches high—is one of a long series, tiny bargain handbooks dubbed "pockets full of knowledge." This one is a readable, well-illustrated introduction to insects, with small color images. It offers a couple of dozen spreads on evolution, classification and the biology of the phylum, as well as another 40 spreads on particular examples, arranged by habitat, from temperate woodlands to the garden. There is a spread on insect-rearing projects here, too, but no recipes.

Discovering Dinosaurs in the American Museum of Natural History, by Mark A. Norell, Eugene S. Gaffney and Lowell Dingus. Alfred A. Knopf, 1995 ($35).

Many of this year's dinosaur books present the beasts mainly visually for readers of almost any age. The colored, patterned reconstructions are vivid, based on pleasing analogy with birds and lizards—alas, all guesswork. Probably there were many colorful dino species, but from fossil remains and casts alone we cannot say which monsters were brilliant as toucans, which drab as crows. We might tolerate more guesses if a few words admitted doubt, but such qualifications are usually wanting. Fancy images and animated motions have carried dinosaur hype to flood height. An effort at judicious restraint is welcome; here it is, in a text centered on family reading, but open to kids in the higher primary grades.

These three New York paleontologists have led the work on the large new Halls of Dinosaurs installed this year. The first dino fossils that came to their museum arrived a century ago. We see that big *Diplodocus* femur being dug out of the Wyoming hills by two celebrated predecessors of the present authors. Plenty of fine pictures of fossils, tracks, casts and older graphics fill the well-written, well-designed volume (which could have used a fuller index).



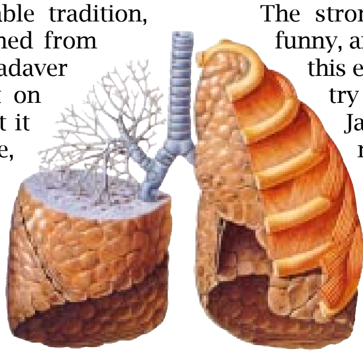
Almost the first half of the book is organized as very readable question-and-answer essays. Nearly as many more pages present the many exhibits now in the museum halls, one of the most interesting being the many large footprints of the Palauxy River Trackway. The last part of the book records five dinosaur expeditions of the museum. Roy Chapman Andrews, then an American Museum of Natural History star, explored the Gobi for dino bones in the 1920s, found eggs as well and may be seen as a major source for the romantic film hero Indiana Jones. The senior author of this book returned to the Gobi sites between 1991 and 1995 in partnership with the Mongolian Academy of Sciences. The newer finds show a small dinosaur found by Andrews near a nest to be more likely a parent than a predator: the eggs were of its own species! *Oviraptor* was most likely not the "egg stealer" of its Latin name.

No way are these authors mere stick-in-the-muds. They offer fresh, compelling arguments that dinosaurs include both *Tyrannosaurus rex* and modern birds. Birds retained dinosaur forelimb structures, but at last they invented feathers. Our ostriches and canaries are the last dinosaurs.

Around the glossy jacket of this instructive book runs an extended image, a skeleton with skull, spine and tail aligned and high. It is the real *T. rex,* colors unknown. Not for the youngest readers, this book will enrich any others who are hooked on dinosaurs.

SOME BODY! by Pete Rowan. Illustrations by John Temperton. Alfred A. Knopf, 1995 ($20).

The oversize pages are fully justified by the opportunity to display drawings of the human body at life size. The reader served here is a high school biology student or anyone older who wants a good look at the classical macroscopic anatomy. A foldout offers a remarkable panorama of the whole bony leg, from toe to pelvis. Even more striking perhaps is the full-size fetus close to term, seen afloat within the womb. The skillful illustrator works in a valuable tradition, color paintings softened from the hardness of the cadaver to mute their impact on the inexperienced. But it is all here, big as life, along with the mapped systems of lymph and lungs, the cutaway heart, liver and other organs—even a distorted body drawn with surface regions sized in accordance with their cerebral motor areas, showing the sense organs unexpectedly magnified.



An original style of annotation works extremely well, especially for this youthful audience. It is based on the wildly popular *Guinness Book of Records.* Most of the drawings are keyed and labeled with any superlatives that may apply, half a dozen a page, each accompanied by a few lines of explanatory text. The largest nerves in the body are the two sciatic nerves, the greenest substance in the body is the liver's bile (it "looks like motor oil") and so on. These reviewers were delighted to learn that the smallest muscle—the stapedius—is "a tenth the size of a flea." Within 40 milliseconds, it can move to limit excessive sound signals to the brain by modifying mechanical contact among the tiny earbones.

The English author-illustrator team has walked a surprisingly fresh route down a very well traveled trail.

Symmetry and Perception

THE CROCODILE AND THE DENTIST, by Taro Gomi. Millbrook Press, Brookfield, Conn., 1994 ($14.40).

"I *really* don't want to see him…but I must." We sympathize with the brown crocodile, his four large, white teeth showing, as he stands in front of his dentist's office. "I *really* don't want to see him, but I must," says the green-robed dentist at his desk, the croc's shadow on the office door. We sympathize with him, too, for the crocodile's toothy mouth is big enough to engulf hand, drill and all. "I must be brave," both say. The croc can't help closing down when the dentist can't help entering that back tooth. Two speak the same words: "OUCH! What an awful thing to do. But getting angry won't help." It all ends happily. After they part with polite bows, each murmurs: "I don't really want to see him again next year." There is a way: the croc must recall just what the dentist says about brushing teeth.

The strong, broad drawings are funny, and the near perfection of this endearing human symmetry elevates this tale by a Japanese artist for young readers straight to mathematical glory.

COLORS EVERYWHERE, by Tana Hoban. Greenwillow Books, 1995 ($16). **EVERYDAY MYSTERIES,** by Jerome Wexler. Dutton Children's Books, 1995 ($14.99).

Here are two books of pictures by two photographers well recognized for their artful use of eye and lens to challenge and delight the eye and the mind. Tana Hoban shows us images ablaze with color, whether a jar of jellybeans, a macaw, a many-bladed plastic whirligig, a tangle of netted balloons or a child in a rainbow domino mask. Next to the photograph appears a striped bar in the image's hues, widths roughly proportional to each color area. This analytical device, not unlike the computer-generated histograms that guide printers, is a surprise. Hoban's book as usual is wordless, save for a final page identifying this Paris artist—the abstract sample somehow strengthens and makes memorable our view of these scenes, probably even for the youngest who look at them. It took only three hues to evoke a glorious sunflower.

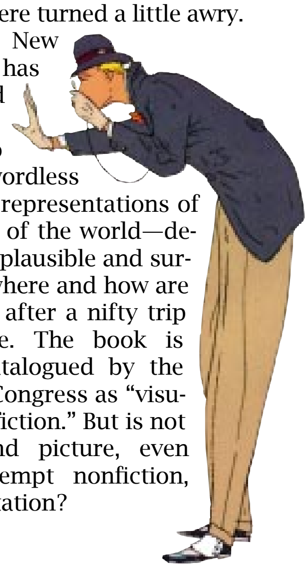
Jerome Wexler's book has a few pages of text, setting explicit problems for good young readers, but it is perhaps not for the very youngest. They will see magnified parts, surfaces, edges, cross sections and silhouettes in color photographs of familiar objects. These may appear quite unfamiliar, everyday mysteries of abstraction. (Each complete object is rendered in a small image at the end of a section.) The Jack of Hearts is hard to recognize by his elegant midriff alone. A waffle can be named from a bit of its coffered surface, but a strawberry seen at high magnification is a seedy puzzle. The edge of a dime is easier to make out than a key shown against a strong yellow ground. This good-looking book amuses again and again, even when you can recall the object.

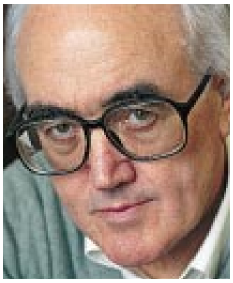
RE-ZOOM, by Istvan Banyai. Viking Penguin, 1995 ($13.99).

A book free of words opens with a close-up of a rock painting. Soon that is seen to be drawn on an enviable wristwatch worn by a young streetwise archaeologist, who is busily making a rubbing of hieroglyphs on the wall of a deep shaft that somehow ends up in a subway car that we watch diminish into two red lights as it moves off into a dark tunnel. Is that Einstein sitting a few seats away from the boy reading the comic book? Within this chain are linked many images: the Paris obelisk under the floating Goodyear blimp, the palms in the TV studio, the elephant bearing Alfred Hitchcock and a stout blue Krishna, and that caravel at sea. Are they all in the boy's comic book?

Perhaps. The idea of successive zooms that search the earth, the microworld or the galaxies is here turned a little awry. An imaginative New York City artist has wittily exploited 30-plus zooms upon zooms to take us on his wordless journey among representations of representations of the world—detailed, colorful, plausible and surprising. What, where and how are open to debate after a nifty trip across thin ice. The book is thoughtfully catalogued by the U.S. Library of Congress as "visual perception—fiction." But is not every book and picture, even those that attempt nonfiction, only a representation?

Perhaps.





CONNECTIONS

by James Burke

Top to Bottom

The other day I came yet again across that expression most often attributed to Sir Isaac Newton (and overused by people like me) to describe the process of technological advance: "If I have seen further...it is by standing on the shoulders of Giants." Well, maybe. But I like to think ordinary buffoons have a part to play, too.

I have in mind the sad case of an archetypal English eccentric, the 18th-century admiral of the English Fleet who rejoiced in the name of Sir Cloudesley Shovel. Shovel has two claims to a place in the great web of change. One is that he invented the "Shovel wig," a full-bottomed creation (it fell and draped over the shoulder) about which it was remarked at the time that it looked like "nothing so much as a loaf of bread on the head." Shovel wigs were so expensive to buy and maintain that their rich owners were called "bigwigs."

Shovel's greater claim to fame is that he drowned. But he did so in a manner so spectacular as to kick off a chain of events that would end up with one of those essential products of technology without which the modern world wouldn't be the nice place it is.

Shovel drowned because, as I said, he was a pompous buffoon. One nasty night in 1707, while bringing his fleet back from Gibraltar, in spite of having no idea where he was and being surrounded by thick fog, he pressed on, dead ahead. Unfortunately, he was a bit too close to home (in this case, the southwest coast of England), so he hit the rocks. Everything went to the bottom: fleet, 2,000 mariners and Shovel.

Now, too many ships were being lost just like that because they were lost, like that. But with the highly profitable American colonies waiting to be exploited, this was a prime time for investors to sink their money into transatlantic transportation that wasn't sinking. So a very large prize was offered to anybody who could come up with safer ways of getting places. And back.

In 1764 a clockmaker called John Harrison provided a timely solution. The navigational problem centered on the fact that on an earth that rotates 100 kilometers (or one degree of arc) every four minutes, true noon—the moment when the sun is highest in the sky—happens four minutes later for every 100 kilometers you travel west of your home port. And vice versa. So knowing the exact time back at home will tell you how late (or early) the sun is at the place where you are. Simple multiplication will then tell you the number of kilometers east or west to which that time discrepancy corresponds.

Harrison observed, perspicaciously, that pendulum clocks wouldn't be of much help on a constantly swaying ship, so he used a spring. At one end of his (amazing, new) steel clock spring, he put a little brass slider, so that in the various weathers encountered along the way, the brass would expand and contract just enough more than steel did (in the ratio 3:2) so as to keep the expanding and contracting spring the same length, whatever the temperature. Harrison's chronometer lost only 15 seconds over a trip to the Caribbean and back. Because the earth rotates seven kilometers in 15 seconds, that accuracy meant that you could use the location of the sun or stars to hit a spot accurate to within seven kilometers of your home port. So, no more wrecks. Well, fewer.

Harrison's clock spring was amazing and truly new, thanks to the work of another clockmaker, Benjamin Huntsman, who had recently noticed some glassmakers taking bits of old, broken bottles, remelting them at high temperatures and coming up with glass that was clearly superior. Back in Harrison's day, conventional steel was no good for springs, because it was too brittle. Huntsman's trick was to concoct a mystery ingredient (he never did reveal the secret) that he added to clay to make crucibles that could withstand the fantastically high temperatures without which people couldn't re-melt the old kind of steel into a stronger, more resilient form. Now, using Huntsman's crucible, they could.

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Huntsman's steel was also so tough that if sharpened, it could cut iron like cheese, which was the lifelong ambition of an obsessive ironmaker, John Wilkinson. He made a set of iron coffins (three for himself, the rest offered as gifts to friends), built an all-iron church, paid his workers in iron money and slept with an iron ball in his hand. (The last was so that when he dreamed of a good idea he would twitch, the ball would fall and wake him up, so he could make a note of the idea and go back to sleep.) In 1774 Wilkinson used Huntsman's steel on the cutting head of a new cylinder-boring machine. It could cut metal so precisely that Wilkinson was able to make the kind of piston cylinders James Watt needed, accurate to "the thickness of an old shilling." Watt was then able to use those same cylinders to drive his own (first ever) steam-powered blast furnace. Hence the Industrial Revolution.

And then, the one in France. Because the other thing Wilkinson's gizmo could do was bore out cannon barrels that were thinner and more precise than those that came before, so precise that they were interchangeable. Disguised as "iron piping," these barrels were smuggled to France (with whom England was at war); the new barrels made possible the development of horse artillery because of their light weight.

This last feature gave added value to the work of a French military type named Jean-Baptiste Vaquette de Gribeauval, inspector general of artillery, for whom Wilkinson made his barrels (his other customers were the Turks and Americans, both of whom the English were also fighting at the time). From 1776 on, Gribeauval had begun the total reorganization of French artillery, reducing to four the many different calibers of gun and standardizing everything from ammunition to gun-carriage wheel size. Thanks to Wilkinson, he now had mobile weapons that could be rushed from place to place in battle. This was an unheard-of way to behave. Cannons were supposed to take all day to position and then all the next day to move again. So Gribeauval's movable guns changed the face of war and (when the idea was taken up enthusiastically after 1792 by an ex-artillery officer and innovations freak called Napoleon Bonaparte) the face of Europe.

In 1810, once Napoleon had used his English cannons to good effect and was, as a result, comfortably ensconced on the imperial throne, he decided to drag French industry into the 19th century by motivational means, offering prizes for inventions by Frenchmen. His grand plan was to make France militarily independent, so that the next time he fought, his *matériel* would be as French as was the word for it. Initially, therefore, it may seem odd that one of the first prizes to be awarded went to a guy called Nicolas Appert, who bottled champagne. But Appert, realizing that no army marches on its stomach quite like that of the French, sealed vegetables in some of his bottles and stuck them in boiling water for several hours, thereby killing the germs he didn't know existed. Months later the French military (actually the navy, in the Caribbean) opened his bottled veggies and declared them to be as good as fresh, the answer to scurvy and, in terms of supply logistics, a quartermaster's dream.

A little later, in Paris, some passing Englishmen happened on Appert's bottling patent and bought the rights. Because one of these men had a pal who owned a tin-making outfit, they switched containers from bottle to can. Which is why we have canned food today.

During their patent-acquisition trip, however, what should these British investors also come across but an even more interesting improvement to French industry. It was an automatic papermaking machine: pulp was auto-scooped onto a shaking, traveling wire mesh, passed between felt-covered rollers that squeezed out the water and then hung up to dry. The process almost completely bypassed the human hand. The result: no more need for all those workers (who were running around Europe with Napoleon's horse artillery, anyway).

For some strange reason, the French had not picked up on the idea, so the English buyers went home with this patent, too. By 1840 automated paper machines were turning out lengths of material that made possible the wallpaper we all love to tangle with today. And providing opportunities for artists-cum-social reformers such as William Morris to cover the paper with back-to-rustic designs, which soon began to adorn the walls of every decorous Victorian home.

Those homes were made more decorous by another new improvement: lavatories. Thanks to three cholera outbreaks (and 100,000 deaths) in England, sewers and water mains and sanitationware (such as flush W.C.'s and enamel baths) had started appearing everywhere. And, because of that continuous-process papermaking technique from France, the socially upwardly mobile were now also able to add to their colorful and hygienic new lifestyle one final essential: the toilet roll.

All…from the Shovel connection. So never mind the "shoulders of giants." Let's hear it for buffoons.

ANNUAL INDEX 1995

AUTHORS

ARTICLES, BY KEY WORDS

THE AMATEUR SCIENTIST

MATHEMATICAL RECREATIONS

by Ian Stewart

ESSAY by James Boyk

The Endangered Piano Technician

As a pianist, I have a recurring nightmare that the piano will disappear as a concert instrument, not because people won't want to hear it or play it, nor because fine pianos won't be built, but because good concert piano technicians are vanishing.

Technicians repair and adjust the mechanism of the piano, with its roughly 2,000 moving, vibrating or adjustable parts. A concert technician does all this, plus tuning, under performance-day pressure, while being supportive of the artist. This medley of abilities requires complete mastery and a special temperament, a combination that is increasingly rare.

On tour, we pianists take potluck in technicians, but when I am home I am lucky enough to have the services of Kenyon Brown. For 25 years, he was the Steinway concert technician here in Los Angeles, responsible for pianos used by artists from Elton John to Arthur Rubinstein, in venues ranging from concert halls to recording studios to the Hollywood Bowl. The great Rubinstein, who played all sorts of pianos in his career of 80-plus years, called Brown one of the five or six best technicians in the world.

Brown sees to it that the key mechanism, or "action," follows the subtlest volume changes and the fastest repeated notes, that the hammers create a rich and clear tone, that the pedals respond delicately and work silently, and that the tuning is beautiful and stable. He also repairs broken strings, tightens loose bearings and eliminates buzzes.

Consider what must happen when I perform Beethoven's *Moonlight Sonata*. The flowing three-note groups introduce and accompany the famous melody, which arises naturally from them because it is made from their overtones. This relationship is heard only if the tuning is accurate—as Brown's is. And because he knows how to stabilize the tuning pins in the laminated pin block, the piano stays in tune even as the arrival of the audience makes the hall warmer and more humid, and as previous works on the program tend to stretch the strings with repeated hammer blows.

Brown may perform any of a dozen adjustments to make the keyboard action responsive. For instance, the hammers fly free for a fraction of an inch before hitting the strings. When this distance is set just right, playing the melody's subtle rises and falls feels as natural as adjusting a light dimmer. When it is wrong, the keys feel instead like switches: simply on or off, either playing a note or not.

To make the piano's tone expressive, Brown files the crowns and shoulders (tops and sides) of each hammer to their proper shape if they are worn, fluffs up the hammer felt and, if necessary, brightens the tone by applying a lacquer solution under the crowns of the hammers. Then, during the measurable moment when a hammer hits the strings, its contours and resilience will damp ugly harmonics while exciting the right ones to give a singing tone.

Every technician does these things; few do them well. When done correctly, work like this spiritualizes my relationship with the instrument. I have a better chance of rising to the heights of performance, where the notes are transparent to the music and the music transparent to the emotion. Brown tells me that a technician "shouldn't be allowed to do concert work for 10 years," because it takes that much experience to be ready; thus, there will never be too many fine concert technicians.

STEINWAY & SONS

In fact, there is a desperate shortage, a crisis that came to my attention when Ken Brown moved out of town. Having trouble finding his replacement, I consulted a person who works with many technicians for a major piano maker. He said, "I couldn't recommend anyone to you at this point. There are just too few of those guys around." Talking to piano professionals around the country, I find unanimity on this point. Steinway's Peter Goodrich says, "There aren't as many concert-level technicians as we would like or as concert artists would like." Lloyd Meyer of (recently defunct) Mason & Hamlin comments more bluntly, "I think there are very few in the country of the caliber I would want to work on my piano."

As the current crop of expert technicians retire, they are not being replaced at anything resembling an adequate rate. Apprenticeship, the traditional training system, seems almost dead. The only U.S. bachelor's-degree program in piano technology, at Michigan State University, closed recently when its director retired. At least four other programs have shut down in the past few years, and none has opened. The four programs remaining in the U.S. offer just one or two years of training and among them graduate only about 30 students a year. Because of the lack of well-trained technicians, owners may never know the pleasure of a playing a piano that is in good shape.

Does it really matter if pianos in superb condition vanish, replaced perhaps by electronic synthesizers? These already seem as numerous as a plague of locusts. Unfortunately, they sound like them, too. I have never heard an electronic instrument on which each note was interesting and beautiful, as it is on a fine piano.

This beauty, which entrances novices as much as concert artists, combined with the piano's ability to play harmony, makes it the working tool of all types of composers and the optimal teaching machine for students. Except perhaps for the human voice, the piano has the largest and greatest literature of any instrument. The life of this literature is central to our musical culture and utterly dependent on "oral transmission" through performance.

The importance of the piano technician can be summed up in a little story. One evening, Brown, having prepared and tuned Rubinstein's piano at the Los Angeles Music Center, waited in the wings in case a problem arose. Greeting Rubinstein after the performance, Brown exclaimed, "That was very beautiful, Mr. Rubinstein."

Said Rubinstein, "*We* have made it so."

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