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DEPARTMENTS

THE COVER depicts the launch of a small car by a reconstructed medieval engine of war. Successor to the catapult, the trebuchet could hurl missiles weighing a ton or more over castle walls. It was sometimes used to loft the bundled corpses of diseased animals and humans into besieged cities, an early form of biological warfare. This modern reconstruction in a Shropshire pasture tossed a 476-kilogram Austin Mini 80 meters (see "The Trebuchet," by Paul E. Chevedden, Les Eigenbrod, Vernard Foley and Werner Soedel, page 66). Painting by George Retseck.

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LETTERS TO THE EDITORS

Controlling the Crowd

In "Population, Poverty and the Local Environment" [SCIENTIFIC AMERICAN, February], Partha S. Dasgupta omitted discussion of the enormous difference between reducing total fertility from seven children to four (which is rapidly being achieved) and further reduction from four to three, which is needed to reach stability. Dasgupta writes, "I know of no ecologist who thinks a population of 11 billion (projected for the year 2050) can support itself." I will go further and state that I know of no scientist who has realistically identified the "policies that will change the options available to men and women so that couples choose to limit the number of offspring they produce" to less than three—the target necessary to prevent further population growth.

DONALD B. STRAUS
Mount Desert, Me.

A Forgotten Risk

A female patient of mine was infected with HIV through sexual contact with a male bodybuilder whose only risk factor was sharing needles to inject anabolic steroids. I was disappointed that John M. Hoberman and Charles E. Yesalis ["The History of Synthetic Testosterone," SCIENTIFIC AMERICAN, February] failed to mention that the illicit use of synthetic testosterone by injection is a route for the spread of HIV. Half of the one million anabolic steroid users in the U.S. rely on injection. The spread of HIV infection through shared needles may become the most significant chapter in the history of synthetic testosterone.

JOSIAH D. RICH
Miriam Hospital, Brown University
Providence, R.I.

Artistic Bias?

In "Manic-Depressive Illness and Creativity" [SCIENTIFIC AMERICAN, February], Kay Redfield Jamison fails to demonstrate anything more than a statistical correlation between mental illness and artistic creativity. It seemingly never occurs to her that there may be a simple Darwinian explanation for this correlation. Perhaps those segments of the mentally ill population possessing extraordinary abilities in professions not requiring significant accountability (such as painting or writing) are able to survive and reproduce, whereas those similarly gifted in high-accountability professions (such as engineering or medicine) are weeded out. This interpretation might also explain why Jamison's "mad geniuses" are predominantly male. Historically, women have had only one career option: motherhood, a high-accountability vocation.

COLLEEN A. CANNON
Berlin, Germany

Jamison states that "recent studies indicate that a high number of established artists—far more than could be expected by chance—meet the diagnostic criteria for manic-depression or major depression." She later states that "the common features of hypomania seem highly conducive to original thinking; the diagnostic criteria for this phase of the disorder include 'sharpened and unusually creative thinking and increased productivity.'" It strikes me that the reasoning in this article is somewhat circular.

JAMES ALTIZER
Sunnyvale, Calif.

Jamison replies:

Cannon's suggestion that individuals having mood disorders will gravitate toward artistic professions is to some extent certainly true, but I cannot agree that the arts are without significant accountability. Conversely, there is a great deal of anecdotal evidence—though unfortunately little systematic research—linking accomplishment in other fields, including science and business, to manic-depressive illness. (Since the publication of my article, I have been deluged with letters from scientists describing their experiences with the illness.) "High accountability" fields such as medicine and motherhood do not in fact have lower rates of mood disorders. Several studies have found an increased rate of mood disorders among physicians, and women are twice as likely as men to suffer from depression and equally likely to develop manic-depression.

I have discussed the issue of circularity in detail in *Touched with Fire.* Distilling a 370-page book into a short article inevitably results in omissions and oversimplifications.

Plutonium Puzzles

Demanding that other nations forgo the use of commercially valuable recycled fissile material, as suggested by the Nuclear Control Institute in Tim Beardsley's news story "Pass the Plutonium, Please" ["Science and the Citizen," SCIENTIFIC AMERICAN, March], will ensure the failure of the Nuclear Non-Proliferation Treaty. Use of plutonium to generate energy gets rid of the long-lived transuranic elements, which otherwise would remain radioactive for thousands of years. To deal with the proliferation risk, we should take the plutonium that already exists and permanently destroy it via transmutation in nuclear reactors.

GILBERT J. BROWN
University of Massachusetts
Lowell, Mass.

The real, albeit small, possibility that Yucca Mountain in Nevada may not be an acceptable site for the permanent disposal of spent nuclear fuel highlights the importance of establishing a temporary storage facility. The present situation involves de facto storage at 70 nuclear power plants, which were not designed to maintain the material for extended periods. The result is higher costs for electric utility ratepayers, who have already paid more than $10 billion into the nuclear waste fund. Reform legislation is needed that would allow the Department of Energy to establish an interim storage facility. Such a facility would sorely demonstrate needed progress toward establishment of a permanent disposal system.

THEODORE M. BESMANN
Oak Ridge National Laboratory
Oak Ridge, Tenn.

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50 AND 100 YEARS AGO

JULY 1945

As a result of a new development in injection molding, the wooden heel cores of women's shoes can now automatically be given an evenly distributed coating of cellulose acetate approximately $^1/_{16}$ inch thick. The new plastics-covered heels, which are said to have wearing qualities far exceeding those of any other shoe, will not scratch or scuff, nor will the coating wear off, split, or peel. The improved heels can be made in any size, shape, or style and can be made with either dull or glossy finish in practically every color."

"An interesting new device is simply a giant pillow used to jack aircraft on soft ground or after they have made crash landings. The equipment weighs 220 pounds and comprises a set of three bags and one gasoline-engine-driven blower or compressor. Each bag when inflated is six feet high and can support 12 tons. Even a motorist might at times like to have something of the kind instead of painfully manipulating a conventional automobile jack."

"Preliminary details have been worked out for what is believed to be the first all-welded hospital building in the country. It is proposed that the framework of the new unit, to be known as Kahler Hospital, located in Rochester, Minn., will be designed as a continuous structure of beams and their connecting members. In preparing the specifications, the architects discarded all concepts of riveted construction, which tends to restrict the range of application of certain welding details."

"Activated carbon, a chemical cousin of both diamond and coke, is a powerful tool of many increasing uses, ranging from life-saving service in gas masks to salvage of a host of valuable materials. Activated carbons can be tailor-made to fit various needs, and, according to Drs. Ernst Berl and Walter G. Berl of the Carnegie Institute of Technology, the large, pitted, and porous surface 'is a powerful tool for the adsorption, elimination, or recovery of a host of desirable and undesirable substances.'"

"Looming on the horizons as something that industry has ready for the housewife is what has been called 'automatic dusting.' Actually, it is a part of an air-conditioning system that, by electronic means, removes dust from the air before it has a chance to settle on furniture and hence reduces the dusting chore to a minimum. The 'automatic duster' makes it unnecessary to dust more than once a month."

JULY 1895

Usually at this season there are calls for colored fires; on account of their poisonous and explosive nature, the utmost care in their manipulation is necessary. In the preparation of colored fires the ingredients, which should be perfectly dry, must be separately powdered and sifted through a hair sieve, and put into well stoppered, wide mouthed bottles until ready for mixing. Sulphur, and the salts of the poisonous metals—antimony, arsenic, mercury, etc.—should not be used in making colored fires for indoor use."

"The richest and most complete bath yet found in the remains of Pompeii has recently been discovered. It is a large building, with sculpted basins, heating apparatus, lead pipes, and bronze faucets. The walls and floor are tiled. Everything is in an almost perfect state of preservation, owing to the roof having remained intact when the city was buried in the year 79."

"The eminent naturalist Thomas Henry Huxley died on the 29th of June 1895, his mind remaining clear to the last. His death now leaves Herbert Spencer the sole survivor of the grand quartet of mental giants, Darwin, Tyndall, Huxley and Spencer, who succeeded in forcing their views regarding man's relations to lower forms of life and to the cosmos, commonly called 'evolution,' upon an unwilling and recalcitrant public."

"The most interesting phenomena of the atmosphere take place in the almost inaccessible parts, but ballooning and mountain observatories have led to some unexpected findings at these altitudes. Namely, many clouds which had generally been regarded as consisting of vapor are composed of minute crystals of ice; also, at different heights the direction of the wind is different, and the temperature does not get steadily lower as the earth becomes more distant, but alternate layers of hot and cold air were encountered."

"Among the ruins left upon the ground by Spanish troops after the 1868 Cuban insurrection were a large gear wheel and a fly wheel. These are shown in our engraving as they now appear after a lapse of 25 years, during which time a jaguey tree has sprung up between the spokes of the gear wheel. The growth of this tree gives some idea of the Cuban flora and the rapidity with which it springs up and spreads over the ground."

Relics of a Cuban insurrection

Darwin Denied

Opponents of evolution make gains in schools

Antievolutionists are using a new weapon in their fight to bring the supernatural into science curriculums. The U.S. Supreme Court held eight years ago that compelling public schools to teach "creation science," a doctrine that argues that science supports special creation, was unconstitutional. But opponents of Darwinian evolution are currently pushing "intelligent design," a theistic formula that posits an unnamed intelligent force to explain the diversity of life.

Volume orders of a glossy textbook promoting this thesis, *Of Pandas and People: The Central Question of Biological Origins,* by Percival Davis and Dean H. Kenyon, have been shipped to public schools in more than 12 states, according to the book's copyright holder, the Foundation for Thought and Ethics in Richardson, Tex. Director Jon A. Buell says the organization has sold 19,000 copies. The text informs students that evolutionary theory is incompatible with life's complexity, which "owes its origin to a master intellect"; it fails to mention that almost all biologists conclude that evolution is the only plausible scientific explanation of life. Buell has written to supporters asking for prayers and inviting readers to become part of a "quiet army" opposing the "metaphysical naturalism" of other textbooks.

Because *Pandas* scrupulously avoids suggesting divine creation, it may elude the 1987 Supreme Court ruling, which was based on the conclusion that creation science is actually religion. The book leaves its intelligent force unnamed—"like *Hamlet* without Hamlet," as one wit describes it. Buell counters that *Pandas* is not religious, although it is "congenial to theism." Critics are, however, underwhelmed by the distinction. One reviewer, Kevin Padian of the University of California at Berkeley, wrote that the book was "fundamentalism in disguise."

Buell refuses to specify where *Pandas* is being used. But the school district of Louisville, Ohio—where creationism was taught until the American Civil Liberties Union (ACLU) threatened a lawsuit in 1993—has accepted a donation of between 100 and 150 copies, according to the ACLU's Raymond Vasvari.

Pandas seems to mark a trend. Eugenie C. Scott of the National Center for Science Education in Berkeley, Calif., which monitors creationist activity, says antievolutionary sentiment is strong in many small towns. Although there are no national data, a 1991 survey of Kansas biology teachers by J. Richard Schrock of Emporia State University found that one in four favored giving creationism and evolution equal time. Schrock also notes there was a flurry of pro-creationist pickets of schools after last November's elections.

"Antievolutionism seems to be having a resurgence," agrees Ellen Chatterton of Americans United for Separation of Church and State. She points out that groups headed by the Christian Coalition are placing supporters on school boards and state committees across the country. The representatives typically argue that children should be given the benefit of a variety of theories.

Alabama is one case in point. Under the 1987 ruling, teachers are not prevented from advocating creationist ideas. After the intervention of Alabama's governor, Fob James, and members of the Eagle Forum, a Christian organization that opposes sex education, the state board of education recently accepted a science course modified to remove obstacles to "creation science." John C. Frandsen of the Alabama Academy of Science predicts the religious right will make a "strenuous effort" in September to gain state approval for a nakedly creationist book or for *Pandas.*

Similar clashes are occurring elsewhere. Voters in Plano, Tex., threw two pro-*Pandas* members off the school board in May in a bitterly contested election. In Merrimack, N.H., a local Baptist minister has promised to launch a second attempt to develop a creationist curriculum—and has packed school board meetings with supporters.

Scott notes that almost all seminary-trained rabbis and ministers from most Christian denominations accommodate

MAX AGUILERA-HELLWEG

DIORAMA at a creationist museum in California distinguishes between "correct" and "evil" practices. The second set, adorning the evolutionary tree, includes "scientism."

evolution. Only biblical literalists are genuinely conflicted by Darwinism. Yet among the lay public the perception is widespread that natural selection is inimical to all religious belief. "The only thing we are against is bad science," Scott says. "Sooner or later we are going to have to go to court over *Pandas*." Given the depth of feeling on both sides, perhaps nine important justices in Washington had better start reading up on intelligent design. —*Tim Beardsley*

On the Level

Central Asia's inland seas curiously rise and fall

Over the past three decades, rivers feeding the Aral Sea in formerly Soviet central Asia have been increasingly diverted for irrigation, and as a result its water level has plummeted. So sudden has been the drop—some 15 meters in the past 20 years—that fishing boats, once grounded in shallows, were completely isolated from the retreating shoreline and have rusted amid the newly formed dunes.

This scene has become somewhat of an environmental symbol. In his 1992 book, *Earth in the Balance,* Vice President Al Gore used the powerful image of camels walking past derelict "ships of the desert" to show the dangers of interfering with nature. The U.S. Agency for International Development has instituted programs to aid communities surrounding the shrinking sea, and the World Bank may fund a restoration project.

But the lessons to be drawn from central Asia are not so straightforward. For although the Aral Sea is indeed emptying, the nearby Caspian Sea—a much larger body of water—is rising.

Like the Aral, the Caspian long appeared to be obeying an elementary principle of hydrology: river modification upstream leads to less water downstream. For decades the Caspian's height moved in concert with efforts to harness inflowing rivers, such as the Volga. In the 1930s numerous hydroelectric dams were erected, and the Caspian fell; during World War II, such projects were suspended, and sea level stabilized. After the war, construction of dams and reservoirs intensified, and sea level dropped further.

In 1977 a strange turnabout occurred. Human use of the rivers continued to grow, but the Caspian began inexplicably to rise. Soviet hydrologists initially considered the shift to be a temporary aberration and completed a dam to isolate the shallow Kara-Bogaz Bay on the eastern shore. Cutting off evaporative loss from the bay was seen as a way to slow the overall decline in sea level.

But the Caspian kept on swelling. Because many settlements and industrial sites were finding themselves underwater, the government of Turkmenistan decided in 1992—after the sea had risen two meters—to breach the Kara-Bogaz Dam. "The approach they used in earlier years was that 'we can change nature,' " says Sergei N. Rodionov, formerly of the State Oceanographic Institute in Moscow. "Now the approach is the opposite." Although resigned to let nature take its course, scientists nonetheless would like to understand what is happening and why.

NOVOSTI/LEHTIKUVA OY *SABA*

***DESERT SHIPS** haunt dry portions of the Aral Sea. The nearby Caspian, meanwhile, keeps rising.*

Most researchers attribute the rise to changing weather patterns over the Caspian drainage basin: more precipitation increases river influx. Several Russian scientists argue, however, that recent tectonic shifts in this geologically active region might also contribute by affecting the seafloor. Other Russians have suggested that water from the Aral—perched some 70 meters higher in elevation—may be flowing underground into the Caspian, deftly explaining the seesawing levels of both.

Philip P. Micklin of Western Michigan University, a leading American specialist on the Aral Sea, discounts that idea as "totally crazy." He points out that there is not enough water being lost from the Aral to account for the Caspian's rise and that increased discharge from the Volga clearly indicates where the excess water is coming from: "Why look for far-out explanations when it's clear what's happening?"

Micklin does recognize, however, that alternating phases in these neighboring inland seas take place. He notes that the Amu Darya River, which currently feeds the Aral from the south, has been known to flow through its left bank and empty into Lake Sarykamysh to the west. That body, in turn, spills into the Caspian. Such redirection probably happened repeatedly in the past, sometimes spurred on by invading armies. Because flow of the Amu Darya toward the Aral has depended on dikes and dams upriver, their destruction has at times raised Sarykamysh and lowered the Aral.

Past acts of strategic environmental manipulation may explain why Dimitriy O. Eliseyev of the Leningrad Pedagogical Institute found submerged tree stumps in the northern Aral in 1990. The ancient trees showed that the sea was once even lower. According to Micklin, U.S. and Russian researchers established that the trees grew for several decades, about 400 years ago. This period corresponds to the years that the Amu Darya last flowed west toward the Caspian, before shifting north in 1575 to feed the Aral.

Thus, the conviction that humans could bend nature to suit their will apparently held well before the Soviets arrived in central Asia. Yet Russian planners seemed to show an unmatched enthusiasm for such pursuits. They even worked out a strategy for feeding the Caspian and Aral seas by diverting river water that was flowing into the Arctic Ocean.

Had the political and meteorological winds sweeping the Soviet Union been delayed, planners might have been able to pursue their grand schemes for diversion. Such efforts may well have proved their premise—"We can change nature"—correct, although catastrophic Caspian flooding might not have been the change they were expecting. As it is, the rise and fall of two seas remains hard to handle. —*David Schneider*

JERRY OHLINGER'S MOVIE MATERIAL STORE, INC.

BLACK HOLES abound in science fiction, such as the 1979 film **The Black Hole,** *but some physicists still doubt their existence.*

Bashing Black Holes

Theorists twist relativity to eradicate an astronomical anomaly

Black holes breed paradoxes. Although black holes are being "discovered" with numbing regularity these days, many prominent physicists still consider them far from demonstrated. "I don't believe in black holes," declares Philip Morrison, a physicist at the Massachusetts Institute of Technology (and a longtime book reviewer for this magazine).

Such doubters are heartened by two recent theoretical attempts to stamp out black holes—or at least their more far-fetched aspects. Both proposals accept (as Morrison does) that space harbors objects that are extremely massive and dense; astronomers have found ample evidence for such gravitationally powerful beasts. But the theories modify general relativity—Einstein's theory of gravity—in order to make these objects more sensible.

According to conventional relativity, black holes are not just dense but infinitely dense; in their hearts, which are called singularities, space, time and causality itself are mangled beyond recognition. So obscene are black holes that they must be hidden from the rest of the universe by membranelike event horizons, which also strain credulity. Time runs so slowly in an event horizon, relative to the rest of the universe, that anything falling into it is stuck there, seemingly, for eternity. Outside observers thus never actually see anything fall into supposedly voracious black holes.

A proposal advanced by Hüseyin Yilmaz, a physicist affiliated with Tufts University and Hamamatsu Photonics in Japan, would eliminate these paradoxes. Since the 1950s Yilmaz has tried to construct a theory that preserves the basic framework of general relativity while doing away with its more anomalous effects. Only recently has Yilmaz produced what he considers to be a consistent version of his idea.

Yilmaz modifies general relativity by assuming that a gravitational field, as a form of energy, also tugs on itself. As one colleague of Yilmaz has put it, "Gravity gravitates." The addition of this factor, for various technical reasons, would prevent large masses from undergoing the catastrophic collapse that spawns singularities and event horizons.

Yilmaz has an enthusiastic supporter and collaborator in Carroll O. Alley of the University of Maryland. The proposal is a "well-defined alternative" to general relativity that "makes a lot of sense," Alley declares. Papers by Yilmaz and Alley have been published in the 1995 *Annals of the New York Academy of Sciences.* Alley notes that Einstein himself was appalled at some of the odd predictions of his account of gravity. "We regard this as the completion of Einstein's work," Alley says.

But John W. Moffat of the University of Toronto hardly agrees. According to his analysis, the Yilmaz theory might eliminate event horizons but not singularities. That would leave the singularities "naked," Moffat adds in horror. "This is a disaster." Of course, Moffat may be biased: he prefers his own modified version of general relativity. Together with a graduate student, Neil J. Cornish, Moffat describes his work in this month's *Journal of Mathematical Physics.* In their take on relativity, space-time may be twisted as well as bent in response to the presence of a large mass; the addition of this extra "torsion" parameter ousts event horizons and singularities.

Moffat claims his hypothesis also whisks away one of the most troubling problems of modern theoretical physics. Various theorists, notably Stephen W. Hawking, have argued that Einsteinian black holes destroy information and thereby violate basic notions of cause and effect. But if there are no Einsteinian black holes, Moffat contends, there is no information loss.

MARIAN HYMAN AND MARVIN W. ROWE

Both Yilmaz and Moffat are trying to find ways—short of visiting black holes—to test their hypotheses. Ironically, Yilmaz's work helped to inspire an experiment that might falsify his proposal. In the late 1950s a physicist named George Pugh, after hearing Yilmaz present an early version of his model, proposed a complex experiment—involving a gyroscope in a weightless environment—that would rigorously test general relativity. Pugh's plan, combined with others, evolved into the $500-million Gravity Probe B Relativity Mission. The experiment is scheduled to be launched on board a rocket in 1999.

Most theorists think Einstein's version of relativity is far more likely to survive such a test than are the alternatives. The Yilmaz suggestion is "junk," "garbage," "not even a real theory," sneers Clifford M. Will of Washington University. The Moffat account, while more deserving of respect, also suffers from technical problems, Will says. But then, he confesses he does not believe there is really a need for such theories, because he does not consider singularities and event horizons to be so odd: "These other theories are much more exotic."

Morrison, needless to say, disagrees. The proposals by Yilmaz and Moffat could come to naught, he says, but they are nonetheless "examples of what you need to have" to make astrophysics sensible again. *—John Horgan*

Artistic Genes

Putting a date on ancient art can be tough, and resolving the list of ingredients in the paint is particularly difficult. Now, for the first time, researchers have used DNA analysis to identify the animal tissue in 4,000-year-old rock paintings. A group led by Marian Hyman and Marvin W. Rowe of Texas A&M University examined figures similar to this one, found near the Pecos River in Texas. By analyzing fragments of DNA preserved under a layer of minerals, the team discovered that the pigments contain material from an ungulate, or even-toed hoofed mammal—ruling out egg albumen or yolk, which had been suggested. In that area of Texas, such animals were most likely bison or deer; the scientists are conducting further tests to determine which of the two was used. The work may ultimately help archaeologists understand the images: Was deer tissue used to depict only deer? Was painting part of a hunting practice? The findings, of course, may just add to the mystery. *—Sasha Nemecek*

Fright of the Bumblebee

Bugs at the scene of the crime aid police

What do you call a bloodhound with wings? If you answered *Calliphora vicina, Lucilia illustris, Phormia regina* or any other species of blowfly, go to the head of the class. Better yet, go to the police. Your expertise may help them put murderers behind bars.

In recent years law-enforcement officials have started to appreciate the creeping clues that coroners used to wash down the drain. The stomach-turning fact is that any dead body left unattended will begin to attract insects, especially blowflies, almost immediately. Those bugs can reveal all kinds of information about the time of death and the scene of the crime.

DAVID SCHARF

***MOSQUITO** may someday aid detectives by serving up a suspect's DNA.*

"Our approach is an ecological one," says Robert D. Hall, professor of entomology at the University of Missouri–Columbia and a member of the Council of American Forensic Entomologists—a group of 12 or so experts who regularly assist in criminal investigations. (For obvious reasons, they also go by the name "The Dirty Dozen.") The flies that quickly infest a corpse lay eggs that go through a well-understood sequence of time-dependent metamorphic stages. Further, waves of new insects, such as beetles, arrive at the scene at standard intervals to feed on the decomposing body and the fly maggots.

"After the discovery of the corpse, sampling of the insects stops a biological clock, which we can use to date back to the time of death of the victim," explains E. Paul Catts, professor emeritus of entomology at Washington State University. Temperature can also affect the initial sequence of events, so "you would be concerned with what the weather conditions were like from the time the meat hit the sod," he adds.

This estimate of the so-called postmortem interval, or PMI, is usually the forensic entomologist's biggest contribution to a murder investigation. (For O. J. addicts: the bodies were very likely found too quickly for entomology to be a factor.) But insects have also given away attempts to falsify a murder scene. Because the "seepage area" under a corpse develops its own faunal community, the area under a relocated body hosts insects that indicate a different PMI than do the insects found in the body. Species on the corpse that just do not belong in a certain environment—such as typically urban-dwelling flies in a rural setting—can also lead investigators to the true scene of the crime.

In cases involving drugs or poisons—in which a corpse has decomposed past the point of toxicological testing—insects can actually serve as surrogates for organs or fluids. "Even though the tissues may be gone," notes M. Lee Goff, professor of entomology at the University of Hawaii, "whatever drugs or toxins were present will be stored in the maggot. By treating the maggot as a normal toxicological specimen, you can get an indication of what was present in the remains."

Continuing advances in molecular biological techniques could extend the scope of what entomologists tell police—and could make criminals want to fumigate an area before committing their nefarious deeds. Scientists have been able to extract human DNA from blood taken from the gut of insects: lingering mosquitoes collected at a crime scene may one day supply police with samples of a suspect's DNA. "The technology will increase our ability to use parasitic insects, such as crab lice, that take a blood meal," Goff describes. "This can be used to put suspects at the scene of a rape, where you have a transfer of the parasites." Last year researchers from the Federal Bureau of Investigation and the University of Miami School of Medicine studying lice removed from volunteers showed that human genetic markers could be tracked even in the arthropods' fecal pellets.

Genetic technology could improve the identification of some insects themselves—which could strengthen their

role as evidence. "There is plenty of DNA work to be done on eggs and larval stages that we can't identify well morphologically," says Neal H. Haskell, the only full-time forensic entomologist in the U.S. in a private consulting practice (and the only one whose car sports an Indiana license plate reading "MAGGOT").

For now, though, insects most often play a supporting role in criminal cases. "We can use this unbiased quantitative scientific evidence to pin down or refute other physical or testimonial evidence," Haskell says. On occasion, however, insects do claim center stage. A Tacoma, Wash., case in 1990 featured a dead man in bed with a bullet through his neck and no indications of a struggle. Catts came up with a PMI based on the flies at the scene, and a subsequent police canvass of the neighborhood turned up reports of a nearby loud party, featuring gunshots, at the suspected time of death. "That case really hinged on the fly evidence," Catts says. "Nobody broke into the house and shot this guy. It was just by chance he got hit." The gunman pleaded guilty to manslaughter.

Although bodies crawling with maggots tend to nauseate most observers, Catts and his colleagues often have backgrounds that have conditioned them against squeamishness. Hall's father was a blowfly expert. Goff got assigned to a pathology laboratory in the army in the 1960s and assisted on autopsies. Haskell was a sheriff's deputy who handled insect-infested bodies.

"It's a grisly field—there's no question about that," Hall admits. "To a certain extent, that gives it a macabre fascination for people. But I think the emphasis should be on the wonderful things that can be done with these insects because they're seldom fooled. If you ask them the right questions, they will give you right answers. As our understanding improves, we will probably have the most effective group of bloodhounds out there." —*Steve Mirsky*

The Waterfall Illusion

An odd optical puzzle yields clues to consciousness

In 1834 a Mr. R. Adams wrote in a British philosophy journal about an optical effect known as the waterfall illusion. The effect is evoked by staring steadily at a rapidly moving object—a waterfall is ideal—and then quickly glancing at a stationary object, such as a tree. For a brief period, the tree will appear to surge skyward, in a direction opposite to the flow of the water.

Adams could only guess why this illusion occurs, but modern neuroscientists have the tools to discern the neural processes underlying what they call the motion aftereffect. Researchers working with one of those tools—magnetic resonance imaging (MRI)—have just gone a long way toward solving the puzzle. Their experiments may offer clues about the locus of the most inescapable yet elusive of all mental phenomena, subjective awareness.

In the experiments, a group led by Roger B. H. Tootell of Massachusetts General Hospital had subjects gaze at concentric rings expanding outward, like the ripples generated by a stone dropped in a pond. When the rings stopped moving, they appeared to the subjects to reverse direction and move inward for as long as 10 seconds.

Meanwhile the MRI scans revealed what was happening in the subjects' brains. When the subjects watched the rings move outward, a section of the visual cortex called V5 showed marked neural activity. This area is considered one of the "higher" regions of the visual cortex; it processes and integrates signals from places further down in the hierarchy (V1, V2 and so on). Previous experiments have also indicated that neurons in V5 respond to motion in specific directions (just as other neurons respond to specific colors or to lines oriented in certain directions). When the rings stopped moving, neural activity in V5 *increased* slightly.

Tootell notes that some neuroscien-

FIELD NOTES

In the Atomic Corral

IBM may bring to mind drab blue suits and corporate mores, but that impression is hardly the fault of its scientists. Take Donald M. Eigler of the giant's Almaden Research Center in San Jose, Calif. Dressed in a white shirt, baggy gray pants, tennis sneakers and a purple-splashed necktie that matches his watchband, Eigler hardly exudes conservative culture. Maybe that is the privilege of being a scientist—or of living in California. In any event, it seems appropriate for someone who spends his days and nights shoving atoms around one by one using a scanning tunneling microscope.

I met him in March on a journalists' tour of the facilities. After explaining his research, Eigler promises to let us move individual atoms if there is time after stopping by a colleague's lab next door. It's not long after that visit before we charge back into Eigler's lab. I'm not sure why everyone wants to push an atom around. After all, we all can move untold billions of them every second.

Imaged on the computer screen is a blob of atoms—"'BL' on the periodic table," Eigler cracks. The microscope, which sees by detecting electrons that tunnel between the tip of the microscope and the atom, is housed in another room. Eigler has hooked up his microscope to a stereo system, which translates the tunneling current of electrons into a staticlike hum. I poise the cursor over a BL atom before clicking on the mouse, which lowers the tip onto the blob that rests on a smooth substrate. Pop! An atom has clung to the tip. Then I drag the cursor across the screen. Clunk! The atom has just plopped into the next unit cell of the molecules that make up the substrate. Clunk! Another unit cell over. An updated image sweeps across the monitor: the blob has moved a tad to the left.

Carbon Monoxide Man

IBM ALMADEN RESEARCH CENTER

Eigler, of course, is far more adept at controlling atoms. Over the years, he and his colleagues have used them to spell out the company's logo and to draw stick figures with carbon monoxide molecules. He has trapped electrons in atomic corrals, rendering visible the wave nature of the electron. Graphics of his manipulations have graced the pages of several publications.

Eigler's techniques promise much more than an entertaining sound-and-video show. The scanning tunneling microscope could store data as atom-size bits or forge molecules to custom specifications. The process would also prove useful, as Eigler presents it, for "spin excitation spectroscopy." He may not wear IBM blue, but he certainly does not let you forget he's a physicist. —*Philip Yam*

JIM CORWIN *Tony Stone Images*

***WATERFALL EFFECT** can be induced by gazing at a rapidly moving object, such as a waterfall (unfortunately, only real waterfalls and not mere photographs will suffice). If one then glances away at something stationary, such as a tree, it will briefly appear to flow skyward, in the direction opposite that of the waterfall. Magnetic resonance studies have revealed the neural processes underlying this optical illusion.*

tists had thought the motion aftereffect stemmed simply from the tendency of neurons to decrease firing, or become habituated, after prolonged exposure to a stimulus. When the stimulus is removed, according to this model, neurons sensitive to motion in the opposite direction would be relatively more active and thus create the motion aftereffect. In this view, activity in V5 should have decreased after the rings stopped.

Of course, the MRI results told a slightly different story. The fact that the activity increased, Tootell observes, suggests that the firing of neurons sensitive to motion in one direction actively inhibits the firing of neurons responsive to motion in other directions. When the stimulus is removed, the previously inhibited neurons erupt in a brief frenzy of unrestrained firing, creating the motion aftereffect. Experiments on monkeys have also turned up evidence for this inhibition effect, Tootell adds.

One neuroscientist delighted by these findings is Christof Koch of the California Institute of Technology. For years, Koch and Francis Crick of the Salk Institute for Biological Studies in San Diego have speculated about where the neural activity underlying visual awareness—the subjective experience of seeing—takes place. Studying awareness can be difficult, Koch explains, because the simple act of looking at an object triggers many neural processes in the brain, not all of which contribute to awareness. Optical illusions, which are, after all, purely subjective, serve as excellent phenomena for isolating and thus studying visual awareness.

In the same issue of *Nature* that includes the Tootell paper, Koch and Crick cast doubt on the possibility that awareness is tied to V1, the area of the visual cortex that receives signals most directly from the retina. Awareness, the researchers contend, is much more likely to stem from V5 or other higher-level regions of the visual cortex, which are more closely tied to parts of the brain involved in decision making and other cognitive functions. Tootell's report supports these conclusions, Koch argues. The viewers, he elaborates, showed little or no activity in V1 and marked activity in V5 while they were subjectively perceiving—but not actually looking at—moving rings.

Antonio R. Damasio, a neuroscientist at the University of Iowa, agrees with Koch's interpretation. In a commentary that accompanies the two papers, Damasio writes that Tootell has helped narrow the search for the neural correlates of visual awareness—and, ultimately, consciousness itself. On the other hand, Damasio cautions, neuroscientists still have much to learn about how, rather than simply where, the brain engenders awareness. —*John Horgan*

Toxins Abounding

Despite the lessons of Bhopal, chemical accidents are on the rise

In December 1984 the lethal escape of methyl isocyanate in Bhopal, India, unleashed a wave of concern about chemical calamities. Legislation in the U.S. and India strove to lessen the danger to communities, and the United Nations renewed its efforts to warn about toxins. But a decade later industrial chemicals remain poorly understood: when similar accidents occur, doctors are just as likely to be faced with a mysterious poison as they were in Bhopal.

Moreover, the potential for catastrophe is scarcely diminished. In the eight years preceding the disaster, the Organization for Economic Cooperation and Development recorded 74 major accidents; in the eight years following, the number reached 106. And between 1980 and 1990 the number of gas releases that exceeded Bhopal in quantity and toxicity totaled 15 in the U.S. alone.

"Unlike pesticides and drugs," explains Donald J. Lisk of Cornell University, "industrial chemicals were not intended to be ingested." Thus, studying them is not a priority. Adequate toxicology exists for only 2 to 3 percent of the more than 70,000 substances used to create about five million products, observes Joseph LaDou of the University of California at San Francisco. For 75 percent, there is no toxicology at all.

In the U.S. the 1976 Toxic Substances Control Act was designed to fill this gap, but the task proved too enormous. Consequently, more than 60,000 existing chemicals were "grandfathered in," with the Environmental Protection Agency requiring scattered tests on no more than about 100. Of the chemicals introduced since 1979, the EPA restricts the use of 7 percent. But older substances make up 99.9 percent of the six-trillion-pound total.

Although the Occupational Safety and Health Administration mandates Material Safety Data Sheets for at least 600 chemicals to which workers might be exposed, companies are not required to perform tests—they need only list what they do know. So humans may end up serving as guinea pigs. Solvents, resins and glues have been implicated in the testicular cancers and other disorders of 5,000 male employees at Lockheed, according to Daniel T. Teitelbaum of the University of Colorado.

The lack of information about toxics continues to haunt communities, not just workers. In 1986—after the Union Carbide incident in Bhopal and a subsequent release at the company's sister plant in Institute, W. Va., where a chemical leak sent 135 neighbors to the hospital—the Emergency Planning and Community Right-to-Know Act was passed. It required facilities using certain chemicals to report their amounts and locations to Local Emergency Planning Committees (LEPCs), which were to plan responses to accidents. The federal government did not authorize funding for the 4,100 LEPCs, however. In 1990 the EPA concluded that most of these groups were dominated by industry and government representatives and had failed to inform communities of hazards, for fear of causing "counterproductive panic."

According to Fred Millar, an accident prevention expert based in Washington, D.C., some of the LEPCs panicked when they saw the facts. The "plume map" for Houston, for example, showed that more than 50 percent of the city is vulnerable to toxic releases. The New York State Attorney General's Office has calculated that some gas clouds could travel a mile in 17.6 minutes; alerting certain communities, let alone evacuating them, might take up to an hour.

In 1990 environmentalists and labor groups pushed through amendments to the Clean Air Act that required companies to conduct hazard assessments and to make public their worst-case scenarios. But the EPA missed its 1993 deadline to draw up the required rules, and the Chemical Safety and Hazard Investigation Board, which the amendments also established for independently investigating accidents, does not yet exist. Nor is it funded.

Just Scratch It

Itch remains the most mysterious of cutaneous sensations—of all sensations, perhaps," says Jeffrey D. Bernhard, director of dermatology at the University of Massachusetts Medical School at Worcester. No one even seems to know how often a dermatologically healthy person scratches, but, let's face it, we're an itchy lot.

For years the neurological mechanisms of itching ("pruritus" in medical jargon) were thought to be identical to those of skin-based pain. But "over the past 10 years or so, there has been an accumulation of

In New Jersey and California, active programs do exist for reducing the likelihood of accidents. Nevertheless, dangers persist. According to Peter Costanza, a New Jersey regulator, the contents of any of up to 20 railroad tank cars of chlorine in the state, some in crowded areas such as Elizabeth and Newark, could kill thousands. "We make sure the valves are tight," Costanza reflects, but that would not prevent a truck from puncturing one of them.

The National Environmental Law Center concludes that 10 billion pounds of "extremely hazardous chemicals," such as chlorine, are currently stored in the U.S. About once a day, an event involving immediate injury, evacuation or death is reported to the Emergency Response Notification System database. (That number is probably optimistic: between 1988 and 1990 the system listed only 13 percent of the accidents recorded by New York State.) Apart from such histories, no measure of the risk from accidents seems to exist in the U.S.

In many places, the situation is even worse. After Bhopal, the United Nations Environment Program strengthened its efforts to make data on toxic materials available to developing nations. Unfortunately, firefighters and hospitals there rarely receive the information. "In terms of accessibility," LaDou states, "the U.N. efforts are 30 years behind the U.S."

Worldwide the rate of chemical catastrophes is on the rise. Bhopal prompted several nations to support an agreement, known as Prior Informed Consent, requiring countries exporting hazardous substances to inform the importing nation. No such system exists for hazardous processes and technologies; even if it did, observers doubt that developing countries would use it. "In the current climate," notes Peter M. Haas of the University of Massachusetts at Amherst, "any investment is fine, regardless of what technology it brings." For its nylon project in Goa, Du Pont has secured an agreement with its Indian partners that the multinational will not be liable for any accidents.

In India, projects based on hazardous technology are mushrooming despite the legislation that Bhopal prompted. The Environmental Protection Act of 1986 directed companies to supply information about toxic inventories, allowed for inspections and also created laboratories. A 1987 amendment to the Factories Act set guidelines for handling dangerous materials. But the acts cause information to flow to the government, not to concerned communities.

***CHEMICAL EXPLOSION** in New Jersey killed four in April.*

Methyl isocyanate, at least, is no more to be found in India. After Bhopal, some U.S. companies started to use the substance in a closed-cycle process, so that the unstable fluid did not have to be stored. But at least 150,000 pounds of it reside at the Institute plant, which now belongs to Rhône-Poulenc. In case of a spill, residents are advised to "Shelter-in-Place": bring in pets, shut windows, stuff wet towels under doors and tune in for instructions. As yet, no plan exists for dealing with the worst-case scenario involving the chemical: death within the first nine miles of a plume stretched, by the usual wind conditions, right over town—which begins a quarter mile from the factory. "No way the community can get out," states Pamela L. Nixon, a medical technician who serves on the LEPC. Shelter-in-Place could well become, in Millar's words, "Gassed-in-Your-Home." —*Madhusree Mukerjee*

This is the second of a two-part article on the legacy of Bhopal.

evidence that itch is a distinct and separate sensation from pain, despite some similarities," Bernhard notes. Like some kinds of pain, itch begins when nerve endings in the skin are stimulated, either chemically or physically, or both. Still, pain and itch differ in other respects, including their relief. It is not entirely clear why scratching an itch makes it go away; apparently it sends a new signal that either breaks up the spinal nerve vibrations or substitutes a new sensation.

Some allergic reactions and various conditions—eczema, psoriasis and hyperthyroidism, among them—are infamously itch inducing. Some itches, on the other hand, defy explanation. Children studying in school or ostensibly practicing their musical instrument seem to itch unnaturally, as do major league baseball players at bat on national television. Bernhard has also come across some more obscure problems. What would you call the case of the woman who itched after amorous contact with her spouse, or that of the woman whose marriage was so stressful she itched until she divorced? ("Till *itch* do us part"?)

Those who have managed to escape these conditions need not feel left out. There is always pruritus idiosyncratica, everybody's own little itch, according to Bernhard: "some spot they find themselves scratching from time to time." He named the condition based on his own "extremely informal" clinical observations. "People come in and say, 'You know, I itch here,' and we don't have any explanation for it. Right now I'm itching my leg, for example." —*Glenn Zorpette*

MICHAEL CRAWFORD

An Inside Job

IL-12 attacks tumors on two fronts, but can it win the battle?

Several years ago oncologists saw great promise in interleukin-2 (IL-2), a chemical messenger in the immune system that calls killer *T* cells into action. Once alerted, these cells seek and destroy unhealthy tissues in the body. Cancer, it seemed, simply failed to summon this response. So researchers suggested that injections of IL-2 might sic killer *T* cells on tumors. In clinical trials, though, IL-2 fell short of this expectation.

Now another immune messenger, interleukin-12, is raising hopes. Like IL-2, this molecule enlists the body's intrinsic cancer-fighting abilities. In addition, workers have discovered that it can stunt the growth of new blood vessels in solid tumors. Deprived of a blood supply, cancer cells cannot receive the nutrients they need to spread. Hence, some scientists believe that although IL-12 may not be able to cure cancer, it could potentially keep many forms of the disease in check.

The finding, from Judah Folkman of Harvard University and his colleagues, appeared in May in the *Journal of the National Cancer Institute.* To test IL-12, the group placed tiny pellets of a compound known to promote blood vessel growth—a process termed angiogenesis—in the eyes of mice. Within five days, new capillaries covered the cornea. When the mice were given IL-12, however, the capillaries vanished. "This is the first description of the fact that IL-12 might have an adverse affect on angiogenesis," says Robert S. Kerbel of the University of Toronto.

In fact, IL-12 does not retard blood vessel growth itself but causes immune cells to secrete gamma-interferon, which stimulates the production of inducible protein-10. This recently discovered protein appears to be one of the most potent in a series of angiogenesis inhibitors identified since the late 1980s. Although the notion of starving cancer cells instead of killing them has been slow to catch on, clinical trials of eight drugs having that effect are now under way. "This kind of alternative strategy would have been unheard of 10 years ago," Kerbel observes. "But molecules such as IL-12 make it a reasonably attractive paradigm."

Part of the tactic's overall appeal is that it may enable physicians to avoid the problem of drug resistance. "Even when traditional chemotherapy initially succeeds, in most cases the cancer returns more resistant," Kerbel notes. "Cancer cells have a formidable capacity to develop resistance because they shuffle their genetic deck very readily." In contrast, the genes found in the endothelial cells of developing blood vessels are far more stable and would very likely build drug resistances at a much slower rate, if at all.

IL-12's charm is that it can stall angiogenesis *and* stimulate the immune system. IL-12 even stirs up more immune activity than does IL-2. Both interleukins prompt the production of gamma-interferon, which makes *T* cells into the killing kind, but IL-12 does so earlier in the immune response. This timing makes an enormous difference, says Michael T. Lotze of the University of Pittsburgh Cancer Institute. "IL-2 arms the warheads, sets the triggers and drops the bombs, but IL-12 is the ammunition factory."

Clinical trials of injectible IL-12 began in May 1994—one year before Folkman's group reported its finding. So far, Lotze says, the results look promising. Last month he launched additional clinical tests of an IL-12 gene therapy. In mice the intervention eliminated existing tumors and helped the animals reject new ones as well. Other workers are investigating whether IL-12 might ameliorate the symptoms of AIDS and hepatitis. "We have every reason to be excited about IL-12," Lotze states. Still, it will be years before anyone will know for sure whether IL-12 lives up to its potential. As Folkman is quick to caution, "Many things work in mice and not in people." *—Kristin Leutwyler*

A River (of Mud) Still Runs Through It

Four years ago Mount Pinatubo in the Philippines awoke from six centuries of slumber, sending a mass of volcanic material skyward. Finer particles made it into the upper atmosphere and were transported around the world. But most of the spew fell on local inhabitants, showering them with a mixture of ash and rain that resembled falling cement. The eight cubic kilometers of material ejected by the volcano left surrounding areas laden with ash thick and weighty enough to collapse buildings. The volcano covered the entire planet with a blanket of sorts, made up of stratospheric aerosols that scattered enough sunlight to cool the earth appreciably.

Global climate effects have since abated, but local suffering endures. Massive flows of volcanic ash, called lahars, which form in the wake of violent volcanic eruptions, persist. These viscous rivers of mud (*right*) can be devastating—often more so than the explosion itself. In 1985 lahars from the eruption of Nevado del Ruiz in Colombia killed some 23,000 villagers. Around Mount Pinatubo lahars have displaced hundreds of thousands of people, who continue to wait for the mountain's loosely consolidated new surface to stabilize. But after spending nearly 600 years asleep, Pinatubo seems in no hurry to settle down. *—David Schneider*

OLIVIER RAFFET

THE ANALYTICAL ECONOMIST

Computation Outstrips Analysis

The law of demand—that people will buy less of something if its price goes up, more if its price declines—is about as secure a proposition as economics offers. Lately the methods of economics itself have been following that law, and as a result economists are fashioning a new kind of theory.

The price that has been changing is that of computation. On any given day, for the past 20 years at least, the cost of adding or multiplying two numbers has been half of what it was 18 months earlier. At Los Alamos in 1943, a calculator was a woman who did calculations for a team organized by Richard Feynman. Today systems of hundreds of equations are a job for an average PC.

This change in degree has become a change in kind. Instead of reasoning about the economy on the basis of a few highly simplified, mathematically tractable assumptions, researchers can build more realistic models of economic behavior and see how they run. This notion has been taking hold throughout the sciences: in a new book, *Darwinism Evolving: Systems Dynamics and the Genealogy of Natural Selection,* David J. Depew and Bruce H. Weber trace similar stages in evolutionary theory. From Charles Darwin's publication in 1859 until about 1900 came the prequantitative origin (so to speak), from 1900 to 1975 or so the "Boltzmannian" statistical stage, and then computer simulation.

The statistical stage is the one that most observers of science are familiar with. Ludwig Boltzmann introduced statistical methods to physics to deal with the aggregate behavior of a gas. In 1877 no one could even imagine following the individual histories of thousands of gas molecules colliding with one another, and so Boltzmann opted for following average behavior, which is what statistical theory is good at.

Economics is just finishing its Boltzmannian stage. The statistics used by economists were invented for experiments in agronomy and perfected in the 1930s. During the 1940s and 1950s, these techniques, which let economists deduce properties of individual actors from gross measures such as price levels, spread to the rest of economics.

In discussions of monetary policy, for example, the prequantitative stage contends with philosophical issues such as "Should the government interfere in financial markets?" or "It seems reasonable that raising interest rates will throttle demand and reduce growth." Boltzmann-style analysis looks instead at whether the numbers the government collects show connections between discount rate and gross national product. The Boltzmann era ends when economists have enough computing power to test directly their ideas about how molecules of economic behavior will interact in mass. Assuming researchers agree on underlying economic behavior, the answers will be unobscured by all the confounding factors that beset real data.

This story of evolutionary progress highlights the two competing intellectual traditions—with differing attitudes toward computation—that have long coexisted. In the Greek tradition, theoreticians prove things on abstract principles. The proof of the Pythagorean theorem, for instance, does not depend on the particular sizes of the right triangles in question. The Babylonian tradition, in contrast, discovers by brute force that a million different right triangles all seem to have the same relation among the squares of their sides.

In modern economics the Greek tradition succeeds in the work of Nobel laureates Paul A. Samuelson and Kenneth J. Arrow, who applied mathematical reasoning to a minimum of data. The Babylonian tradition is more checkered: in Isaac Newton's time, it allowed calculation of hypothetical costs to show that the Somerset Levels wetlands should be drained at public expense. In 1973 Wassily Leontief won a Nobel for input-output analysis—yet his work had little practical application.

Since then, however, the law of demand, combined with the ever decreasing cost of computation, has put Greek science under a sentence of death. Elegant analysis still costs as much time and effort as it ever did, but number crunching becomes ever cheaper. The kinds of questions that the new Babylonian economists are asking are more amenable to answers, and so they will be asked more often. That's the way the marketplace of ideas works.

DONALD N. McCLOSKEY is professor of economics and history at the University of Iowa.

Environmental Secrets

Medea brings intelligence in from the cold

The end of the cold war may not have produced a peace dividend, but it could still produce a treasure trove of data. A high-level committee of scientists is pioneering an effort to extract vital environmental measurements from classified information currently being gathered by spy satellites and other sensors. The potential utility of this information far exceeds that of the spy satellite pictures from the 1960s that President Bill Clinton ordered declassified this past February. Such access could permit precise assessments of deforestation and of possible indicators of global warming.

The committee studying the secret data is called Medea, after the sorceress of Colchis in Greek mythology. Medea helped Jason of the Argonauts steal the Golden Fleece and became his wife. Jason is, in turn, the name taken by another group of scientists that has for many years provided secret advice to the government on national security issues. (Medea and Jason are united in the person of a shared representative from the Central Intelligence Agency, Linda Zall.)

Medea, established in 1993, is the descendant of an environmental task force set up by the CIA in 1992. The initiative came about in response to a request from then Senator Al Gore of Tennessee that the agency assess what data it could make available to researchers without undermining secrecy. The task force played a key role in persuading the CIA and other agencies to declassify the 800,000 photographs taken by reconnaissance satellites between 1960 and 1972. But although the former Soviet Union was well covered, many areas of scientific interest were not photographed at high resolution.

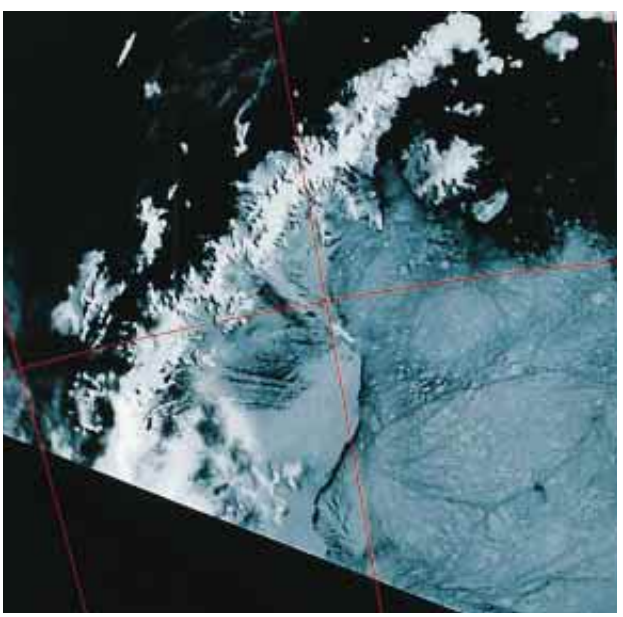
The best images from these early sets have a resolution of about two meters, better than the 15-meter resolution of *Landsat*. The present generation of spy satellites, however, is widely believed to resolve objects less than 15 centimeters across. Medea was founded when it became clear to the task force that environmental science and intelligence gathering could each gain from the other's expertise in the design of sensors and the interpretation of data.

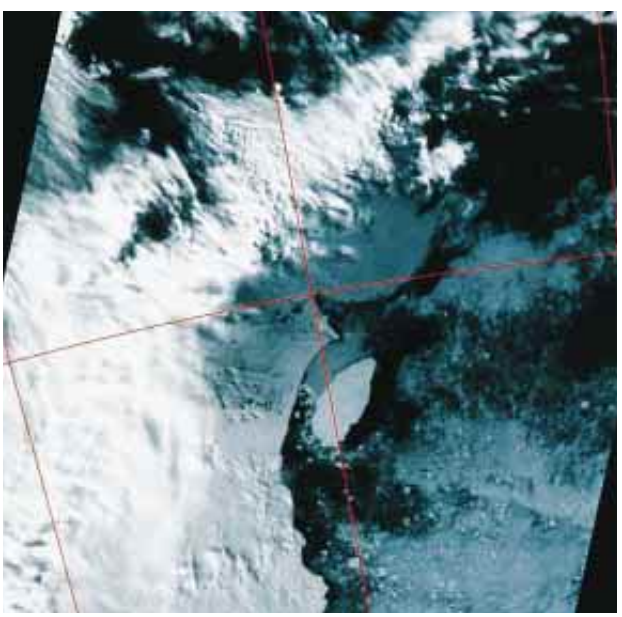
Medea is now wrestling with how to share with scientists measurements extracted from contemporary as well as archived intelligence. The main sticking point is the sensitivity of information about when and where images were obtained, says Jeffrey Dozier of the University of California at Santa Barbara. Such knowledge might allow an adversary to calculate the orbits of satellites, which would then make it possible to hide sensitive equipment by conceal-

It's Melting, It's Melting

Antarctica is heating up, and the evidence is in the ice—or at least in its melt. One satellite image from this past January (*left*) shows the spidery-looking James Ross Island surrounded by water (*top right*): ever since the first maps were made 100 years ago, it has been connected to the Antarctic peninsula by an ice shelf. The image also shows the peninsula, composed of a chain of mountains (*lower left to upper right*), surrounded by dark patches of sea; the gargantuan Larsen ice shelf appears at the lower left. A satellite image taken shortly after, in February (*right*), documented further changes. The ice shelf has retreated; a 50-mile-long iceberg has calved; and the northernmost part of the shelf, just above the center of the picture, has disappeared, creating a plume of ice rubble.

Other Antarctic ice shelves are also retreating, and "they are all ones we said would be sensitive to climatic change," notes David G. Vaughan of the British Antarctic Survey. Vaughan says the west side of Antarctica has warmed 2.5 degrees Celsius over the past 50 years. But any link with global warming is unproved, he cautions. —*Tim Beardsley*





BRITISH ANTARCTIC SURVEY

ing it while a sensor passed overhead.

The committee's main effort is devoted to trials of procedures for creating "derivative products"—that is, to determining how intelligence material can be declassified in such a way that it is still scientifically meaningful. This filtered information has already been used to create some accurate topographic maps.

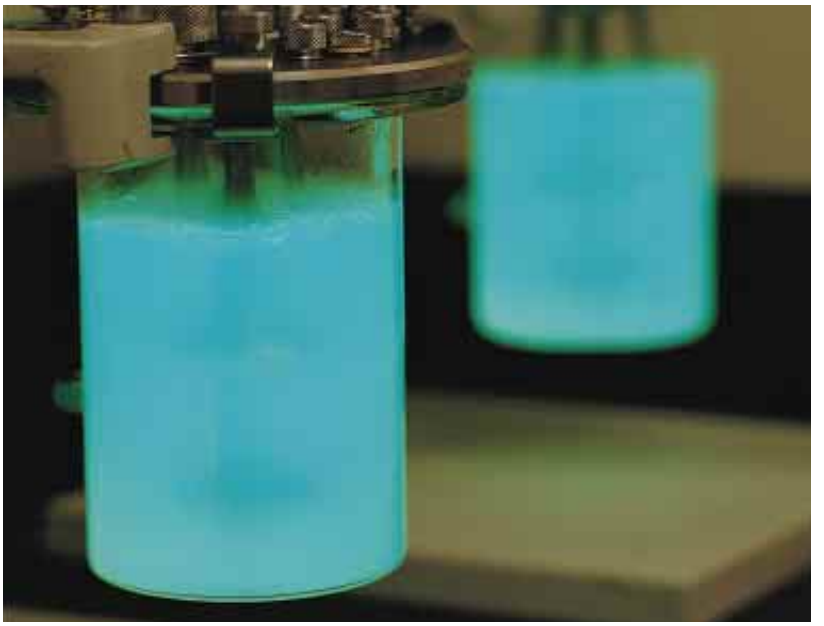
Dozier chairs a subcommittee of Medea that is establishing "global fiducials," reference sites that will be monitored by reconnaissance satellites for evidence of any long-term changes. Some places will be well-studied areas that evaluate the sensors' abilities. Others will be environmentally sensitive regions, such as desert margins.

Robert Smart of the National Oceanic and Atmospheric Administration, who uses satellite images to mark changes along shorelines, says many researchers have learned that with intelligence-grade material "you can learn a lot more" than with commercial images alone. (Commercial services may soon be offering additional satellite imagery with a resolution of about one meter. Lockheed Martin, for instance, recently obtained government approval to launch a satellite that would provide that level of detail.)

The U.S. Navy had previously released statistical data on submarine measurements of polar ice. Studies to determine how to obtain more detail are under way, as are similar efforts to increase the resolution of records from microphones lying on the ocean bottom that listen for submarines. Medea is also trying to declassify information about the earth's precise shape and gravitational field. These data are sensitive because they could be used to target long-range missiles. The committee has already brought into the public domain aircraft photography stretching back to the 1930s. "Most of the people associated with this effort have been very pleased," says Gordon J. MacDonald of the University of California at San Diego, one of Medea's co-chairs.

Medea has to contend with legal issues as well as with security concerns, MacDonald notes. Intelligence agencies are prohibited from gathering data inside the U.S. without special authorization, although there are exceptions for certain emergencies, such as forest fires. That restriction could impede the use of intelligence assets for monitoring the U.S. environment. But could Russia help? MacDonald says preliminary discussions with officials there have just begun. Former adversaries are finding that by cooperating they have a world to gain. *—Tim Beardsley*

Food Indigo



PATRICK MURPHY-RACEY *SABA*

Peering apprehensively at the green image in their night-vision goggles, Secret Service agents watched as then President George Bush fed the bacteria. Soon the genetically engineered specimens emitted a faint blue glow in the darkened room at the University of Tennessee, signifying their satisfaction with a light lunch of the hydrocarbon naphthalene.

Five and a half years later *Pseudomonas fluorescens* is finally going to be freed from the laboratory so it can feast on pollutants in Oak Ridge National Laboratory soil. The event, to take place this fall, will be the first release of organisms genetically engineered to consume toxic chemicals—including naphthalene, anthracene and phenanthrene. The strain was created by Gary S. Sayler, who fused genes for bioluminescence from a marine bacterium to those in *P. fluorescens* responsible for the degradation of naphthalene. The resulting creature glows when breaking down the hydrocarbon, giving cleanup workers visual confirmation that the chemical is present and that it is being degraded. Those living near potential sites need not invest in darker sunglasses; this photograph, showing the bacteriological equivalent of a feeding frenzy, required an exposure of half an hour. *—Glenn Zorpette*

When Smog Gets in Your Eyes

Cooking, not cars, may explain much of Mexico City's pollution

For about 80 hours every month, the yellow, eye-smoldering smog of Mexico City reaches dangerous levels. At these times, the government restricts driving and orders industries to reduce their activity. But new findings suggest these solutions may fail to tackle one of the biggest sources of the city's smog: unburned liquefied petroleum gas, or LPG, that is somehow leaking into the air.

The composition of LPG—used for cooking and heating in most homes in the area—can vary greatly, and the Mexico City version is ideal for creating air pollution. Mexican LPG is about half propane, with the other half a mixture of butane and butenes. Butane and butenes are highly efficient at forming ozone, the main component of smog. As Donald R. Blake of the University of California at Irvine explains, butenes make up only 5 to 9 percent of Mexican LPG, but that fraction "forms about as much ozone as the remaining components" of the fuel. (In contrast, the type of LPG used in Los Angeles consists of 95 percent propane, very little butane and no butenes and is therefore less effective at forming smog.)

Furthermore, according to Blake and F. Sherwood Rowland, also at Irvine, Mexico City's problem is exacerbated by the fact that LPG seems to be leaking at a surprising rate. Indeed, Blake and Rowland estimate that as much as

KEITH DANNEMILLER *SABA*

***AIR POLLUTION** in Mexico City is notorious. A substantial part of the problem may be caused by leaks of liquefied petroleum gas used in homes.*

one third of the smog could result from this source. Nearly 200 air samples taken over the past several years showed elevated levels of propane, butane and butenes that could only have come from seeping LPG. Residents of Mexico City take the fuel from individual tanks, rather than drawing it from a citywide distribution system; Blake estimates that more than one million homes use LPG. Consequently, finding the source of leaks, as well as fixing them, could be extremely difficult.

Blake and Rowland believe that changing the composition of Mexican LPG—in order to eliminate the butane and butenes—would reduce total ozone pollution by 10 to 20 percent. The researchers have not yet approached Petróleos Mexicanos, the company that distributes LPG in Mexico City, but they say they plan to do so soon. It remains uncertain how much such a reformulation would cost.

Other cities might want to consider these findings. Studies of smog in several cities in eastern Europe have revealed high levels of propane, butane and butenes in the air—an LPG fingerprint, according to Blake. The Irvine group also intends to investigate 20 U.S. locations with some type of air pollution problem. Although many developed countries do not have high levels of butane or butenes in their LPG, which alleviates some of the ozone worry, substantial leaks could happen anywhere.

The fossil fuels used in vehicles and industry, of course, are still a major source of smog around the world. Changing levels of butane and butenes in LPG may not be a "cure-all," Blake says, "but it could improve the problem significantly." —*Sasha Nemecek*

A Prime Patent

Legal rights to a number upset programmers and lawyers

Roger Schlafly has just succeeded in doing something no other mathematician has ever done: he has patented a number. The seemingly bizarre event is the latest twist in the saga of assigning software patents that has vexed the U.S. Patent and Trademark Office for more than 20 years. "I'm sure if you just went to someone and said, 'Can you patent a prime number?' they would say to you, 'No, that's ridiculous,' " says Schlafly, a computer consultant who lives near Santa Cruz, Calif.

Schlafly, of course, hasn't patented just any number. His figure—which is nearly 150 digits long—has a property that makes it possible to take a certain shortcut when performing modular division. A little improvement in division is big news for people using the Diffie-Hellman public-key cryptography system, which uses repeated modular divisions as a tool for encrypting and decrypting secret codes. Cryptographic keys are typically numbers hundreds of digits long, so a small improvement can mean a big savings in time.

But even as this patent is helping speed up a few mathematical calculations, patents in general are slowing down the progress of developing software. Such patents are on the rise: 4,500 were granted in 1994, and nearly 5,400 are projected to be granted in 1995, says Gregory Aharonian, who publishes the Internet Patent News Service. "It is hard to believe that all these 9,000 patents reflect novel and unobvious ideas," Aharonian notes.

In 1972 the U.S. Supreme Court ruled that computer algorithms could not be patented. But in 1978 that decision was reinterpreted by a lower court, which concluded that the higher court really meant only to prohibit patenting mathematical algorithms. Unfortunately, the ruling never defined what a mathematical algorithm actually was. Ever since, the number of software patents issued has been steadily rising—as have the number of lawsuits.

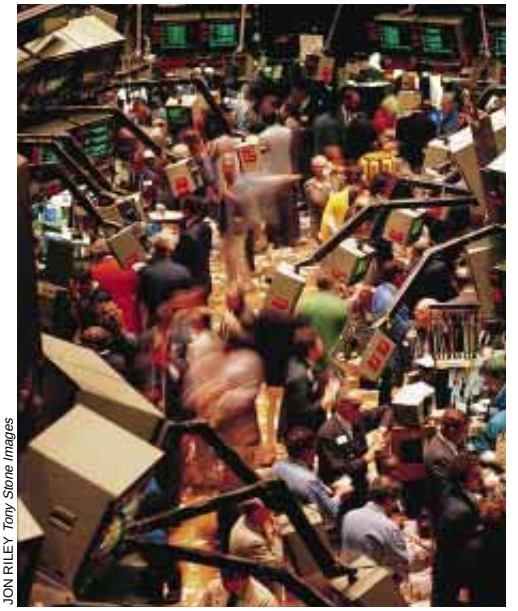
Indeed, Schlafly's patent seems to fit right in with current Patent Office policy. The patent, entitled "Partial Modular Reduction Method," describes an algorithm for finding prime numbers that have this particular property. Most patent applications would stop there. But Schlafly's goes further, claiming prime numbers that have the property. The first and most famous is roughly 150 digits long; a second is about 320. Nevertheless, the figures satisfy the primary requirements of patentability. They are novel, because there is no record they have been used before, and they are useful, in this case for cryptography.

"I was kind of interested in pushing the system to see how far you could go with allowable claims," explains Schlafly, a member of the League for Programming Freedom, an organization that opposes software patents. Although Schlafly can now sue anybody for using his numbers, he is not worried about people infringing on his rights. "When you get to numbers that are so big that nobody has used them before, well, there are lots of them up there," he says.

The same cannot be said of cryptography algorithms themselves. Schlafly is at present embroiled in a lawsuit with Public Key Partners (PKP), a California partnership that maintains the rights to the most important patents in the domain of public-key cryptography. The group claims that one of its patents covers the entire field. A second PKP patent, meanwhile, is at the heart of a program that Schlafly wrote, called Secret Agent, which is used to encrypt electronic mail. —*Simson Garfinkel*

Follow the Money

A new stock market arises on the Internet



JON RILEY *Tony Stone Images*

STOCKBROKERS and analysts could become dinosaurs in pinstripes.

Cyberspace, pointed out cyberpundit John Perry Barlow, is where money goes when it is not in somebody's pocket. Financiers are following that money. Entrepreneurs in Cambridge, England, are setting up the Internet's first stock market. The progress of their venture, called Electronic Share Information Ltd. (ESI), illustrates the problems and opportunities of a novel breed of market—and its impact on the broader economy.

In a now classic prediction Tom Malone of the Massachusetts Institute of Technology argued that information technology would help break apart big companies, shifting work out of the corporate hierarchy and into electronic markets. By making it cheaper to gather information, Malone argued, computers would make it easier to shop around for the best and least expensive supplier. More shopping around, in turn, would mean less work for outlying divisions of sprawling corporations and a fundamental shift toward small firms.

So far a fair amount of evidence supports Malone's theory. In the mid-1970s, after centuries in which firms grew larger, the size of companies in industrial nations began to shrink. And Malone's student Erik Brynjolfsson found a correlation between investment in information technology and decline in firm size. Succeed or fail, ESI's bold venture to create stock markets in sectors of the economy where none have traded before will provide an intriguing example of the principles underlying the trend.

At the heart of ESI's opportunity is the simple observation that stockbrokers are a very expensive form of computer terminal. Many things brokers commonly do—placing orders and sending out financial information—require them merely to type into their computer instructions given them by a customer. As networks become more ubiquitous, more customers will want to execute those commands directly.

ESI's first step was simply to substitute computers for brokers. It serves up financial analysis and allows clients to buy and sell shares electronically, on existing markets. So far, so mundane. What makes ESI interesting, however, is its realization that such technology not

only could trade existing shares for less but also might create an unique form of stock market, one that would sell shares of companies that could not otherwise afford a stock-market listing.

To hear Jack Lang, technical director of ESI, tell the tale, the idea to set up an entirely new stock exchange came about almost by accident. With about 1,000 small high-tech firms, Cambridge is the closest thing Britain has to Silicon Valley; local entrepreneurs say there would be more start-ups were there more venture capital. So when ESI began plotting its course, someone suggested it act as a kind of marriage bureau, providing financial information about small firms seeking investment. Someone else pointed out that marrying investors with companies is precisely what a stock exchange does. Lightbulbs clicked on over heads.

Assume, as does Lang, that ESI can operate at a tenth of the cost of the London Stock Exchange. ESI could then compete with the banks and venture capitalists financing small firms. The minimum a company could raise on the market, taking into account the costs of offering stock, falls from about £10 million to £1 million. Given trading costs of only a few pounds, Lang posits that investors will want to trade hundreds of pounds' worth of shares, rather than thousands. And the same technology that relays buy and sell orders from investors can be used to provide them with information about companies.

Regulation poses somewhat more daunting problems for ESI. The fledgling exchange will have to reassure Britain's Securities and Investments Board—the same body that regulates the London Exchange—that ESI is honest and properly equipped. Because the exchange will be on the Internet, and accessible from outside Britain, it will also have to convince foreign regulators, notably the U.S. Securities and Exchange Commission, that it is doing no more than a British stockbroker would do in picking up a telephone call from a U.S. client.

The biggest trick lies in enticing would-be investors. To understand that challenge—and the potential repercussions if ESI and its ilk succeed—pause for a moment to consider the economic theory underlying Malone's predictions.

Following in the footsteps of Nobel laureate Ronald H. Coase, most economists reckon that the size of a firm is determined by the equilibrium point between the costs of gathering resources—money, equipment, raw materials—from outside markets and the overhead of creating them in-house. The more expensive transactions are, the more resources firms will find it worthwhile to provide for themselves and thus the larger they will be.

Information technology makes it easier to get the data necessary to compare products. What it often fails to do, however, is to translate data-on-a-screen into the understanding-in-a-head needed to make a decision. Ultimately the economics of understanding will shape firms, and that is turning out to be different from the economics of information in ways that are subtle but also profound.

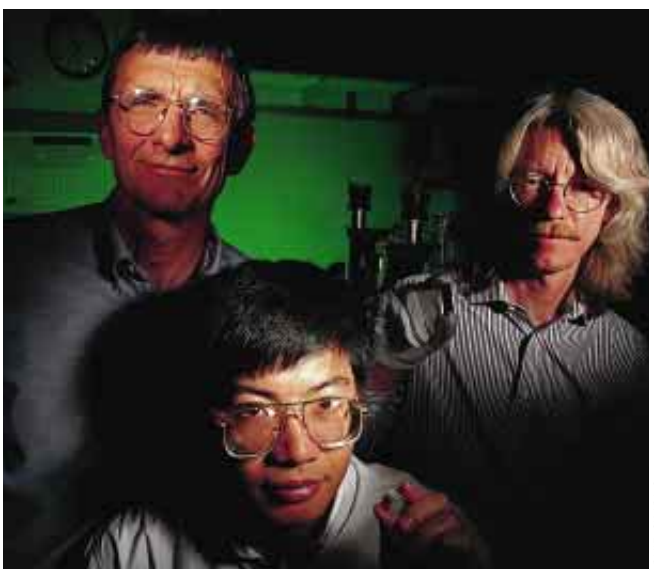
ESI will thus provide an intriguing experiment. Its technology can certainly move information at a fraction of the cost of today's investment markets. But that attribute does not mean investors can achieve the understanding needed to balance risk and reward at a fraction of the cost. If they can, then many financial intermediaries are simply dinosaurs in pinstripes. If the costs of understanding do not track those of information, however, bankers and venture capitalists do indeed have a valuable role to play. For those who want to put money on the answer to that question, ESI says it hopes to open its new market for trading in the autumn of 1995. —*John Browning*

Ceramic Superwire

A superconductor moves nearer the real world

The high-temperature superconducting ceramics that amazed physicists when they were discovered in 1986 have been amazing materials scientists ever since—with how difficult they are to make into anything useful. But researchers at Los Alamos National Laboratory appear to have overcome a major problem besetting one of the most promising of the new materials.

Using a technique called ion-beam assisted deposition—first developed by workers at Fujikura, a high-tech conglomerate in Japan—scientists have produced a superconducting tape that operates at high temperatures and in powerful magnetic fields. If it can be made cheaply enough, the tape could be used in wires that might actually deliver the practical applications everyone has been hoping for: small, powerful motors and generators, more efficient electrical controllers and circuit limiters, and magnetic resonance imaging machines with higher resolution. "It's a very important step forward in commercial development," observes Paul C. W. Chu of the University of Houston, "but there is still a lot to do."



CHIP SIMONS

SUPER TAPE is held by Los Alamos researchers Paul Arendt, Xindi Wu and Steven R. Foltyn. The tiny sample may mark a breakthrough, bringing superconductors closer to market.

Superconducting ceramics initially generated wild excitement because they could offer resistanceless flow at far higher temperatures than could existing superconductors. Such temperatures—up to about 90 kelvins—are warmer than liquid nitrogen and are, consequently, cheaper to attain. Previous superconductors had to be cooled to within a few degrees of absolute zero—quite an expensive proposition.

Unfortunately, one of the most promising of the high-temperature superconductors, yttrium barium copper oxide, has a serious drawback. It cannot be easily worked into wires, because its crystal grains do not readily connect to one another; the resulting bad connections disrupt current flow. Several years ago Yasuhiro Iijima of Fujikura hit on the idea of laying down a layer of superconductor on top of

an oriented crystalline layer of inert material that would align the superconductor grains, thereby allowing them to connect more efficiently. The challenge is producing the oriented crystal layer. It can be done by "sputtering" stabilized zirconia onto a nickel substrate using two beams consisting of ions of argon. The first beam blasts zirconium oxide off a target so that it settles onto the nickel. The second beam is aimed at the nickel at a precise angle, which allows zirconia crystals to accrete in only one orientation. Atoms that sit in the wrong place are blown away by the argon ions.

The Los Alamos group has been working on such ion-beam assisted deposition for two years, gradually increasing performance. This past April, Steven R. Foltyn told members of the Materials Research Society that the team had produced samples of yttrium barium copper oxide on stabilized zirconia that conduct more than a million amperes per square centimeter. That performance is 100 times higher than that of other flexible superconductors and 50 percent above the figure that Japanese researchers have reported for the technique. The samples take the form of a flexible tape that could be wound into cables. Because yttrium barium copper oxide is tolerant of strong magnetic fields, there seem to be no purely physical obstacles to the long-predicted high-power applications.

There remain formidable economic obstacles, however. The samples are small—five centimeters by one centimeter—and take two hours to make. The technique "has a long way to go" before it could be cost-effective for large-scale production, comments John Vander Sande, a researcher at the Massachusetts Institute of Technology and co-founder of American Superconductor. That company makes its superconducting wires from a different ceramic, bismuth strontium calcium copper oxide, using a different technique.

The bismuth compound is easier to work with than the yttrium-based material, but its shortcoming is that it fails to superconduct in strong magnetic fields at liquid-nitrogen temperatures. Gregory J. Yurek, president of American Superconductor, points out that if the thickness of the substrate and the zirconia is taken into account, the current density in the Los Alamos samples is no greater than his company can achieve now in kilometer-long superconducting wires. (Nevertheless, American Superconductor's stock fell by 10 percent when the Los Alamos group made its announcement.)

Foltyn is hopeful that ion-beam assisted deposition can be made more efficient. He suggests that using gases other than argon might be one way to speed the process. Employing a thinner zirconia layer would be another way: the Los Alamos group currently uses a layer 0.5 micron thick. Fujikura workers have published results with a layer as thin as 0.1 micron, notes David C. Larbalestier of the University of Wisconsin. Paul M. Grant of the Electric Power Research Institute, which has in part funded the Los Alamos work, says the Japanese group "has been working very hard and has not been reporting what are probably some very good results." The Japanese may also have already applied for key patents.

Grant's institute has conducted a careful analysis of how ion-beam assisted deposition might be scaled up to become an industrial process. The study found no technical snags, he maintains, and therefore "it is easy to imagine" employing ion-beam assisted deposition to make commercially viable quantities of wire. But there are many miles of wire still to go. *—Tim Beardsley*

A Skeptically Inquiring Mind

You communist pervert creep. Breakfast at the San Jose Holiday Inn restaurant has continued for more than three hours now, and it becomes clear why such letter salutations are common for James "The Amazing" Randi. Despite a kindly appearance—he resembles a trimmer and shorter Santa Claus—sacks full of hate mail arrive at his door routinely. "Really vitriolic stuff," he comments, "and then they're signed, 'Yours in Christ.' "

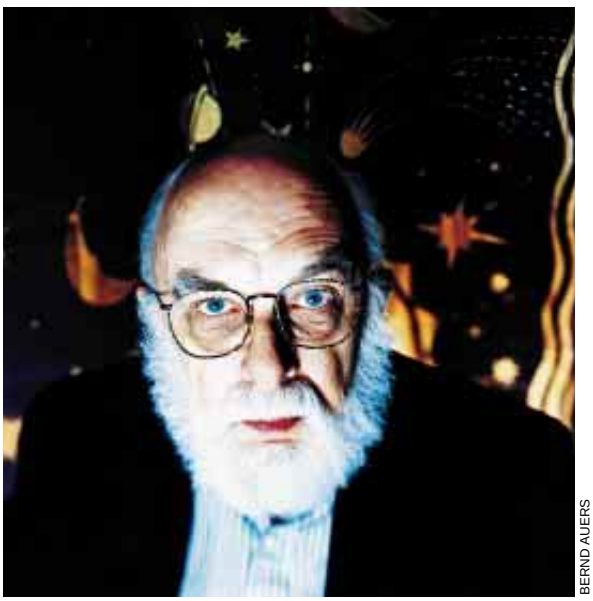
Threats of death only make him testy, though. He invited one such letter writer to a lecture and punched him in the mouth. "I don't take crap from people. I did for a long time in my life. I'm not the nice little boy anymore."

The 66-year-old Randi is an expert on crap. "I lecture on bullshit," he explains by way of indicating his main source of income. The former professional magician has become perhaps the world's leading investigator of pseudoscientific and paranormal claims. His targets have included faith healers, psychics, dowsers and other charlatans. He has been drafted to explore homeopathic results and perpetual motion machines. Along the way he helped to found the Committee for the Scientific Investigation of Claims of the Paranormal (CSICOP), a skeptics organization based in Amherst, N.Y., which publishes the bimonthly *Skeptical Inquirer.*

Years of performing magic—he has accumulated innumerable television appearances, including more than 30 on the *Tonight Show*—have equipped Randi with a useful skill: "I have a peculiar expertise that enables me to do two things very well. I know how people are deceived, and I know how people deceive themselves." Unlike scientists, Randi points out, magicians are taught methods of trickery. Scientists think logically, but the swindler does not, and like a magician, "he gives you lots of very good evidence that's false. A magician doesn't say, 'This is an empty box.' He drops the box on the stage, and it sounds like an empty box."

Because Randi understands such misdirection, he can devise countermeasures. To expose a fellow who claimed to turn the pages of a telephone book by mind alone, Randi sprinkled bits of Styrofoam around the book, figuring that the trickster was actually flipping the pages by exhaling discreetly. A breath would disturb the Styrofoam. Sure enough, the man balked. "You can't slip a trick by Randi," observes Barry Karr, the executive director of CSICOP.

Despite exposing charlatans, Randi does not hesitate to practice some flummery. In explaining the art of deception, he is all too ready to bend a couple of spoons and to make sugar packets and crumpled paper napkins disappear.



BERND AUERS

THE AMAZING RANDI exposes all manner of pseudoscience and the paranormal.

"I'd take that as proof of divinity myself," he deadpans and suggests I pocket the damaged utensils, in case the dutiful waiter who keeps hovering about notices.

Not that scientists should be taught magic tricks. "But what they should know," Randi insists, "is that there are things beyond their expertise." Too many academics think they are too smart to be fooled. "Physicists are most easily deceived, because they deal in a real world of objects," Randi says, noting that their natural inclination is to take anomalies as discoveries rather than as hoaxes.

Of course, scientists fall prey to self-delusion as readily as anyone else. Jacques Benveniste of the University of Paris-South claimed that water could "remember" the molecular structure of antibodies. Then there are Stanley Pons and Martin Fleischmann's pronouncements about cold fusion and John E. Mack of Harvard University, who concludes that some adolescents really were abducted by UFOs.

Some suspicious assertions, though, cannot be debunked easily. Physicist Robert Jahn of Princeton University has found that people seem to be able to influence the outcomes of a random-number generator by mere thought. Randi suggests that the key to this telekinetic claim may lie with Brenda Dunne, Jahn's chief investigator, who is well known in the parapsychology field. "She's not very cooperative. She won't let people see the program or allow them to interfere with the protocol. I think it raises certain doubts whether these experiments will ever be replicated," Randi opines. "It is such a big experiment. Nobody in the skeptics field can afford to do it."

Such practical limits might only exacerbate the current resurgence of belief in the paranormal. "The communications media have made it available to everyone," Randi observes. He cites a self-proclaimed psychic who calls himself "The Great Samaritan." Advertising on Spanish-language television, he asks viewers to dial a 900 number for psychic advice. With caller-identification technology and banks of networked computers at their disposal, operators can obtain financial and health records, convincing their unsuspecting callers of their astrological prowess.

The economic cost of such exploitation is difficult to ascertain, but Randi believes it amounts to hundreds of millions of dollars in faith healing alone. In rooting through nearby dumpsters after one such show, he found many $5 checks—apparently too small a sum to bother depositing, given the suitcases full of cash that had just been loaded into the limousine.

So profitable is the field and so powerful is the allure of the paranormal that exposed psychics can easily set up shop again. A case in point is the faith healer Reverend Peter Popoff, whom Randi defrocked in 1986. Randi intercepted and taped radio transmissions from Popoff's wife to her husband as he worked the audience and "read" their minds. His wife had previously interviewed these people and was directing her husband, who wore a concealed earphone. Obscenities, insults and jokes fill the tape. "A guy showed up with tes-

ticular cancer, and he's there dying, and they're laughing at him," Randi exclaims. After the California Attorney General's Office declined to shut down the ministry (citing the separation of church and state), Randi appealed to a higher authority: Johnny Carson. Public exposure of the tape eventually forced Popoff into bankruptcy.

"But now Popoff is back in business," Randi laments. "There's no continuing agency or law that will stop him from doing the same thing all over again." A change in the name of the ministry and a new location are all that is needed.

Many people reject scientific thinking because science deals with probabilities, not black-and-white answers. Randi finds that devotees of faith healers mostly watch soap operas and professional "wrestling" because those programs provide definitive outcomes. "You will be amused at your own expense if in the long run you don't take them seriously," he warns. "These are facts of life for very many people." A case in point is his own brother. "He believes in cuckoo stuff," Randi remarks of the sibling with whom he has largely lost touch.

Randi developed his skepticism early in life. A child prodigy, Randall James Hamilton Zwinge was given permission at age 12 to study independently out of the classroom. He used the opportunity to his advantage, wandering the streets of his native Toronto and venturing into a theater where he witnessed magician Harry Blackstone, Sr., levitating a woman. "I remember categorizing it," Randi states. "Either it was some sort of misperception, or some sort of mechanical or physical trick." Trips to the library and mentoring by Blackstone enabled Randi to develop his own conjuring abilities.

Those skills served him well. "I didn't find much point in graduating, because I had met several people ahead of me at the University of Toronto, and they didn't seem to know how to think, how to originate material," Randi explains. "That was not my idea of an education." Instead a 17-year-old Randi joined a traveling carnival, in part to overcome his acute shyness: "The most difficult thing to do," he reasoned, "would be to face an audience."

He became known as Prince Ibis, a mentalist who wore "a funny black turban," Randi recalls. "I just about died. It was a terrible experience, having to walk out in front of a really savage crowd." Nevertheless, he stuck with it and soon graduated to the nightclub circuit, eventually adopting his stage name and legally becoming James Randi.

Moving from magic to debunking was a small step. "They're both part of the same thing," Randi says. Even so, his first investigation, at age 15, got mixed results. An evangelist at a local church was apparently answering sealed requests from his congregation by mentally reading the contents. "He was doing the one-ahead method," deduced Randi, who stormed to the pulpit and fished out the last opened envelope to show that the preacher was answering the previous question, not the one in the sealed envelope. For his troubles, he was roundly booed and escorted to the police station. "At that moment, I became determined that I was going to spend some time doing this. One of these days, they will listen," Randi vowed. "And by golly, they are listening."

BERND AUERS

***MAGIC AND DEBUNKING** are essentially the same thing, notes Randi as he levitates some dice—at least momentarily.*

Debunking occupies most of Randi's time. "Nature abhors a vacuum; Randi abhors free time," he sums up. "I've got a busy life ahead and so many projects under way. The minute before I die, I want to be exceedingly annoyed over the fact that I've got a lot of unfinished projects. That's going to be a happy time for me."

For Randi, the rewards for a hectic schedule come in the appreciation he feels from young people, many of whom beat a path to his Florida home in the hopes of following in his footsteps. But the skeptic has not found any suitable protégés. "You have to be a little nuts to fly in the face of what is popularly accepted," he concludes. "You have to be totally dedicated and be a little obsessed."

And being such an outspoken critic does have its drawbacks. He has been sued several times for allegedly defamatory comments, the most notorious about spoon-bender Uri Geller. In an newspaper interview, Randi claimed that Geller's abilities derived from the kinds of tricks printed on cereal boxes. Geller sued both Randi and CSICOP. "In my opinion, he was getting desperate for funds," Randi remarks. "He thought he would always be able to make a living by bending spoons. A dumb profession if I ever heard of it." The courts ruled in favor of the skeptics and ordered Geller to pay $150,000 in sanctions. This past March, CSICOP announced that it had settled with Geller for somewhat less than that amount.

The legal action, however, has had some negative impact. "These lawsuits from psychics have wiped me out financially," Randi complains. That includes the $272,000 MacArthur fellowship he received in 1986. The lawsuits have also made Randi more circumspect in his declarations. "I am being more careful about what I say," he concedes. "I have a right to an opinion—it just depends on how it's phrased." Others seem equally cautious: CSICOP relies on prepared statements rather than any verbal comment.

Perhaps more disconcerting for Randi are his sour feelings for CSICOP. "They got wimpy on me," Randi groans. "They essentially forced me to resign. They were afraid of my continuing to make statements about Geller." The official policy of the organization is that individual members do not speak for the group. As a result, CSICOP's insurance company has been balking at recouping Randi's losses, although he is currently trying to recover some cash.

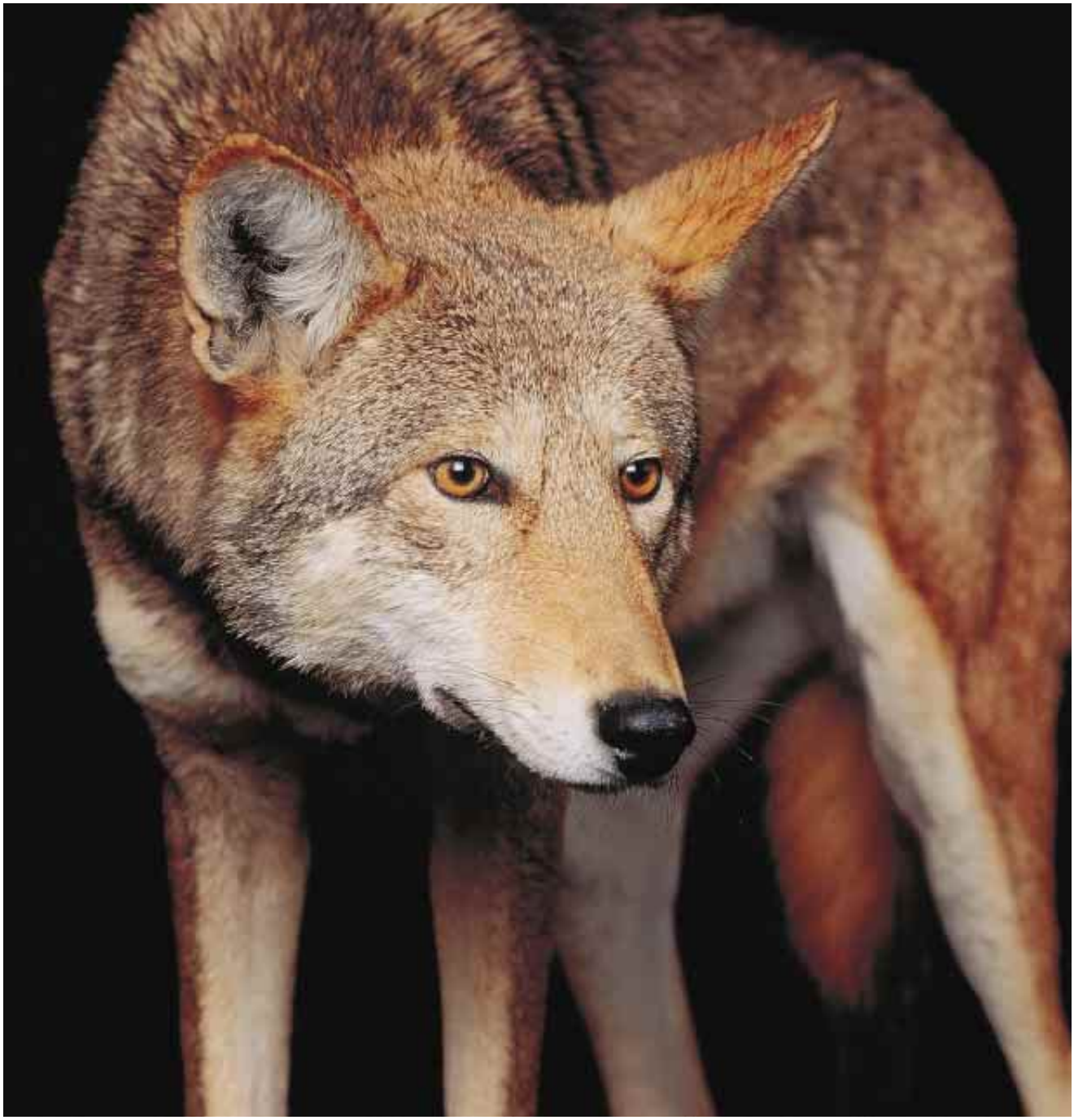
Randi is unsure if he wants to rejoin CSICOP. "I never heard any kind of admission that they had cut me adrift, deserted me when I needed them." Randi becomes somewhat philosophical. "Hey, I'm not complaining, believe me," he says. "I consider CSICOP my baby. I'm happy it's in good hands, and I'll always do anything for the committee to promote it."

It is almost noon. Feeling a bit guilty about the damaged flatware, I leave a larger than usual tip. I wonder what to say to airport security if the bent spoons set off the metal detector. "Do what I do," Randi advises. "Tell them it's a hobby." —*Philip Yam*

The Problematic Red Wolf

Is the red wolf a species or a long-established hybrid of the gray wolf and the coyote? Such distinctions may affect ongoing efforts to save a variety of endangered species

by Robert K. Wayne and John L. Gittleman



In the 18th and 19th centuries, residents of the American Southeast often described encounters with creatures they called red wolves: long-legged, cinnamon-colored animals that came to be named *Canis rufus.* By the early 1970s, however, hunting of animals that preyed on livestock and the conversion of woodlands to crop fields had caused the once widespread red wolf population to shrink to a single group in eastern Texas and southwestern Louisiana. By the late 1970s even that cluster had disappeared.

Fortunately, quick action by the U.S. Fish and Wildlife Service—proceeding under the authority of the Endangered Species Act—established a captive population before the wolves vanished entirely. The task was not easy: many of the remaining animals had mated with an abundant close relative, the coyote (*C. latrans*), producing hybrid offspring. But scientists were able to find 14 red wolves apparently having no trace of coyote ancestry, and they succeeded in establishing a breeding program with those animals. As a result, several hundred red wolves live in captivity today, providing a source for ongoing reintroduction of wolves into such places as the Great Smoky Mountains National Park in Tennessee. The preservation effort has been successful beyond expectation and serves as a model for how to rescue an endangered species from the brink of extinction.

Nevertheless, saving a species through captive breeding and reintroduction is expensive. The projected budget of the Fish and Wildlife Service for field study and maintaining captive breeding facilities for red wolves over the next five years is about $4.5 million. The cost of preserving the red wolf and other endangered species has recently focused new interest on the criteria biologists should use to decide which animals should receive the greatest attention.

The issue remains open because the Endangered Species Act extends to all manner of endangered groups equally, regardless of whether they are species, subspecies (populations displaying minor differences from one another) or, under certain circumstances, hybrids, which result from the cross of two species. Yet in the face of growing numbers of threatened populations and declining resources, conservation biologists are forced to practice a form of triage: they must determine which groups among the many endangered ones should be saved and how much effort to devote to each organism.

Some decisions are straightforward. The giant panda, a symbol of the conservation movement, is nearly extinct and is the only living representative of an entire subfamily of bears. Few would doubt that it is more deserving of preservation than a minor subspecies of an otherwise well-populated species. But many cases are less clear-cut. In those instances, biologists generally concentrate more on the last representatives of a species than on a dwindling subspecies or ephemeral hybrid population. Yet, as our research into the proper taxonomic classification of the red wolf demonstrates, determining whether a population constitutes a separate species can often be problematic.

RED WOLF, protected by the Endangered Species Act, may not be a distinct species after all. New genetic evidence indicates the red wolf could be a hybrid of the coyote and the gray wolf.

What Is a Species?

Deciding whether a given population constitutes a species can be difficult in part because there is no single accepted definition of the term. Years ago evolutionary biologist Ernst W. Mayr, propounding what is called the biological species concept, proposed that the definition be based on reproductive compatibility. Specifically, he considered a species to be a group of animals that can mate with one another to produce fertile offspring but cannot mate successfully with members of a different group.

Yet this idea can be too restrictive. First, mating between species (hybridization), as often occurs in the canine family, is quite common in nature. Second, in some instances, the differences between two populations might not prevent them from interbreeding, even though they are rather dissimilar in traits unrelated to reproduction; one might question whether such disparate groups should be considered a single species. A third problem with the biological species concept is that investigators cannot always determine whether two groups that live in different places are capable of interbreeding.

When the biological species concept is difficult to apply, some investigators use phenotype, an organism's observable characteristics, as a surrogate. Two groups that have evolved separately are likely to display measurable differences in many of their traits, such as the size of the skull or the width of the teeth. If the distribution of measurements from one group does not overlap those of the other group, the two groups might be considered distinct species. Another widely discussed idea designates a species based on the presence of some unique characteristic not found in any other closely related organism—for example, the upright posture of humans—or a distinguishing sequence of nucleotides (DNA building blocks) in a gene.

Proving that the red wolf fits any of these descriptions has been extremely challenging. For instance, the red wolf is not a species by Mayr's definition, because it can breed extensively with the coyote and the gray wolf (*C. lupus*). And efforts to classify the red wolf based on its phenotypic traits have yielded ambiguous results. John James Audubon and John Bachman, who described the red wolf in their classic 1851 book, *Viviparous Quadrupeds of North America,* had difficulty distinguishing the red wolf from the physically similar coyote and gray wolf. Modern researchers looking at phenotypic traits have variously concluded that the red wolf is a subspecies of the gray wolf, a hybrid of the coyote and the gray wolf, and a full-fledged species.

The strongest evidence that red wolves constitute a separate species comes from Ronald M. Nowak of the Fish and Wildlife Service. In 1979 he studied 15 cranial and dental characteristics of domestic dogs, red wolves, coyotes and gray wolves. He found that in size and structure, skulls of red wolves collected before 1930 fell roughly midway between those of the coyote and the gray wolf and could indeed be distinguished from skulls of those two species. Additional analysis of the fossil record in North America led him to conclude that the red wolf first appeared about one million years ago, early in the Pleistocene period and thus before the emergence of the modern coyote and the gray wolf. Because of the red wolf's apparent ancient origin, he surmised it was the ancestor of the other two species and had a long and distinct evolutionary history.

Nowak also determined that red wolf skulls collected after 1930 more closely resembled coyote skulls. He reasoned that beginning in the 1930s red wolves became rare as a consequence of human activities, including destruction of the animals' habitat and establishment of predator-control programs. The remaining red wolves then began to breed with coyotes, so that a red wolf–coyote hybrid population emerged.

Our study has led us to conclude, however, that measurements of skulls are of dubious help in determining the species status and evolutionary history of the red wolf. We now maintain that, in fact, Nowak's cranial data are consistent with the possibility that the red wolf is a hybrid of the gray wolf and the

coyote. If those two species crossbred, one would expect to find precisely the intermediate phenotype Nowak detected. Indeed, coyotes and gray wolves have been observed to mate in certain parts of Canada, and the resulting animals had skull dimensions resembling those Nowak found for the red wolf.

Diagnostic Genes

We came to our conclusion after performing extensive genetic analyses that we originally anticipated would prove red wolves constitute their own species. Dissatisfied with the ambiguity of the existing data, in 1989 we sought evidence that the third definition of species would apply: the red wolf would possess some unique trait—perhaps an unusual stretch of DNA—that marked it as an entity distinct from the coyote and the gray wolf. We therefore examined segments of DNA from both the nucleus and mitochondria of cells obtained from the three putative species.

Nuclear DNA differs from mitochondrial DNA in a few ways. Nuclear DNA contains the multitude of genes that give rise to the physical and behavioral traits of an organism; it is inherited from both parents, so that each individual receives one set of genes from the mother and a matching set from the father. Mitochondrial DNA, in contrast, includes relatively few genes, which primarily code for proteins the mitochondria need in order to produce energy for cells. Mitochondrial DNA is inherited only through the mother. Further, its nucleotide sequence changes, or evolves, faster than that in nuclear DNA—a property that is useful for tracing an organism's genetic history.

Certain species, particularly those that have appeared relatively recently on an evolutionary time scale, cannot easily be distinguished solely by differences in their nuclear DNA. But analyses of selected sections of mitochondrial DNA often reveal changes that can discriminate one species from another. For example, the sequences of nucleotides in the mitochondrial DNA of coyotes and gray wolves differ by about 4 percent, whereas the sequence of African black-backed jackals (*C. mesomelas*) differs from those two species by about 8 percent. This latter difference is comparable to that separating humans and apes, indicating that the jackals are distant cousins of the more closely related gray wolves and coyotes, but all three should be considered distinct species.

We began our genetic studies by comparing segments of mitochondrial DNA from red wolves currently in the breeding program with the corresponding segments in coyotes and gray wolves. We found nothing to distinguish the red wolf from the other two species. For example, one region of mitochondrial DNA from red wolves that we examined was virtually identical to the corresponding region from coyotes living in Louisiana. We subsequently examined mitochondrial samples saved from red wolves, coyotes and their hybrids captured in east Texas between 1974 and 1976, during the establishment of the captive breeding program. (Gray wolves had disappeared from Texas by then.) We found gene sequences characteristic of coyotes and gray wolves but no unique red wolf pattern.

The discovery of coyote and gray wolf sequences in DNA from red wolves was unexpected and is one of the findings that makes us suspect the red wolf is a hybrid. We had an idea of how to explain this odd result because we had previously encountered a similar phenomenon. When analyzing segments of mitochondrial DNA from gray wolves in Minnesota and eastern Canada, we noted that many of the gray wolves carried coyote mitochondrial DNA.

We speculated that this situation arose because coyotes had entered Minnesota and eastern Canada during the previous 90 years, expanding their range as the number of gray wolves declined in response to predator-control programs and altered habitats. The thinly dispersed gray wolves then mated with the numerous and widespread coyotes, producing hybrid offspring. When male gray wolves mated with female coyotes, their hybrid offspring inherited only coyote mitochondrial DNA, which, as noted, is transmitted solely along maternal lines. But these early hybrids inherited half of their nuclear DNA from their coyote mothers and half from their gray wolf fathers. In consequence, they looked like an intermediate between a coyote and a gray wolf.

When these hybrids mated with pure gray wolves, in a phenomenon called backcrossing, the resulting offspring appeared slightly more wolflike than their parents. As subsequent generations of hybrids continued to mate with gray wolves, traces of the original coyote nuclear DNA disappeared, and the progeny increasingly came to resemble gray wolves. But all hybrids that could trace their heritage back to the original gray wolf–coyote cross through female ancestors retained the coyote mitochondrial DNA from the original coyote mother.

JOEL SARTORE *National Geographic Image Collection*

RED WOLF, COYOTE AND GRAY WOLF can be hard to tell apart by appearance alone. But the red wolf (*left*) is generally larger than the coyote (*top, center*),

E. R. DEGGINGER *Bruce Coleman Inc.*

Recalling this scenario, we began to wonder whether the original red wolves in the captive breeding program were actually recent descendants of red wolf–coyote hybrids and possibly even descendants of gray wolf–coyote hybrids. But perhaps early generations—born before frequent crossbreeding began to occur—were pure red wolves. We examined this possibility by going back further in time, to before the 1930s, the era when, according to Nowak, red wolves supposedly had not yet begun to crossbreed to any significant extent. If the red wolf was once a distinct species that began to crossbreed only in the 1930s, historical samples should reveal a genetic sequence unique to the red wolf. Alternatively, if the red wolf resulted from breeding between gray wolves and coyotes, older specimens should also show a mix of coyote and gray wolf DNA, just as the modern samples did.

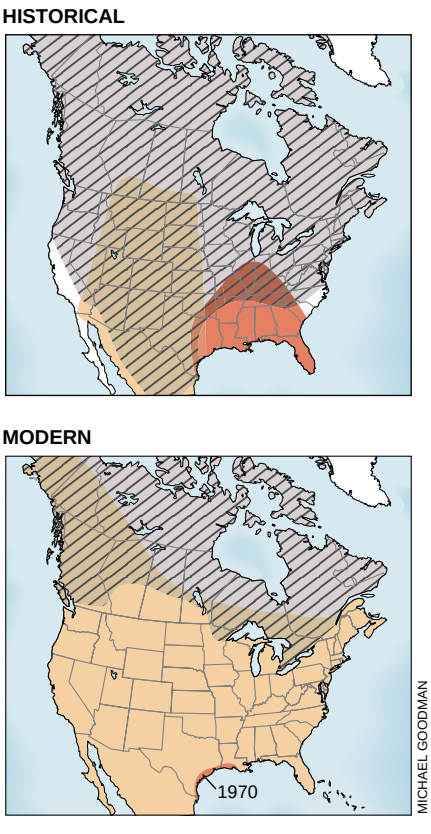
Thanks to the recently developed polymerase chain reaction, which can produce large numbers of copies of selected bits of DNA [see "The Unusual Origin of the Polymerase Chain Reaction," by Kary B. Mullis; SCIENTIFIC AMERICAN, April 1990] and to the Smithsonian Institution's fur vault, we were able to examine sections of mitochondrial DNA from the skins of six red wolves that died before 1930. To our surprise, we once more failed to find diagnosable red wolf DNA sequences different from those of the coyote or the gray wolf. On the basis of such findings, we deduced that the red wolf may not be a unique species.

Our views were not well accepted by the Fish and Wildlife Service, whose researchers argued that their evidence still supported the theory that the red wolf was a species and indeed an ancestor of the gray wolf. Although some of the resistance to our hypothesis may have been motivated by politics—the

TOMO NARASHIMA

and its fur can be tawnier. The gray wolf (*below*) is typically the largest; its coloring varies a great deal. Measurements of skulls have revealed that the dimensions of the red wolf's skull fall in between those of the coyote's and the gray wolf's skulls.

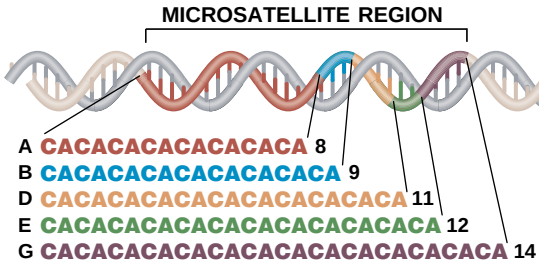
KENNETH W. FINK *Bruce Coleman Inc.*



MICHAEL GOODMAN

OVERLAPPING RANGES of the red wolf, coyote and gray wolf, deduced from historical records (*top*), may have led to considerable crossbreeding among the groups in the 18th and 19th centuries. Human changes to the environment have significantly diminished modern ranges (*bottom*) of the red wolf (shown shortly before protection efforts began) and the gray wolf. But the coyote's range has expanded.

Clues from Nuclear DNA



Distinctive sections of nuclear DNA, known as microsatellites, have provided strong evidence that red wolves do not constitute a unique species. Microsatellites consist of short, repeating sequences of nucleotides; a single microsatellite may consist of, say, eight repeats of a unit composed of two nucleotides—cytidylate (*C*) and adenylate (*A*). If at some given DNA site, or locus, a population possesses a microsatellite that is shorter or longer than the microsatellites found at the same locus in other animals, the divergence can be a sign that the population in question belongs to a separate species.

In a study involving several hundred red wolves, coyotes and gray wolves, the authors catalogued the number of repeating *CA* units that occurred in 10 microsatellite loci. For example, at one selected site, they identified five microsatellite variants, labeled A, B, D, E and G (*above*). Microsatellites in this region from red wolves and coyotes were always of the A or B types (*below*), but those from gray wolves included additional, unique versions. Similar analyses at the nine other loci demonstrated that only coyotes and gray wolves possess unique microsatellites; all microsatellites carried by red wolves can be found in either coyotes or gray wolves. This finding indicates red wolves have not diverged enough genetically from gray wolves and coyotes to be considered a separate species.

RED WOLF	COYOTE	GRAY WOLF
A CACACACACACACA	A CACACACACACACA	A CACACACACACACA
B CACACACACACACACA	B CACACACACACACACA	B CACACACACACACACA
		D CACACACACACACACACACA
		E CACACACACACACACACACACA
		G CACACACACACACACACACACACACACA

MICHAEL GOODMAN

red wolf project was a flagship program for endangered species preservation—complaints that our data seemed inconclusive were fair. After all, we had been able to examine one type of DNA from only six wolves that lived before 1930; perhaps we had simply missed the distinct genetic trait.

To expand our studies, we turned to nuclear DNA, comparing selected segments in red wolves, coyotes and gray wolves. We made use of a discovery by Diethard Tautz, now at the University of Munich, who found that some short, simple and common sequences of nucleotides repeat themselves at particular sites, known as microsatellites, in nuclear DNA and that the number of repeats in these microsatellites can vary from species to species. The length of the final unit can thus serve as an indicator, or marker, that an animal belongs to a particular species.

Along with several colleagues, we studied microsatellite DNA from several hundred contemporary red wolves, coyotes and gray wolves. Again we found no evidence that red wolves form a unique species. Of course, the similarity between red wolves, coyotes and gray wolves may have been the result of recent crossbreeding, and so we sought a historical perspective once more.

Using pre-1930s skins stored at the Smithsonian's fur vault, our colleagues Michael S. Roy of the Institute of Zoology in London and Deborah Smith of the University of California at Los Angeles examined 10 different microsatellite regions from 16 skins identified by others, including Nowak, as deriving from red wolves. Still, we detected no sign that the DNA of red wolves was clearly distinct from that of either gray wolves or coyotes living in the same period.

Hybrid Hypothesis

The collected findings from both modern and historical wolves and coyotes has led us to the following hypothesis, which is accepted by many investigators but is still disputed by some. Sometime in the recent past, crossbreeding between the gray wolf and the coyote began to occur. Our data do not allow us to pinpoint exactly when the crossbreeding began, but we speculate it might have been during the early years of European migration. As European settlements expanded in the 1700s, the conversion of woodlands for agriculture and the killing of gray wolves produced conditions similar to those seen recently in Minnesota and eastern Canada. The gray wolf population dwindled, leading the survivors to mate more frequently with coyotes. The resulting hybrid animals, gray wolf–coyote crossbreeds, were of intermediate size and had characteristics that were later classified as attributes of the red wolf. In subsequent years, as gray wolves disappeared in the southern U.S., gray wolf–coyote hybrids mated with coyotes more frequently and became more coyotelike, a trend we believe is reflected in Nowak's observation that the skulls of red wolves became more coyotelike after 1930.

Furthermore, our study suggests crossbreeding among the three supposed species was well advanced by the turn of the 20th century. Red wolves captured before 1930 are very similar genetically to those captured in the 1970s and used to start the captive breeding program. This result is good news for the breeding program in that it means reestablishment of a wild population of red wolves with individuals from captivity has indeed preserved the genetic makeup possessed by the wild red wolf. News of the genetic similarities among red wolves, coyotes and gray wolves, however, is disappointing to those who believed the program was protecting a long distinct species. Because crossbreeding among the three groups continued during various periods in their history and throughout their range, we feel the red wolf never truly developed into a separate species.

If biologists focused solely on species status as the guide for determining whether an endangered group should be protected, such findings could be the death knell for the red wolf. Yet there are compelling reasons protection should continue. Captive breeding of the red wolf may have preserved unique physical characteristics or behaviors not revealed in the studies done so far. More important, such qualities may not

be easily regenerated through the mating of modern gray wolves and coyotes. Some investigators have suggested that the red wolf arose from hybridization between the coyote and a southern subspecies of gray wolf that is now extinct. Consequently, a cross of the modern eastern gray wolf with the coyote would produce an animal similar in many ways but potentially different in behavior, fur coloring or other characteristics. Thus, the red wolf may be the last, albeit impure, repository of genes from a now extinct gray wolf subspecies and as such should certainly be preserved. Additionally, ecological concerns need to be considered. Red wolves, even if they are hybrids of coyotes and gray wolves, are once again important predators of many wild animals, including rodents, rabbits and deer, in the south central U.S. The red wolf may also play a role in some habitats that its smaller kin, the coyote, cannot entirely fill.

FUR VAULT at the Smithsonian Institution provided skins of red wolves (*at right in inset*), gray wolves (*at left in inset*) and coyotes (*above*) for genetic analyses of animals that died before 1930.

ALEX WEBB *Magnum*

Protecting the Red Wolf

To protect the genetic makeup of today's red wolves, conservation programs must strive to keep red wolves from breeding with coyotes, which are abundant throughout the planned reintroduction sites. Hybridization might be reduced if several red wolf packs were placed in an area simultaneously; large groups of red wolves stand a better chance of excluding coyotes from their habitat than do small groups. Because coyotes are ubiquitous in the American Southeast, it is hard to find regions where they are sparse. Removal or extermination of coyotes might alleviate this problem, but that solution implies a measure of red wolf chauvinism.

The case of the red wolf suggests to us that in deciding which animals to protect most assiduously, biologists must look beyond the taxonomic classification of an endangered hybrid or subspecies; they should also take into account its unique function in an ecosystem or possession of special traits that cannot be reproduced by crossbreeding of contemporary representatives from the parental species.

The fact that the red wolf may be a repository of genes from an extinct subspecies of gray wolf is just one example of this principle. In another example, a hybrid species may result from a single initial crossing of two species and the subsequent evolution of the offspring in isolation from their ancestral species; consequently, those descendants will have unique traits and, in our opinion, deserve protection as a separate species. Many plant species, for instance, arise in this way.

Such situations must be distinguished from those in which crossbreeding occurs frequently over a wide geographic area and may reflect human changes to the surroundings. In these cases, the hybrids may not possess unique traits. Even these hybrid groups, however, should not automatically be excluded from conservation efforts; they should be examined on an individual basis.

Human changes to the environment can sometimes bring together two populations that proceed to crossbreed; we believe the resultant hybrids from such unnatural matches generally should not be protected if their numbers start to fall. But hybrids that have arisen from populations that overlap naturally deserve special consideration as integral parts of their ecosystems.

Molecular analysis of DNA can provide insight into the history of endangered or rare species. Moreover, such an approach can provide a yardstick with which one can measure the differences between populations. For the red wolf, we feel the problem of classification was largely resolved by DNA testing. But the issues raised by identifying the red wolf as a hybrid species highlight the difficulties of determining how to rank endangered species, subspecies and hybrids in protection efforts. Those challenges need closer attention if conservation biologists are to make the best possible choices for the preservation of our natural heritage.

The Authors

ROBERT K. WAYNE and JOHN L. GITTLEMAN are both carnivore biologists who share a concern for problems associated with the red wolf reintroduction program. Wayne, a professor at the University of California, Los Angeles, specializes in molecular population genetics, systematics and conservation. He is particularly interested in the consequences of hybridization between reintroduced red wolves and resident coyote populations. Gittleman is a professor at the University of Tennessee, where he focuses on carnivore ecology and evolution. He is investigating the ecological and evolutionary effects of carnivore reintroduction programs.

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Protecting the Greenback

Digital color systems can reproduce paper money with disconcerting accuracy. The U.S. government's response is a new series of notes

by Robert E. Schafrik and Sara E. Church

LAURIE GRACE

Surprisingly, paper currency remains a cornerstone of modern commerce. The predicted "cashless society," in which all transactions are made with checks, credit cards, debit cards and electronic transfers, has not yet materialized. More than $380 billion in U.S. currency is estimated to be circulating worldwide, and demand for the bills increases annually at a rate of about 5 percent. In the 1995 fiscal year alone, the U.S. Treasury Department's Bureau of Engraving and Printing is scheduled to deliver more than nine billion new notes, with a total value exceeding $130 billion. Almost a fifth of the 50 billion banknotes circulated in the world are U.S. currency.

Internationally, the greenback holds a unique position, serving as a de facto world currency, accepted universally and even held as an investment where local economies are uncertain. Because of this special status, changes to U.S. currency are not made lightly. In fact, the basic design of U.S. currency has not changed significantly since 1928.

During the next few months, however, presses at the Bureau of Engraving and Printing will begin rolling out currency with a fundamentally new design. With a larger, off-center portrait, a matching watermark and other new elements, the first note in this series, a $100 bill, will be issued in 1996. Then, at one-year intervals, the bureau will introduce new $50, $20, $10, $5 and possibly $1 bills. Although such a sweeping currency change in the U.S. is unusual, many countries routinely modify the look of their money. Canada, Australia, France, South Korea and Argentina, to name a few, have all redesigned their paper notes recently or are now doing so.

The main purpose of these programs is to make the currency more secure against counterfeiting—the threat of which has resurged in recent years with the appearance of advanced photocopiers and computer scanners and printers capable of producing high-quality and often convincingly realistic copies. Dealing with this type of misuse is important for the future of paper money because widespread counterfeiting strikes at the credibility of paper currency as an exchange medium.

Countering a New Threat

Counterfeiting is as old as paper money itself, but color reprographics have added a troubling spin. Traditional counterfeiting methods require specialized printing equipment, inks, papers and other materials that raise suspicions when acquired by those unauthorized to use them. Counterfeiters typically invest considerable effort and capital to produce large amounts of phony notes. This modus operandi enables the U.S. Treasury's Secret Service and other law-enforcement agencies to discover and seize most counterfeits before they are circulated. In contrast, the new color reprographic technology allows people—and not just hard-core professional counterfeiters—to make bills in smaller amounts and at the push of a button, with equipment that generally cannot be traced.

The amount of counterfeit generated by all methods and entering circulation in the U.S. is on the rise, although the amount is still low compared with other forms of fraud in financial transactions. In the fiscal year ended September 30, 1993, the Secret Service reported that $20 million in counterfeit bills was passed on to the U.S. public. That amount increased to $25 million in the next fiscal year, and at the halfway point in 1995, $15 million had already been passed. (To put these figures in perspective, fraudulent checks result in losses estimated at $10 billion every year in the U.S., and counterfeit credit cards add at least another $100 million.) Color reprographics accounted for only a few percent of counterfeit currency, but the trend, particularly in the counterfeiting of U.S. notes outside the country, is a gradual but steady shift toward these newer methods.

Counterfeiting of paper money within the U.S. has largely been contained because the Secret Service seizes the vast majority of notes before they are passed. In the fiscal year 1994, $183 million was confiscated—75 percent of it overseas with the help of local law-enforcement agencies. In the following six months, $148 million was seized, 62 percent of it at non-U.S. sites. If phony money keeps turning up at this rate, 1995 will obviously be a banner year

COUNTERFEIT DETERRENCE relies on a combination of features in a single note. Faces are highly recognizable, especially when printed by the intaglio method, renowned for its ability to create fine detail (*highly magnified at lower left*). Pentagonal planchettes shimmer iridescently, and special inks can shift color, for example, from green to orange, with viewing angle. A security strip and a watermark are visible only in transmitted light. A bull's-eye-like figure generates a conspicuous moiré pattern when copied by digital means. (The fantasy collage shown here was not based on any planned U.S. currency.)

for the counterfeiting of U.S. bills, although 90 percent will be intercepted before entering circulation.

The total extent to which counterfeit U.S. notes are in circulation overseas is unknown, although anecdotal evidence suggests that it is a significantly larger problem in certain parts of Europe and South America than it is in the U.S. Interestingly, the most common fake bill found within the U.S. is the $20 bill, whereas foreign counterfeiters prefer the $100 one. Foreign preference for the C-note might be partly explained by the fact that two thirds of all U.S. $100 bills are believed to be abroad.

The maximum sentence for counterfeiting in the U.S. is 15 years' imprisonment and a $5,000 fine. In colonial times the most severe (but rarely imposed) penalty was death. ("TO COUNTERFEIT IS DEATH" or "'TIS DEATH TO COUNTERFEIT" was printed on many notes in the colonies.) Counterfeiting persisted, nonetheless, forcing officials to supplement law enforcement with other means of discouragement. This is where deterrence comes in: legitimate banknote designers and printers have long used specialized skills, technology and materials to make counterfeiting harder.

Change for a $13

Only twice in U.S. history did counterfeiting become endemic—during the Revolutionary and Civil wars. During the Revolutionary War, the British carried out large-scale counterfeiting to undermine the financial stability of the various currencies used throughout the colonies, particularly the notes issued by the Continental Congress to finance the rebellion.

Later, as the young country expanded, the need for cash intensified. In the absence of a federal bank, this cash came mostly from state-chartered banks, whose ranks swelled rapidly. These banks and even some commercial enterprises issued their own currencies, with distinctive designs and denominating systems (including $3, $7 and $13 notes). By the beginning of the Civil War, as many as 1,600 different currencies were effectively in circulation in the U.S. The huge numbers of banks (including some bogus ones), currencies and currency designs, insecure money-printing practices and lax, corrupt or unfair law enforcement combined to engender what is known as the golden age of counterfeiting.

Of course, legitimate money printers were not sitting idly by amid this chaos. Special methods and designs for producing banknotes began taking hold to make the bills more difficult to counterfeit and the genuine ones easier to distinguish. In fact, almost all the basic features and many of the processes used to this day to combat counterfeiting had their origins during this period. Intaglio printing came into wide use for

currency printing in the early 1800s because it required techniques, materials and skills not widely available. In this technique the image is transferred under high pressure from a design engraved into a metal plate.

High-quality "rag" papers consisting of cotton or linen, or some combination of the two, were used, sometimes adorned with watermarks or fiber inclusions. Elaborate designs depicting skillfully executed allegorical vignettes and detailed machine rulings became common. Portraits were also incorporated, to take advantage of the easy recognition of the human face. Although these techniques were certainly steps in the right direction, their usefulness was undermined by the large numbers of designs and issues in circulation in the mid-1800s.

To help the public keep track of the hundreds of currencies, genuine and otherwise, handbooks were available that illustrated the special features and characteristic details of the different notes. The manuals also described the many individual counterfeits in circulation and were updated and reissued as the need arose. A typical example was *Peyton's Counterfeit Detector: The Principal Points Which Constitute a Genuine Banknote.* It enumerated 26 characteristics of bona fide notes, contrasting them with counterfeits. The 1839 edition described 1,395 circulating counterfeits and listed 20 issues of fictitious banks, 43 banks with worthless notes, 54 bankrupt banks and 254 banks with counterfeit notes. By 1863 as much as half the paper money in circulation was thought to be counterfeit.

A National Currency, at Last

The Union's need to finance the Civil War finally compelled the federal government to establish a national banking system and to issue paper money. Thanks primarily to the efforts of Salmon P. Chase, the treasury secretary during Abraham Lincoln's presidency, Congress authorized the issue of the first U.S. Notes and also Fractional Notes—small-size bills worth less than $1. At the Treasury Department, the Bureau of Engraving and Printing was established to print the new money. Along with the notes, first released in 1862, came a comprehensive strategy to combat counterfeiting.

Around this same time, the new technology of photolithography was making the counterfeiter's job easier. By photographing the notes and using the negatives to etch counterfeit plates chemically, the counterfeiter could produce large quantities of bogus notes without going through the tedious process of hand engraving. Photolithography, which is still the most common method of counterfeiting, was limited in two ways. Because of the nature of the etching process, the minute details of the design were lost compared with the original, a limitation that still holds true. In addition, films in those days were sensitive only to dark and light, not to distinct colors. Thus, to copy a subject with two colors required separate steps to remove the secondary ink, produce the plates for the main color and repeat the process for the second color.

To take advantage of these weaknesses, the new notes used finely detailed designs printed with excellent inks on the best paper stock. The new designs were executed by top engravers and intaglio printed on both sides. Such all-around quality made counterfeit copies, with their typically inferior methods and materials, all the more readily distinguishable by comparison. For the U.S. Notes, the main part of the design was printed in traditional black, but other parts were printed in a green ink that could not be removed without destroying the note. This same green was used on the backs of the notes, probably to minimize visibility of the back image through the translucent, slightly green paper, which would obscure the face image and lower the overall quality of the note. This verdant ink gave rise to the moniker "greenback."

Even the paper itself was improved. Partly on the advice of the newly established National Academy of Sciences, a distinctive paper with tinted, nonphotographable fibers embedded within two layers was adopted for the notes. These fibers, or "spider legs," were used mainly for the Fractional Notes. Other currency paper contained one or more long blue fibers in bands or shorter, colored fibers, added directly to the pulpy

£3 colonial note dated March 25, 1776, was printed in three colors and warned, "'TIS DEATH TO COUNTERFEIT." The skeletonized sassafras leaf on the back of the New Jersey bill was intricate and unique, thereby helping to deter counterfeiting.

$30 bill released by the Bank of the United States in Philadelphia on December 3, 1791, was often counterfeited. This note, in fact, is a high-quality fake.

High-density scrollwork known as the "Perkins format" was required for a time on notes from private banks in Massachusetts. This Gloucester Bank $5 bill is dated July 1, 1814.

slurry ("furnish") during paper manufacture. These features, coupled with the distinctive, greenish color, the special furnish and tight control of the supply, separated the paper from ordinary stock. It was—and still is—illegal to possess the distinctive paper used for U.S. currency without special authorization.

For the much counterfeited Fractional Notes, a special ink was developed as a further deterrent. Before intaglio printing, relatively large areas on both sides of the paper were printed with a bronze metallic ink. On the face, the inked area corresponded to the oval within which the central portrait was printed; on the back, the bronze shape repeated the value of the note. The ink's metallic character was not easily photographed or reproduced.

The original colored Treasury Department seal, with its 34 points (representing the 34 states, including the 11 that had seceded the year before), was considered difficult for a counterfeiter to copy. It was added typographically in a separate step. In another separate typographic step, serial numbers were assigned and overprinted on each note. Although the seal has varied in size and character over the years, the basic design survives today. The quality of its design and the sharpness of its points continue to challenge counterfeiters. The color of the seal and serial numbers, which has varied among red, blue, brown, gold and the now traditional green, was a further obstacle.

These features, combined with vigorous enforcement of the counterfeiting statutes by the Secret Service (formed in 1865), worked well. By 1872 a detection and law-enforcement network had been established, and approximately 2,000 counterfeiters had been arrested.

Even with these successes, considerable confusion persisted because of the variety of currency types and designs. In the decades following the Civil War, 15 separate categories of currency in multiple denominations, each with different face and back designs, were issued. These bills included Demand Notes, U.S. Notes, National Bank Notes, Currency Certificates of Deposit, Silver Certificates, Gold Certificates, Treasury Notes, Refunding Certificates and Federal Reserve Notes.

Formal recommendations to standardize currency designs were made as early as 1909. World War I and changing presidential administrations kept the idea from becoming a reality until the summer of 1929, when the Series 1928 notes were finally issued. The portraits and backs selected for this series have remained in use to this day with little change.

Standardization of the portraits and backs within a denomination was itself a deterrent feature, because the simple familiarity of a single portrait and back vignette for each denomination helped people recognize phony bills. The paper for the new notes contained millimeter-scale red and blue fibers, whose random distribution came about quite by accident. The intended localized strips of fiber were chopped and scattered during the papermaking process, and the resulting paper was judged to be even more difficult to counterfeit than it would have been with the originally intended longer bands of fibers. The tiny colored lengths remain a hallmark of U.S. currency. Like today's bills, all the imagery, front and back, was intaglio printed, whereas the seals, serial numbers and bank numbers were overprinted typographically.

After their introduction in 1929, the few changes made to these bills over the ensuing 61 years were cosmetic or sociopolitical, such as the addition of "IN GOD WE TRUST," mandated by a 1955 law. The stability of the design has reflected a more or less unchanging counterfeiting threat. Counterfeiters enjoyed only modest, occasional technical improvements in photography and lithography in this period. All that changed dramatically in the 1980s, however.

Casual Counterfeiting

With the proliferation of high-quality color reprographic systems, such as photocopiers, the once technically demanding and esoteric pursuit of counterfeiting has been opened up to those with hardly any skills. Perhaps most disturbingly, these new tools eliminate the need for specialized—and traceable—equipment and supplies, making the counterfeiters much harder to catch. Besides photocopiers,

Engraved vignette on this $2 note released by the Franklin Bank of Rhode Island on May 1, 1821, reminded bearers that "TIME IS MONEY."

Intricately printed defiant eagle and high volume of scrollwork made this $10 bill harder to duplicate. Dated July 1, 1834, it was distributed by the Bank of the United States in Philadelphia.

$1.25 bill, from the Roxbury Bank in Massachusetts, is dated March 26, 1838.

Stopping Counterfeiting at the Source

An expert system can help deter casual counterfeiting by letting advanced copiers and computer scanners recognize when a user is attempting to copy currency. Canon has patented one promising approach to such a system. According to the company's European patent, an expert system and banknote images are stored in read-only memory. During copying, the successive red, blue, green and brightness scans of the copier provide data regarding the location and orientation of features to the program, which statistically analyzes the data and determines if the features match any of the stored images. If a match is found, the copier can be set to print a blank sheet and require resetting by a service technician. Such a solution to counterfeiting would not foil a technologically knowledgeable counterfeiter, but it would certainly discourage casual money printers.

Another approach to making this kind of counterfeit traceable involves encoding information within the copy that can be correlated with a unique copy-machine serial number. Special equipment reads the code to determine which copier made the counterfeit. The approach could be extended to computer printers, although it may require increased computational power to perform the preprinting processing.

which are actually integrated scanning and printing devices, these computer-based systems include stand-alone scanners that capture an image for storage and manipulation, along with the graphic arts software and color printers typically used with them. These reprographic devices spread from professional graphic arts environments in the 1980s to much larger business and academic communities, making it possible for almost anyone to try counterfeiting.

Fortunately, few people have so far availed themselves of this opportunity. In fiscal year 1994 counterfeit notes produced on color copiers and passed in the U.S. totaled $990,138, or about 4 percent of all counterfeit money circulated in that one-year period. Halfway through fiscal year 1995, $448,168 in color-copier-produced notes had been passed. But only $750,000 was seized before being passed in the U.S.—less than half of what had been seized the year before.

Fiscal year 1995 is the first in which the Secret Service is keeping close track of bogus banknotes produced with inkjet printers. With their low costs and rapidly improving capabilities, these printers are considered a significant and growing threat. Domestically, $13,312 had been passed halfway through this year, whereas overseas the amount was in excess of $4 million. Some $54,400 of these notes was seized before entering circulation in the U.S.

Although the numbers now are modest, the circumstances suggest that this is no time for complacence. The low volume so far of counterfeits produced with color reprographics can be attributed, at least in part, to slower than estimated introduction of the machines into the marketplace. The initial high cost of the equipment—$40,000 for a color copier 10 years ago—inhibited sales, but much more capable color copiers are now becoming available for as little as $4,000. Also, only recently have affordable color-capable personal computers and printers become common.

Foreseeing these problems, the Bureau of Engraving and Printing commissioned the National Academy of Sciences in 1985 and 1987 to assess the potential problem and to recommend countermeasures. Two of the academy's recommendations were put into effect, as can be seen in any $100, $50, $20 or $10 note starting with the 1990 series or in any $5 bill starting with 1993. One is a polymer security thread contained within the paper, on the front left side of the bill. The thread, which lists the denomination and the letters "USA," is visible only when the bill is in front of a bright light. It does not show up in reflected light, which is used by copiers and scanners. The thread makes it more difficult to counterfeit a bill by color-copying or by "raising"—using a lower-value note to generate a higher one, either by bleaching and printing a higher denomination or by pasting on corners from genuine notes of higher value.

$20 bill issued on January 1, 1840, by the Mineral Point Bank in Wisconsin had intricate scrollwork.

Large "3" signified the denomination of this 1850 bill from the Cochituate Bank in Boston and made the note easy to recognize.

Vignettes and fine scrollwork made this 1860 $5 note more resistant to counterfeiting. It was circulated by the Central Bank of Virginia in Staunton.

The other anticounterfeiting feature is the microprinting, six to seven thousandths of an inch high, of "THE UNITED STATES OF AMERICA," repeated in a line around the outside of the portrait. Most copiers and scanners cannot resolve detail this small, and the resulting smear is obvious under magnification.

Nevertheless, like other forms of technology, these color reproduction systems—also known as nonimpact technologies to distinguish them from methods requiring plates or dies—are constantly being improved. Already good as counterfeiting tools, they will only become better. Their potential is such that the academy in a 1993 report deemed some relatively radical changes as necessary.

The time needed for analyzing and assessing new features and for designing, testing and scaling up production is approximately five years. Series of U.S. paper currency are never formally invalidated, or "demonitized." They can only be removed from circulation as they return to Federal Reserve banks; thus, it could take two years or more for the new notes to predominate in circulation in the U.S. So government currency experts must forecast what counterfeiters will be using five to 10 years from now and take steps early to thwart them.

Anticounterfeiting elements must meet many requirements. They must be immediately recognizable, difficult to duplicate or simulate, durable in the face of considerable wear and tear, and made of materials that are nontoxic and nonhazardous in manufacture, processing and even destruction. They also need to be economical: all U.S. notes are now produced for less than four cents apiece. Ideally, the features should also be machine detectable and aesthetically acceptable to the public, the first line of defense against counterfeiting.

Combining deterrent features into a new paper currency requires a delicate balance; changes must be substantive enough to address the problem but not so radical they eradicate the public's familiarity with the currency. People all over the world need time to recognize a new bill; during such a transition, the currency could be more vulnerable.

The new series of U.S. bills, starting with the $100 in 1996, will be fundamentally different. To minimize the impact of the discontinuity, however, their overall appearance will remain consistent with today's U.S. currency. Therefore, in the new design the bills will not change size and will retain the same portrait subjects, vignettes and basic colors as in the current notes.

As of this writing, the Bureau of Engraving and Printing has not completed preproduction testing of the candidate features that were announced in July 1994. Because some of them may be altered or eliminated based on the test results, the final note design has not yet been approved; however, some likely elements of the design are listed below.

Defensive Depth

The most immediately conspicuous features of the upcoming series of notes are likely to be their watermarks and enlarged, off-center portraits. On each note they will be adjacent and will depict the same image. Although watermarks are common in European, Asian and South American currencies, this would be their first large-scale appearance in U.S. currency and the first use of a portrait watermark that is located in the same position on each note of a certain denomination. The inclusion of the watermark, in fact, was a major factor in redesigning the layout of the note; the shifting of the portrait from the center will make room for the watermark, enhance the portrait's visual impact and reduce wear on the image caused by folding of the bill.

Watermarks, which are designs created by variations in the density or thickness of the paper that become visible in transmitted light, are an example of a substrate-based feature—one of three basic types used to combat counterfeiting. Optimum deterrence results from a combination of multiple types in a "layered defense." The three kinds can be grouped together according to their place on the note: engraved designs that are difficult to reproduce convincingly, those that are placed in the paper while it is being made (substrate-based features) and unique printing inks. Besides watermarks, substrate-based features include the paper material itself, tints and paper-furnish inclusions and additives.

Another intriguing substrate-based feature would use iridescent, microprinted planchettes. Traditionally, planchettes have been tissue-paper disks a few millimeters in diameter, distributed either randomly in the pa-

Virginia's state seal and the surrounding inscribed numeral fives would have challenged anyone trying to copy this $5 bill circulated by the Traders Bank of Richmond in 1861.

$7 bill issued by the Monticello Bank in Virginia on April 29, 1861, featured machine-engraved scrollwork. It circulated contemporaneously with Confederate notes.

$2 "fare ticket" was circulated by the South Carolina Rail Road Company in 1873. Often used as currency, such tickets circumvented a 10 percent tax on all paper currency not printed by the Bureau of Engraving and Printing.

ANTICOUNTERFEITING FEATURES of current U.S. bills (other than the $1) include a security strip, or thread, within the paper. Visible only in transmitted light, it cannot be photocopied or scanned. Microprinting around the outside of the portrait, in letters six to seven thousandths of an inch high, is too small to be copied by most systems. Reproduction in this manner creates a smear obvious under low-power magnification.

per or in localized bands. They can be seen in Canadian, Mexican and many other paper currencies but have never been used in U.S. currency. In the new design the planchettes would be made from a coated polymer film that appears in different colors as the angle of viewing is changed, giving a rainbow effect. As an enhancement, the planchettes could be microprinted with text.

The new bills will also have a security thread similar to the ones now in circulation, but possibly upgraded for detection by instruments. The threads may also be located in different parts of the note, depending on the denomination. The small colored fibers might also be supplemented or enhanced for detection by machines, to provide reliable authentication of the bills and their denominations. The features could be helpful in commercial situations in which cash is counted or exchanged—in vending and dollar-bill–changing machines, for example.

Another possibility under consideration involves lines capable of generating moiré patterns. Advanced copiers and computer scanners create images based on digital sampling techniques, and when the spatial detail of the image being sampled is greater than the sampling frequency of the digital device, spurious and striking patterns result in the reconstructed image. These are known as moiré patterns. Images that would generate them when copied are being investigated for incorporation into the notes' designs.

One of the most intriguing possibilities is the use of special ink that changes color as the printing is tilted relative to the light. (In concept, it harkens back to the bronze underprinted shapes that adorned Fractional Notes.) The color shift is caused by small platelets of thin-film interference filters, used as pigments in a regular ink varnish. The angular dependence arises from light beams interfering with one another as they reflect among alternating layers of a light-absorbing material, such as chromium, and a nonmetal, such as manganese fluoride. These layers are applied on top of a reflecting material, such as aluminum. These inks are much more expensive than the normal intaglio ink, so the size of the image printed with them would be limited to no more than about two square centimeters—big enough to exhibit a noticeable shift but small enough to keep costs reasonable.

Vintage Protection

The basic tool kit available to those who deter counterfeiting has changed surprisingly little in over a century. Conceived in an era of printing presses, photography and lithographic plates, it is now being expanded in an era of sophisticated color copiers and scanners. The stakes are high. In today's world of strong economic interdependence, even a relatively brief period of rampant counterfeiting could have devastating consequences.

Given the pace of graphics and printing technology advances in recent years, it is unlikely that the new notes will suffice for six decades, as did the previous ones (albeit with a few well-chosen modifications). To supplement the deterrent value of the new notes, law enforcement—especially international cooperation—will have to expand as the use of the hard-to-trace printing technology spreads worldwide. Manufacturers of advanced reprographic equipment can help by making their equipment less suitable for counterfeiting.

The new notes will surely do much to discourage counterfeiters, both casual and professional, for years to come. Over the longer term, however, they might be considered only the latest salvos in a never-ending war.

The Authors

ROBERT E. SCHAFRIK and SARA E. CHURCH have been involved in assessing counterfeit-deterrence features for the forthcoming series of U.S. paper currency. Schafrik is with the National Research Council (NRC) in Washington, D.C., as both executive director of the National Materials Advisory Board and acting executive director of the Manufacturing Studies Board. He was awarded a Ph.D. in metallurgical engineering in 1979 from Ohio State University. Church is a program manager and research chemist with the Office of Advanced Counterfeit Deterrence in the U.S. Treasury Department's Bureau of Engraving and Printing. A member of the department's new currency design task force, she holds a Ph.D. in physical chemistry from Oregon State University.

Further Reading

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Treating Diabetes with Transplanted Cells

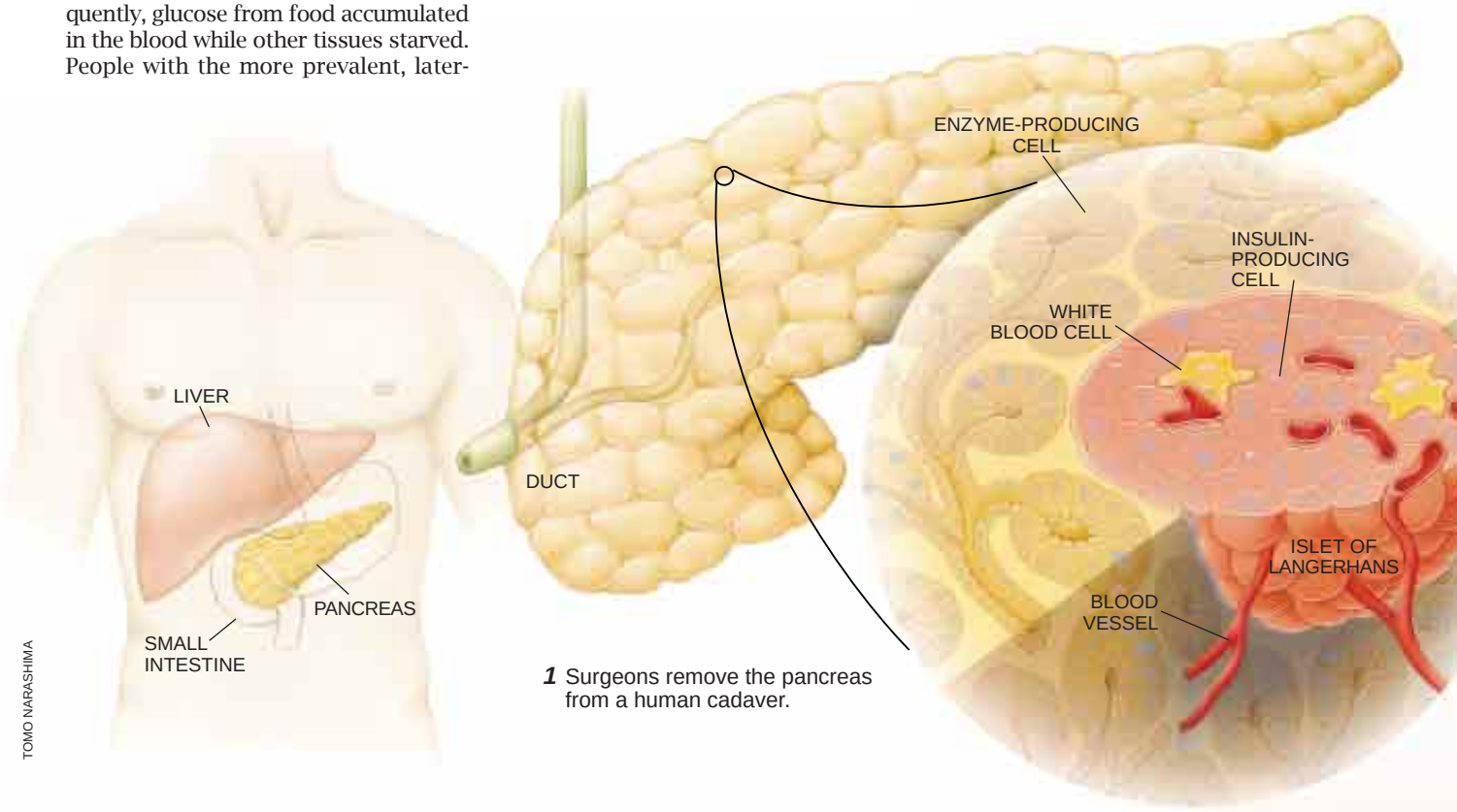
The implants, islet cells of the pancreas, can potentially cure many cases of diabetes. A prime obstacle to wide use—lack of a safe way to avoid immune attacks on the grafts—now seems to be crumbling

by Paul E. Lacy

Until about 75 years ago, the form of diabetes that usually strikes children and young adults was invariably lethal. Families and physicians watched helplessly as robust youngsters wasted away and died within weeks or months of diagnosis. By the early 1900s investigators knew the problem lay with small clusters of pancreatic cells called the islets of Langerhans. It was evident these islets normally secreted a critical hormone, later named insulin, that enabled other cells to take up the sugar glucose from the blood for energy. It was also apparent that in the diabetic patients (today said to have type I, or insulin-dependent, diabetes mellitus) insulin production had ceased. Consequently, glucose from food accumulated in the blood while other tissues starved. People with the more prevalent, later-onset form of diabetes—type II, or non-insulin-dependent—fared better because they continued to make at least some insulin.

Prospects for type I diabetics improved dramatically in the early 1920s, when insulin extracted from animals proved lifesaving. Indeed, for decades thereafter most people assumed daily injections of the hormone were tantamount to a cure. Sadly, they were mistaken. Over the years clinicians gradually came to realize that many patients eventually suffer from potentially devastating diabetes-related disorders. Microscopic blood vessels can slowly become damaged, often culminating in blindness or kidney failure, or both. Larger vessels may become prematurely narrowed by atherosclerosis, and nerves may be disrupted as well, leading to numbness and pain in the extremities. The cause of these "long-term complications" has now been shown to be excess glucose in the blood and the consequent alteration of tissues exposed to the extra sugar. Clearly, the insulin injections on which type I diabetics depend for survival cannot precisely mimic the ability of the normal pancreas to sense blood glucose levels and put out exactly the amount of insulin needed to keep the body healthy.

The key to ensuring long-term health, then, is to provide therapy that can

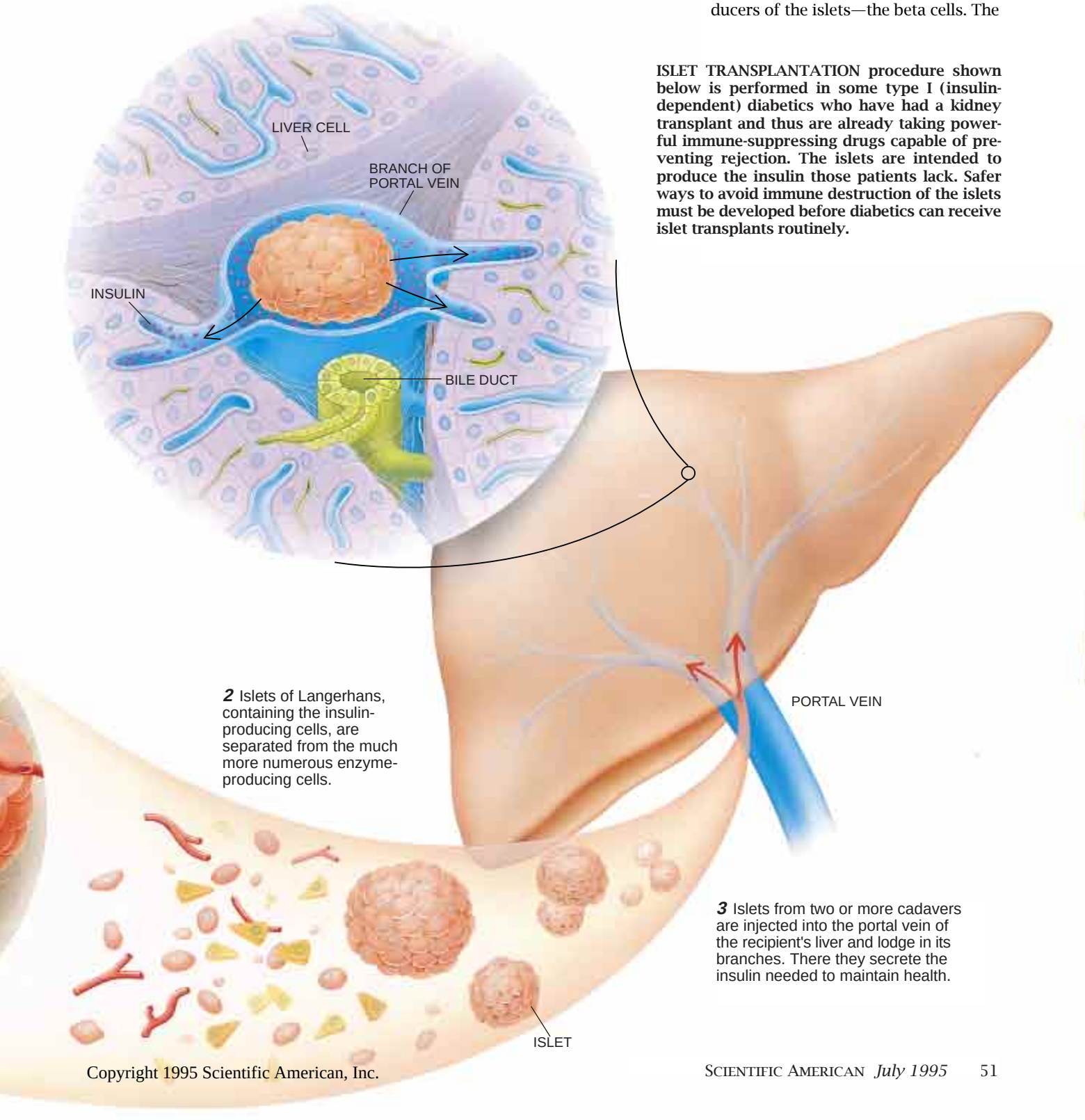


1 Surgeons remove the pancreas from a human cadaver.

TOMO NARASHIMA

maintain glucose values within normal limits at all times from the start of the disease. An ideal treatment would be implantation of islets, because functional islets would restore proper insulin production and, in theory, would have to be implanted only once; native islets survive for many years and carry within them the precursor cells needed to supply replacements for cells that die. Successful grafts would also avoid acute diabetes-related ills. These conditions include coma induced when glucose accumulates to extremely high levels in the blood, as well as insulin reactions (often marked by shakiness, confusion or blackouts), which arise when an injected dose of insulin lowers glucose levels too far. Islet transplantation is conceptually simple but has been difficult to implement. Finally, however, there is good reason to think this potentially curative therapy will be available to many patients within the next five years and will become routine for newly diagnosed patients within a few years thereafter.

My laboratory at Washington University carried out most of the initial work, beginning some 25 years ago, and it continues intensive research on transplants today. At first we were not focusing on therapy; we were merely trying to understand the mechanics of hormone secretion from the insulin producers of the islets—the beta cells. The



ISLET TRANSPLANTATION procedure shown below is performed in some type I (insulin-dependent) diabetics who have had a kidney transplant and thus are already taking powerful immune-suppressing drugs capable of preventing rejection. The islets are intended to produce the insulin those patients lack. Safer ways to avoid immune destruction of the islets must be developed before diabetics can receive islet transplants routinely.

2 Islets of Langerhans, containing the insulin-producing cells, are separated from the much more numerous enzyme-producing cells.

3 Islets from two or more cadavers are injected into the portal vein of the recipient's liver and lodge in its branches. There they secrete the insulin needed to maintain health.

other islet cells produce hormones that help to regulate the amount of insulin synthesized.

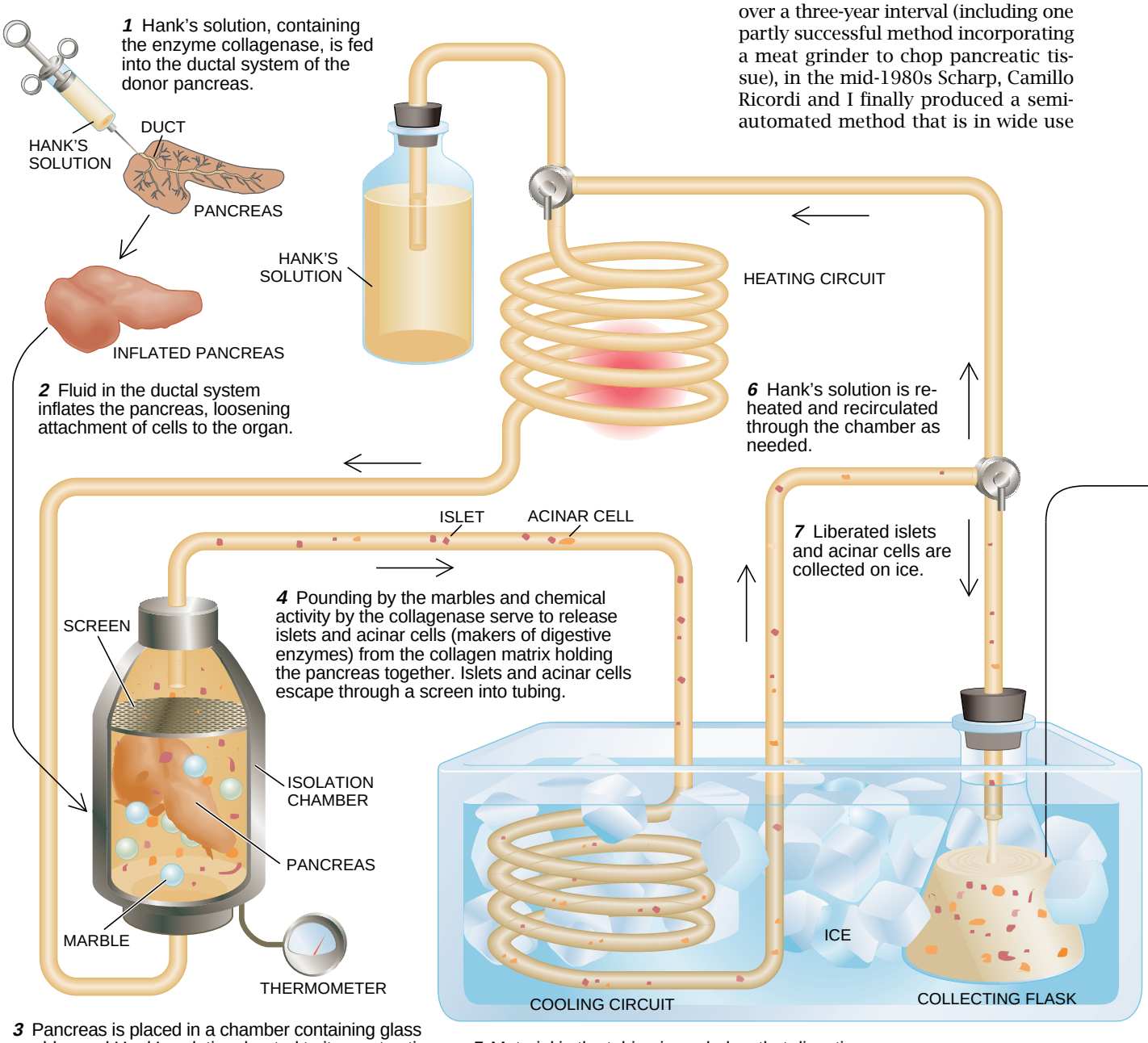
Early Excitement

To carry out such studies, we had to obtain islets from laboratory animals. Yet those cell clusters constitute only 2 percent of the pancreas by weight and are scattered within it. The rest of the pancreas is devoted not to making hormones but to manufacturing potent digestive enzymes. In 1967 we developed a way to collect the needed islets from the rat pancreas. Of course, after we had the islets in hand, we could not resist seeing whether the clusters could control blood sugar levels in diabetic animals and prevent complications. After all, success would mean that islet transplantation might be helpful to diabetic patients.

In 1972, collaborating with Walter F. Ballinger and David W. Scharp of Washington University's department of surgery, we transplanted islets isolated from rats of an inbred strain to other rats of the same strain made diabetic by injection with a drug that specifically destroys beta cells. We chose this particular strain because inbred animals are identical; therefore, the immune defenses of the recipients would not reject the grafts as foreign (nonself). To our delight, the transplants in the rats returned blood sugar levels to normal and kept them there permanently. Later studies revealed islet grafts could prevent or reverse early microvascular complications of the eyes and kidneys in diabetic rats.

These findings made us eager to begin tests in diabetic patients. Before we could design such trials, though, a serious difficulty had to be resolved. Our method for isolating islets from the rat pancreas did not work for the human organ. After trying various approaches over a three-year interval (including one partly successful method incorporating a meat grinder to chop pancreatic tissue), in the mid-1980s Scharp, Camillo Ricordi and I finally produced a semiautomated method that is in wide use

HOW ISLETS ARE ISOLATED FROM THE HUMAN PANCREAS



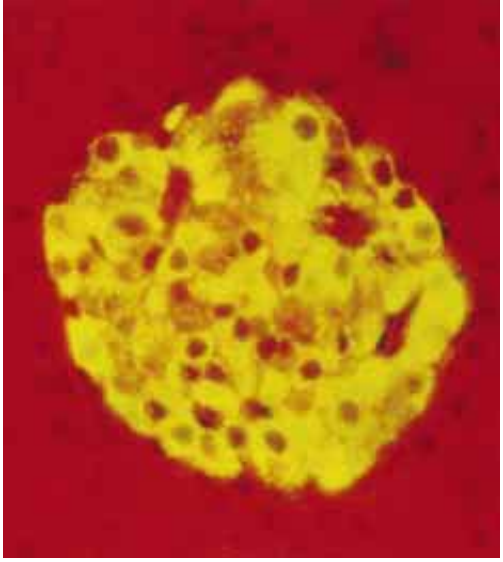
today. Conveniently, the method managed to isolate some 400,000 islets from the approximately one million in a single human pancreas—exactly the amount we estimated would maintain normal blood sugar levels in patients.

Encouraging Tests in Humans

In 1986 we began the first human trials of isolated islets. We could not immediately put the cell clusters into newly diagnosed patients—the ultimate goal—because of the likelihood that the immune system of the recipients would reject the foreign tissue. To avoid such rejection, we would have had to give the subjects immune-suppressing drugs, but those agents can have dangerous side effects, including promoting infection, cancer and kidney damage. The risk posed by such drugs is too high to justify their use in patients who are healthy except for the need to take insulin. Hence, we selected as subjects type I diabetics who had received a kidney transplant and therefore were already forced to take immunosuppressants to protect the new kidney.

Scharp and I decided to place the islets into the network of blood vessels extending from the portal vein of the liver, in part because the system is easily accessible. The islets could be delivered simply by making a small incision near the navel and feeding the islets through a tube into a vein that leads into the portal vein. Once lodged in smaller vessels branching from the portal vein, the islets would have direct contact with blood, which would enable them to sense blood sugar levels constantly and, at the same time, to receive continuous nourishment. If such conditions are met, there is no need to return islets to the pancreas—a much trickier endeavor.

The results were encouraging. In subjects who were given 400,000 islets, the grafts worked, although they did not make enough insulin to enable the patients to stop taking injections. When we later increased the number to 800,000, some patients were freed from injections, at least for a time. Our findings were subsequently confirmed in other laboratories. We also learned that islets preserved by freezing would function well and hence could be banked for future use.

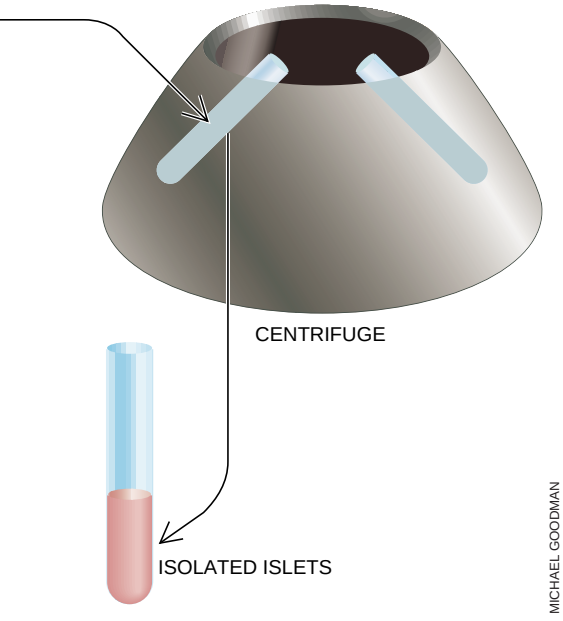


LELIO ORCI *Centre Médical Universitaire, Geneva*

ISLET IN PANCREAS of a rat resembles those of humans. In both species the beta cells (*gold*)—the insulin producers—predominate and cluster in the center. They are surrounded by cells (*not visible*) that secrete different hormones. The red area consists of other pancreatic tissue.

Since 1990, approximately 145 patients worldwide have received islet transplants from cadavers—either as isolated clusters or in some instances as part of less pure preparations. The islets in most patients have been unable to control blood sugar levels completely or have lost some of their activity after three years or less. We suspect that in many cases too few islets were implanted for the individual's needs. In instances where implants failed after controlling blood sugar for a time, strain on the islets may sometimes have been at fault: after performing at maximum capacity for a while, the cells may have become exhausted. Rejection and other immune processes might have played a part in many immediate or delayed failures as well.

In spite of these imperfect results, many physicians are now considering routinely giving type I diabetics new islets at the time they receive a kidney graft. They are exploring this option because even when patients must still take some insulin by injection, the presence of productive islets can help them keep blood sugar levels consistently in the all-important normal range. Further, islet transplantation is much simpler than replacement of a whole or partial pancreas, a procedure sometimes done in diabetics who receive a new kidney. (The aim is to preserve the donated kidney by avoiding exposure to excess glucose.) Islet transplantation is also less costly than organ transplantation. Delivery into the portal vein can be performed with the help of local anesthesia for a few thousand dollars; a pancreas transplant, in contrast, involves major surgery and can cost as much as $100,000.



MICHAEL GOODMAN

8 Islet cells are isolated by spinning the collected material in a centrifuge. Some 400,000 islets can be retrieved from a single human pancreas, roughly half the number needed to keep blood glucose at a normal level.

Taking Aim at Passenger Cells

Once studies of immunosuppressed patients demonstrated that transplanted islets could be induced to perform in recipients, many investigators stepped up efforts to develop safe ways of preventing rejection. Two basic strategies have been pursued in animals for some time. One such tactic is based on a suggestion made back in 1957 by George D. Snell of Roscoe B. Jackson Memorial Laboratory in Bar Harbor, Me. He proposed, correctly as it turns out, that rejection of an organ is triggered not by the primary constituents of an organ but by white blood cells, or leukocytes, that are carried along with the graft. If these "passenger" leukocytes are at fault, eliminating them before a transplant is undertaken should avoid rejection.

Snell's insightful concept lay fallow until 1975, when Kevin J. Lafferty, then at the John Curtin School of Medical Research in Australia, resurrected it. In experiments involving the transplantation of thyroids from one strain of mice into another, Lafferty found he could prevent rejection by culturing the donor thyroids in the presence of high amounts of oxygen before implanting them. He concluded that the grafts survived because the oxygen had destroyed the passenger leukocytes—and only those cells—in the grafts.

Lafferty also proposed a reasonable explanation for why passenger leukocytes elicit rejection and why the main constituents of transplanted tissue do

not. It is believed that host white blood cells known as killer *T* lymphocytes are the agents of transplant rejection. Lafferty suggested that these cells must receive two signals in order to leave their resting state and attack other cells. The initial signal is issued when the *T* lymphocytes recognize certain proteins on the surface of implanted cells. These proteins are known as class I major histocompatibility antigens or, as they are commonly called, tissue-typing proteins. The second signal is probably issued when foreign cells release certain small proteins, or cytokines, that act on the *T* lymphocytes.

Presumably, passenger leukocytes carry the appropriate antigens and also secrete the necessary cytokines. In contrast, other cells in a graft, such as the hormone-producing cells of pancreatic islets, generate the first signal (they display the surface antigen) but cannot produce the second one (they do not release cytokines). Once passenger cells activate killer *T* lymphocytes, the lymphocytes attack any grafted cell bearing the recognized antigen, even if that cell cannot itself generate the second signal. But if *T* lymphocytes receive only the first signal, they apparently become tolerant of cells bearing the recognized antigen.

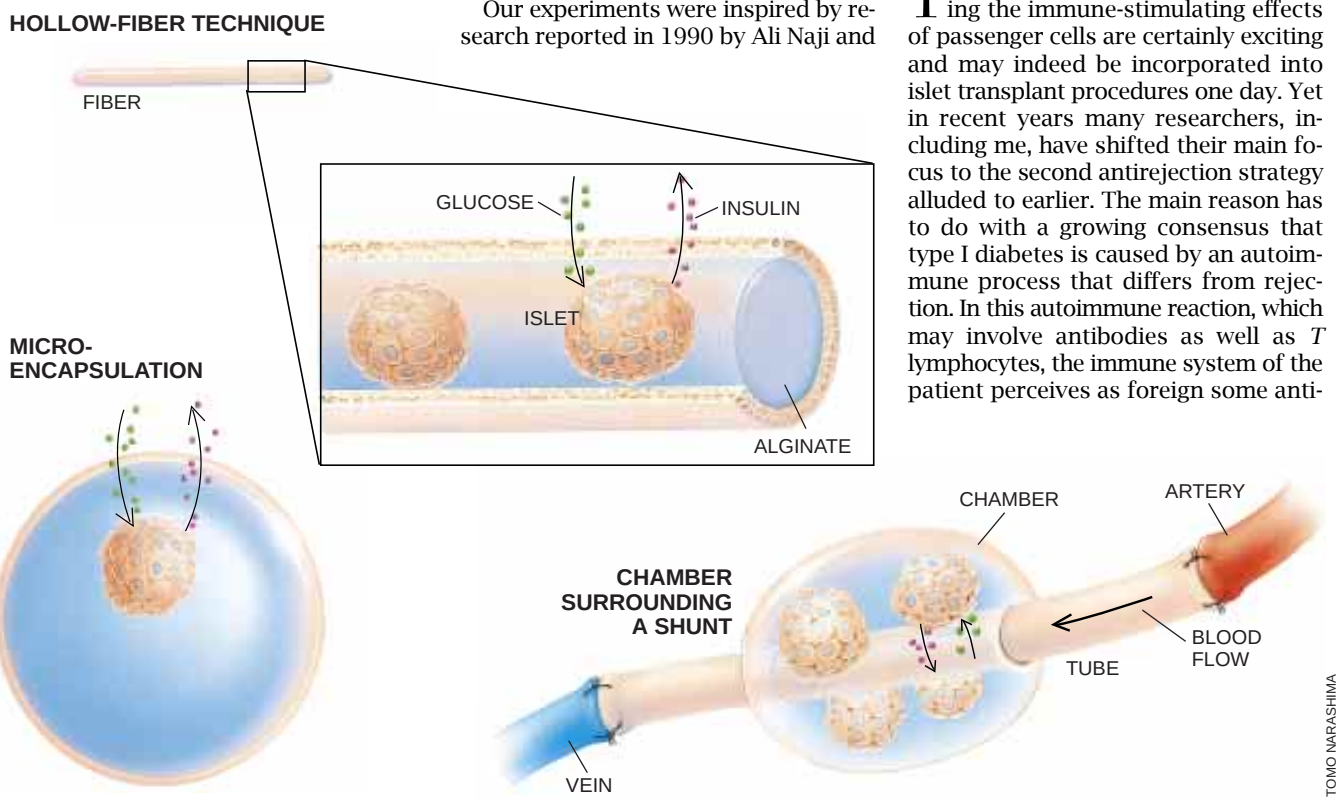
To our disappointment, Lafferty's method for destroying passenger leukocytes did not work for islets; the high levels of oxygen destroyed the hormone-producing cells. But, after much trial and error, in 1979 my colleague Joseph M. Davie and I devised a culturing technique that harmed only the passenger cells. When we placed approximately 1,500 treated islets from one rat strain into the portal vein of another strain and gave the recipients a single injection of a compound that temporarily inactivated their immune system, rejection was prevented completely. What is more, the same basic procedure prevented rejection of islets transplanted across species—from rat to mouse. Many other approaches for altering or destroying passenger leukocytes in islets were then developed in our laboratory and others.

Unfortunately, a central aspect of the procedures effective in rodents cannot be copied in humans. Investigators essentially handpick the islets they deliver to rodents, making sure that lymph nodes and other troublesome contaminants are excluded. Such a step is feasible when 1,500 islets are being transplanted but cannot be managed when hundreds of thousands are needed. Studies we completed in 1993 suggest a solution, however.

Our experiments were inspired by research reported in 1990 by Ali Naji and his co-workers at the University of Pennsylvania. Naji's team demonstrated that transplantation of rat islets from one strain into the thymus of another strain induced tolerance to those islets and to identical islets later put elsewhere in the body. Intrigued, my colleagues and I decided to see whether implanting a small number of cultured rat islets in other tissues of mice would block rejection of a subsequent transplant consisting of many untreated islets. (We accompanied the transplants with single injections of antibodies against rat and mouse white blood cells, hoping to destroy any remaining passenger leukocytes and to suppress temporarily immune surveillance in the recipient.) Sure enough, after cultured rat islets were placed in the portal vein of the liver in mice and supported by antibody injections, untreated islets delivered to the same site were accepted by the recipients. This finding, which we hope to replicate next in dogs, encourages optimism that human patients can be "preimmunized" with relatively few, carefully selected islets and then given the balance of the cells after tolerance has been induced.

Hiding Islets from Immune Cells

The various approaches for eliminating the immune-stimulating effects of passenger cells are certainly exciting and may indeed be incorporated into islet transplant procedures one day. Yet in recent years many researchers, including me, have shifted their main focus to the second antirejection strategy alluded to earlier. The main reason has to do with a growing consensus that type I diabetes is caused by an autoimmune process that differs from rejection. In this autoimmune reaction, which may involve antibodies as well as *T* lymphocytes, the immune system of the patient perceives as foreign some anti-



ENCAPSULATION OF ISLETS in semiporous plastic is one promising way to protect them from attack by the immune system. Three approaches under investigation are depicted. In all cases, the plastic allows glucose from the blood to reach the cell clusters and enables insulin that is secreted in response to escape into the bloodstream, but the material bars white blood cells and antibodies of the immune system (*not shown*) from reaching the islets.

gen on the individual's own beta cells and specifically destroys the beta cells as if they were unwanted invaders [see "What Causes Diabetes?" by Mark A. Atkinson and Noel K. Maclaren; SCIENTIFIC AMERICAN, July 1990]. Hence, even if we manage to forestall rejection, an autoimmune attack targeted specifically to beta cells could wipe out the insulin makers in the transplanted islets.

Autoimmune destruction might be prevented by purposely implanting islets whose tissue-typing antigens do not match those of the recipient's islets. But many investigators are taking a less chancy approach to circumventing both autoimmunity and rejection: they are exploring ways to encapsulate donor islets in a semipermeable plastic membrane. When the pore size is ideal, such membranes permit glucose to reach the encased islets and allow insulin made by the islets to escape, but the membranes bar lymphocytes and antibody molecules—which are much larger than glucose and insulin—from crossing to the islets.

In 1975 William L. Chick, then at the Joslin Diabetes Center in Boston, developed one of the earliest encapsulation techniques. He put the islets in a chamber surrounding a plastic tube, or shunt, and connected the shunt to an artery and a vein in rodents. As blood flowed through the tube from the artery to the vein, glucose passed across the wall of the shunt into the chamber, where it contacted the islets. Then the islets released insulin, which seeped out of the chamber and into blood flowing through the tubing; meanwhile lymphocytes and antibodies in the blood floated past the chamber, oblivious to the islets within. Moreover, the device corrected glucose levels in the blood—for a while. The islets died when blood coagulated on the wall of the plastic tube, clogging the pores. The biocompatibility of the device has since been improved, and canine islets transplanted into diabetic dogs have normalized blood sugar in studies that lasted for several months.

I worry about this approach for human diabetics, however, because shunts can be difficult to maintain. If one were damaged in the course of, say, a teenager's football game, it could rupture. It would not only lose function, it could also cause dangerous internal bleeding. Furthermore, blood clots could compromise the operation of the implants and might migrate to critical arteries and block them.

Franklin Lim of the Medical College of Virginia and Anthony M. Sun of the Connaught Research Institute in Toronto invented a different procedure in 1980. They prepared isolated islets for transplantation by suspending them in a viscous solution of alginate, a substance derived from seaweed. Addition of calcium to the solution caused it to gel, so that one or two islets became enclosed within a small alginate droplet. These fragile droplets were then coated with plastic and placed in the abdominal cavity. This site was used because fluid from the blood passes into the cavity and back into the bloodstream; it can thus inform the islets of blood sugar levels and can also carry insulin from the islets into the circulation. The capsules controlled blood sugar in rodents and prevented rejection, but the plastic coating stimulated the growth of fibrous tissue around the outer surface, depriving the islets of nutrients and killing them.

Plastic-coated droplets that are more biocompatible have been made and have reportedly reversed diabetes temporarily in a patient. But they still have drawbacks for human application. Although each capsule is small, measuring less than 0.5 millimeter in diameter, the several hundred thousand needed to control human blood sugar levels fill a large volume. To be feasible for broad use, the capsules would have to be smaller and more stable. In addition, investigators would have to develop a way to retrieve all the capsules readily in the event removal became necessary.

To avoid the drawbacks of the other two approaches, my laboratory has encapsulated islets in a hollow, semipermeable acrylic fiber as thin as the wire in a small paper clip. We selected this polymer fiber in 1990, after researchers at Brown University, who were studying Parkinson's disease, found it to be remarkably biocompatible. In initial studies we injected rat islets into a hollow fiber, sealed the ends and put one or two of the loaded vessels into the abdominal cavity of diabetic mice. The blood sugar levels became normal and stayed that way for up to 12 days, but then the animals became diabetic again. We thought we had hit a dead end; the islets had been rejected.

Yet microscopic analyses of the implants revealed they had failed because the islets within had clumped together, causing those at the center of the aggregates to starve. That problem was easy to correct—by suspending the islets in gelled alginate within the hollow-fiber vessel. Implants put into the abdominal cavity or under the skin then maintained normal blood sugar levels throughout a year of observation (half of a mouse lifetime). Equally important, the mice tolerated the implants well, generating little fibrous tissue around the outer surface of the fine plastic

PAUL E. LACY

HUMAN ISLET (*sphere*) in a hollow fiber was kept under the skin of a diabetic patient for two weeks before being removed and examined. The islet retained its ability to secrete insulin—an indication that such fibers, or similar ones that store islets more compactly, can protect islets implanted in patients.

tubes. Last year Scharp and I began preliminary tests of the approach in humans. We put fibers carrying a small number of islets—150 to 200—under the skin of subjects with type I and type II diabetes and kept the implants in place for two weeks. Happily, the islets were protected from both immune rejection and autoimmune destruction.

The Next Steps

To date, then, the collected research in animals and patients strongly suggests that encapsulation of islets in a biocompatible membrane should be well tolerated. If enough islets are supplied, they should reverse diabetes, perhaps indefinitely. Technical obstacles remain, however. Most of them relate to the demand that huge numbers of islets be implanted.

For instance, although hollow-fiber membranes store islets with more compactness than can be achieved by encapsulating each islet separately, one would still have to implant several meters of fiber in order to accommodate all the islets required. We are now testing a membrane that is made of similar material but is flatter and so enables us to pack islets closer together. We estimate that a flat sheet, about the size of one and a half dollar bills, could hold 800,000 islets and be implanted easily in the abdominal cavity. We hope to do a safety test in humans in the near fu-

WILL VAN OVERBEEK

DONALD E. SMITH of Pampa, Tex., received new islets after undergoing his second kidney transplant operation. He has been free of insulin injections for more than 16 months and free to eat whatever he likes without fear that his blood sugar level will fluctuate abnormally. Most patients who have been given new islets have not fared as well, but investigators are optimistic that techniques now under study will eventually make it possible to maintain transplanted islets for a lifetime.

ture. If a way could be found to pack islets even more densely, we might be able to stack two small devices under the skin, where they could be readily retrieved if necessary.

Before any device can be used on a wide scale, physicians will require access to a plentiful supply of islets. Human pancreases, like other organs, are in short supply from cadavers. Roughly 700,000 Americans have type I diabetes, and more than 13,000 new cases are diagnosed each year. Moreover, about two million type II diabetics are treated with insulin. Yet fewer than 5,000 cadavers provide organs of any kind for transplantation every year, and only approximately 1,000 pancreases are recovered.

To cope with the shortage, some investigators are exploring implantation of islets from aborted fetuses. They are drawn to this solution partly by the prospect that precursor cells able to give rise to islets could be isolated and induced to produce islets in quantity. But research into the use of fetal tissue is preliminary. One day physicians might also be able to implant insulin-making cells alone. The cells could be obtained from beta cell tumors, which generate new cells indefinitely in laboratory dishes. Such tumor cell lines already exist but have lost the ability to modulate the amount of insulin they secrete in response to glucose. Methods to restore that ability, and to ensure that the transplanted beta cells would not spawn tumors in the body, are being explored.

For the immediate future, the logical alternative to human islets is pig islets. Those cells are an attractive option because they are readily available and the insulin they produce is almost identical to that of humans. Further, we and others, anticipating that porcine islets would be useful, have already developed methods for isolating them from vast numbers of pancreases at once. If the islets are hidden from the immune system by encapsulation, transplantation across species should not trigger the rejection that would normally be expected. Human trials of encapsulated pig islets in patients given no immunosuppressants are likely to begin within a year or two.

Transplantation of encapsulated cells may be helpful for other diseases as well, particularly those in which a specific hormone or other substance secreted by cells is missing. The implanted cells could be healthy versions of malfunctional ones or could be of a different type altogether but genetically engineered to make a selected molecule. Hemophiliacs, for instance, should benefit from having cells able to produce the blood-clotting factor they lack, and patients with Parkinson's disease should benefit from having cells that make the neurotransmitter dopamine. It is already known that injection of dopamine improves muscle coordination temporarily in many patients, and studies in animals with experimentally induced Parkinson's disease have yielded a similar benefit when hollow fibers containing dopamine-secreting cells are placed near the diseased area of the brain.

As research into encapsulation of islets progresses, so does investigation of a very different insulin-delivery system: a fully artificial pancreas. A miniaturized mechanical system would continuously monitor blood glucose levels and, in response, release exactly the amount of insulin needed by the individual. The intractable challenge here has been devising a sensor that is at once small, durable and accurate. Undoubtedly this roadblock, like those impeding the way to islet transplantation, will eventually be overcome. In both cases, success will make it possible to achieve perfect blood sugar control from early in the course of diabetes and thus to prevent the complications that devastate too many lives today.

The Author

PAUL E. LACY is professor emeritus of pathology at the Washington University School of Medicine in St. Louis, where he was Robert L. Kroc professor from 1985 until this past April. He received his M.D. from Ohio State University in 1948 and his Ph.D. in pathology from the University of Minnesota in 1955; he joined the faculty of Washington University the following year. Lacy has won a host of awards in his long career and has two annual lecture series named after him: one at the Washington University School of Medicine and one sponsored by the National Diabetes Research Interchange to honor innovative research using human tissue and organs.

Further Reading

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STATUS OF ISLET CELL TRANSPLANTATION. Paul E. Lacy in *Diabetes Care,* Vol. 16, No. 3, pages 76–92; March 1993.

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Light in the Ocean's Midwaters

Beneath the surface of the ocean, sunlight is gradually extinguished, but the resulting darkness yields to a host of bioluminescent creatures

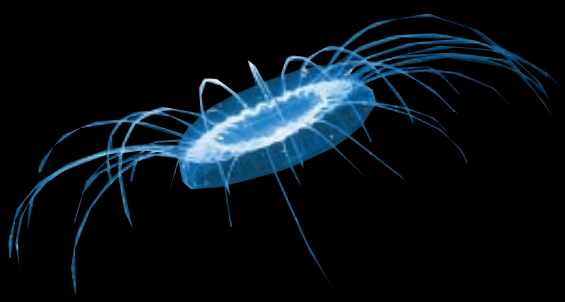
by Bruce H. Robison

HATCHETFISH
Sternoptyx diaphana
(2.5 to 9.0 centimeters)

FANGTOOTH
Anoplogaster cornuta
(15 centimeters)

JELLYFISH
Catablema sp.
(Bell diameter: 4 centimeters)

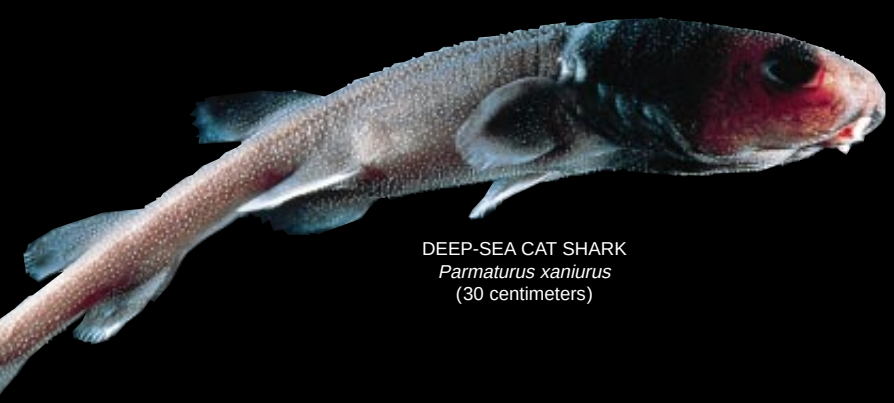
Vampyroteuthis infernalis
(25 centimeters; inverted configuration at right)



NARCOMEDUSA
Solmissus marshalli
(Bell diameter: 15 centimeters)

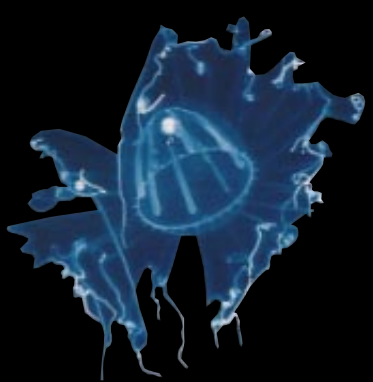
SNIPE EEL
Nemichthys scolopaceus
(1 meter)

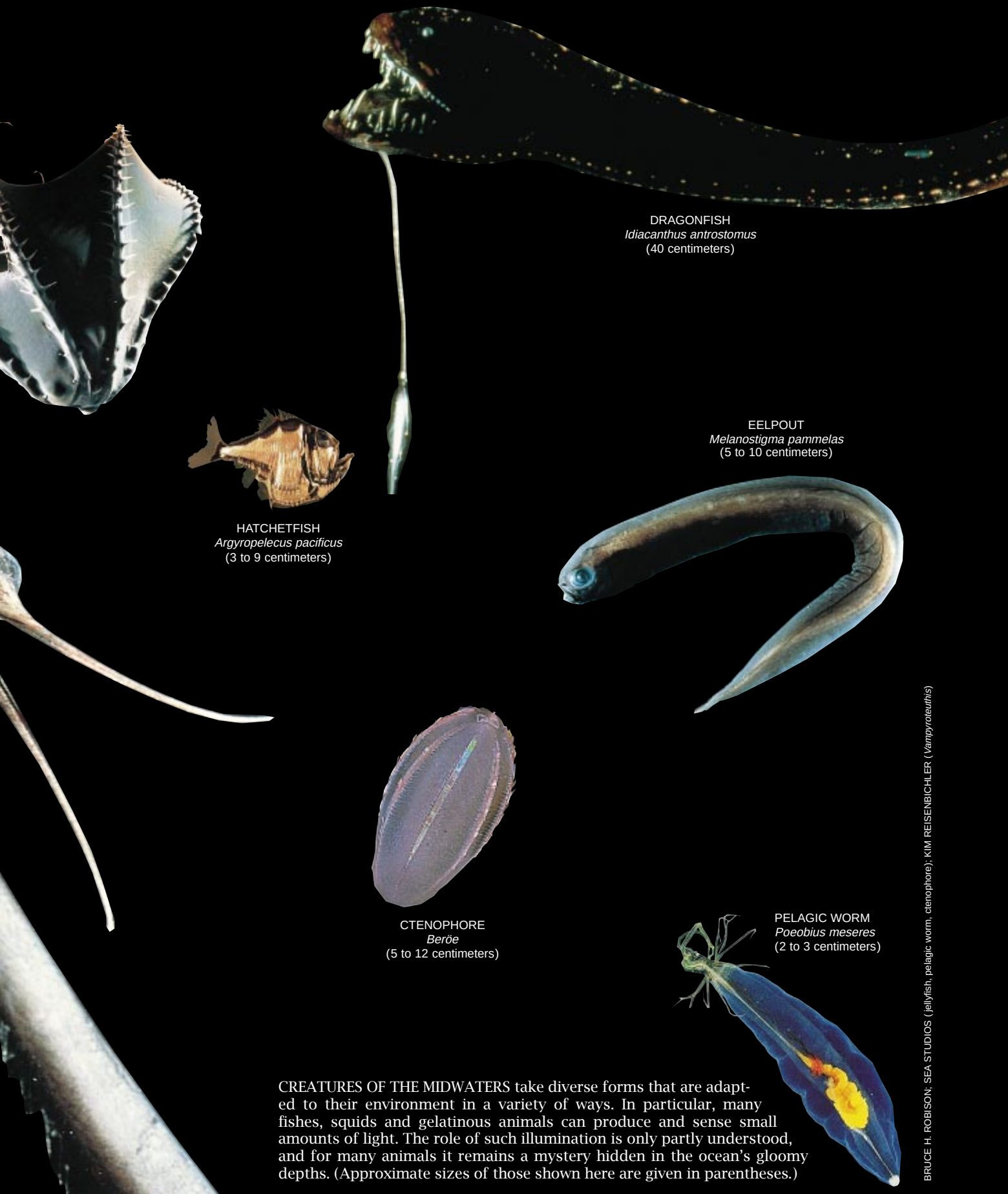
Periphylla periphylla
(Bell diameter: 7 centimeters)



DEEP-SEA CAT SHARK
Parmaturus xaniurus
(30 centimeters)

Colobonema sericeum
(Bell diameter: 2.5 centimeters)





CREATURES OF THE MIDWATERS take diverse forms that are adapted to their environment in a variety of ways. In particular, many fishes, squids and gelatinous animals can produce and sense small amounts of light. The role of such illumination is only partly understood, and for many animals it remains a mystery hidden in the ocean's gloomy depths. (Approximate sizes of those shown here are given in parentheses.)

BRUCE H. ROBISON; SEA STUDIOS (jellyfish, pelagic worm, ctenophore); KIM REISENBICHLER (*Vampyroteuthis*)

The most expansive animal habitat on the earth lies between the sea surface and the floor of the deep ocean basins. Within this enormous volume live the largest and perhaps most remarkable biological communities anywhere. Yet because this region is so foreign to the world of normal human experience, we still know extraordinarily little about its fauna. But the quest to understand the nature and behavior of these unfamiliar organisms has been making steady progress. Over the past few years my colleagues and I at the Monterey Bay Aquarium Research Institute in northern California have been able to explore the ocean below the sunny surface waters and to examine local ecology from the novel perspective that modern oceanographic technology affords. And, as is often the case when one gets to view something from an entirely new vantage point, that undersea world looks very different from what we had imagined.

My studies of the biology of the ocean's midwaters—a zone that reaches from about 100 meters to a few kilometers below the surface—have benefited enormously from countless hours spent on board *Deep Rover,* a one-person research submarine. Less adventurously but just as effectively, my work has also taken advantage of a remotely operated vehicle (or ROV) named *Ventana,* a maneuverable, computerized platform about the size of a small car that is fitted with an arsenal of cameras, instruments, sensors and samplers.

These two underwater vehicles boast capabilities that far surpass the relatively crude tools that supported previous midwater research. During the 1950s, for example, the marine biologist Eric G. Barham of Stanford University also examined the ocean near Monterey Bay, but at that time he was limited to using sonar and trawl nets towed behind a ship to identify and track the movements of midwater fauna. In the course of his pioneering studies he uncovered a rather limited set of animals—shrimps, lanternfish, squids and arrow worms—and determined the broad patterns of their vertical migrations, from depths of around 300 meters during the day, up to the surface layers at night.

But with the primitive technology then available, Barham's early research missed a tremendous amount of detail in the ocean simply because he could not view it directly. With *Deep Rover* and *Ventana* my colleagues and I have found that the ocean's midwaters contain a far greater variety of organisms than Barham could possibly have caught in his nets: some forms of sea life are simply too fragile to be extracted from

Exploring the Midwaters with Camera and Robot

The submersible *Deep Rover* can carry a single occupant to depths in the ocean as great as one kilometer for up to eight hours at a time. The vehicle's transparent passenger housing—constructed from a massive acrylic sphere 160 centimeters in diameter and 13 centimeters thick—offers the pilot panoramic views of the surrounding waters. The pods underneath the sphere contain banks of lead-acid storage batteries that power the vehicle's lights, electric thrusters and hydraulic manipulator arms, as well as its many other pieces of scientific, navigational and life-support equipment.

In contrast to submersibles such as *Deep Rover, Ventana*—a remotely operated vehicle (ROV)—carries no pilot on board. Instead controllers communicate with the underwater robot through a cable attached to *Ventana*'s support ship. Electric power for lights, thrusters and other equipment passes continuously downward through copper conductors within the umbilical tether, and data and video images travel upward, encoded on optical fibers at the core of the cable. Keeping vigil at the monitors of a shipboard console, scientists and pilots control *Ventana*'s movements and can, if need be, maintain the vehicle's subsurface research tasks around the clock.

BRUCE H. ROBISON

DEEP ROVER **submersible vehicle hovers inches above the surface—just before its deployment.**

VENTANA **rises from the sea, lifted by a crane on the support ship (*left*). The front of *Ventana*'s frame supports cameras, sensors, samplers and a mechanical arm (*bottom center*). Pilot and scientist operate the vehicle together from a control room on board the ship (*bottom right*).**

their supportive, watery environment. In many respects, we now think of this delicate marine life as *forming* much of that midwater environment.

Among the larger pieces of biological substratum pervading this region are the bodies of gelatinous animals, along with their extended feeding structures and discarded body parts. The most striking contributions of this kind in Monterey Bay are generated by the elongate siphonophores, linear assemblages that can stretch as much as 40 meters—making them some of the longest creatures on the earth. Whether these animals should be regarded as organized colonies of individuals or as a single, complex superorganism remains unclear. I think of them as living drift nets.

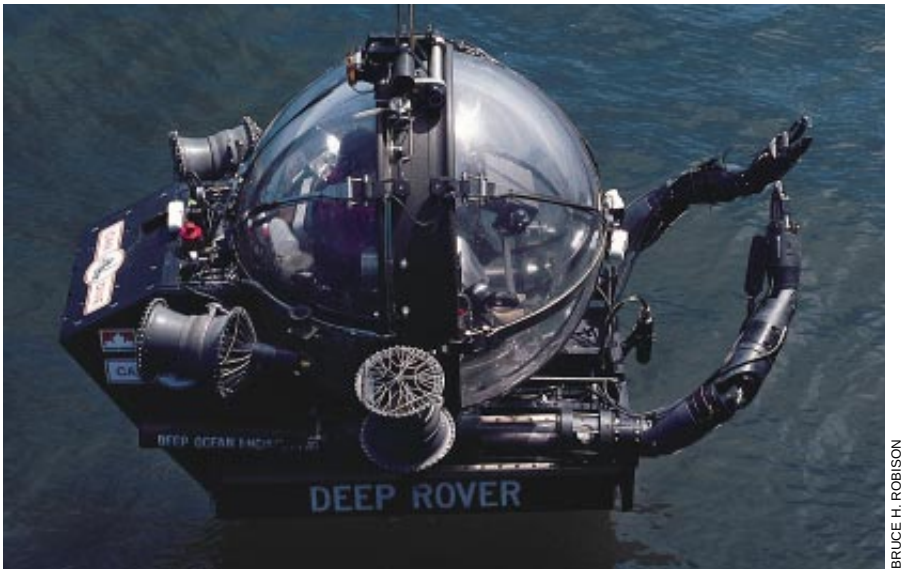
Another part of the biological backdrop common in midwater is composed of the balloonlike feeding filters of animals called appendicularians. The most prominent examples are those produced by the giant form, *Bathochordaeus,* an animal that secretes sheets of mucus that look to an underwater observer like floating islands. Because a multitude of midwater animals regularly cast off feeding structures and other body parts, at times the water can become thick with them.

The best way to visualize the midwater environment might be to imagine a dim, weightless world filled with ragged, three-dimensional spiderwebs. Although my colleagues and I have made a host of surprising discoveries about this wispy realm during our explorations, perhaps the most intriguing result to emerge from these efforts to probe the ocean's darkness has been an appreciation for the role of light.

Life in the Twilight Zone

Marine biologists had for decades believed that sunlight could penetrate perhaps 300 to 400 meters below the surface of the sea before it became too weak to support vision—a belief they held despite their knowledge that fishes and squids with large, highly developed eyes lived at depths below these levels. But now that we have been able to observe denizens of supposedly dark parts of the ocean, it is becoming clear that these animals are in fact influenced by the tiny amount of sunlight that does filter down to their abode.

Not until I was able peer directly into this world could I begin to appreciate what the midwater habitat is really like. Submerged alone in *Deep Rover* more than half a kilometer below the surface, I have often switched off the lights of the submarine and looked out at the blackness that surrounds the vehicle's transparent passenger sphere. After letting my eyes fully adjust, I can perceive only that looking up is somewhat less dark than looking down. Yet it has become clear to marine biologists that a variety of animals must utilize this subtle difference. Moreover, we have be-



BRUCE H. ROBISON

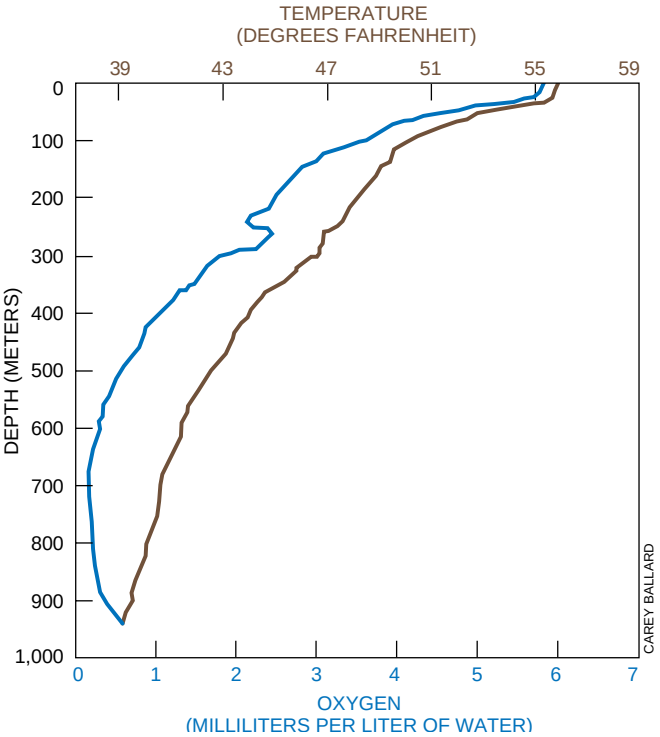

BRUCE H. ROBISON


MONTEREY BAY AQUARIUM RESEARCH INSTITUTE

The ROV carries both a black-and-white and a broadcast-quality color video camera. In addition to the two cameras and the powerful video lights, shipboard controllers can employ a scanning sonar system to "peer" into the vehicle's surroundings using high-frequency sound waves. Guided by these devices, scientists are able to make measurements and perform experiments using a variety of special-purpose hardware. These instruments include dye injectors (to track subtle currents), a transmissometer (to measure optical clarity) and a structured light array (to map the density of particulates). The ROV's operators can also capture and recover objects of interest with several types of apparatus. Four detritus samplers, for example, easily encase small but delicate specimens, and a suction sampler is able to draw extended gelatinous animals into the vehicle.

A new ROV called *Tiburon* (Spanish for shark) now under construction at the Monterey Bay Aquarium Research Institute in California should prove even more capable than *Ventana.* Engineers at the institute are also designing and building prototypes of autonomous underwater vehicles. In years to come, these mobile robots will be able to carry out research missions of long duration without the need for a constant human presence—or telepresence—as is now required for operations with *Deep Rover* and *Ventana.*

MARSH YOUNGBLUTH *Harbor Branch Oceanographic Institution*



SIPHONOPHORE deploys an intricate array of tentacles (*above*). If unsuccessful in catching prey, this creature remains in place for only a few minutes before hauling in its elaborate fishing gear and moving to another position. Most animals of the midwaters move effortlessly in three dimensions, but few venture into the anoxic zone near a depth of 700 meters, where oxygen concentration falls to a minimum (*right*).

come keenly aware that most creatures of this twilight world are able to augment the scant sunlight reaching them with another form of natural illumination, bioluminescence.

Although bioluminescence is a relatively rare phenomenon in terrestrial ecosystems, the vast majority of the animals that inhabit the upper kilometer of the ocean are capable of producing light in one way or another. Moreover, much of the particulate matter and biological detritus that floats suspended in these waters will glow after it is physically disturbed. These effects can interrupt the normal blackness of the deep ocean with an eerie light.

Midwater animals employ bioluminescence in myriad ways. Some use it as a burglar alarm, coating an advancing predator with sticky, glowing tissue that makes the would-be attacker vulnerable to other visually cued hunters—like bank robbers marked by exploding dye packets hidden in stolen currency. Others use bioluminescence as camouflage. The glow generated by light-producing organs, called photophores, on the undersides of some fishes and squids acts to countershade them: the weak downward lighting effectively erases the shadow cast when the animal is viewed from below against lighted waters above.

The midwater squids *Chiroteuthis* and *Galiteuthis,* for example, clearly demonstrate this use of bioluminescence. Their bodies are transparent except for their dense eyes and ink gland. Ornate light organs arrayed underneath these opaque structures shine downward to countershade them, whatever the position of the squid—head up, head down, inverted or upright. I have found it a bit unnerving to stare eyeball to eyeball with a creature that can pivot its body around a rigid eye that neither blinks nor changes orientation.

Although marine biologists have been able to understand the usefulness of countershading, other examples of bioluminescence have long eluded our logic. One such enigma is a newly discovered species of tomopterid worm, an active, agile swimmer that has a multitude of paired legs along its tapered body. From specimens caught with nets, biologists have known that some species have structured light organs at the ends of their legs, but only last year James C. Hunt of the University of California at Los Angeles (as well as the Monterey Bay Aquarium Research Institute) and I found a new form of bioluminescent display in a tomopterid that has pigmented pores in roughly the same location as typical leg photophores. This species is a "spewer": when stimulated, it squirts a bioluminescent fluid from each of its leg pores. The discharge forms a luminous cloud that can completely enshroud the body of the worm or leave a glowing trail as it races away. A thimbleful of the ejected fluid contains hundreds of tiny rods that glow brightly yellow. Other types of spewers are known; their strategy may be to cause a visual distraction. But this species remains puzzling. What is the purpose of the display? Why are the tiny light sources rod-shaped? Why is the light given off colored yellow when most midwater animals have eyes that are sensitive only to blue-green?

Another mysterious application of bioluminescence involves much of the suspended particulate matter and most of the larger gelatinous animals living in midwater: they produce light when stimulated mechanically. "Contact flashing" can happen throughout a large volume of this otherwise dim habitat. Most of the time, the surroundings remain tranquil, with abundant flashers at rest in the dark. But the disturbance of driving *Deep Rover* through these depths of the ocean can trigger a barrage of exploding lights. The scene underwater can quickly begin to resemble something out of a *Star Wars* movie.

The natural movements of animals can also cause the ambient biological lighting to turn itself on, and such bioluminescent responses, when they occur on a large scale, can lead to one of the most remarkable sights in midwaters: a propagated display. This phenomenon starts with local motion triggering contact flashers to fire; these bursts then elicit further flashes like an echo through the adjacent water. Previously poised animals begin moving when the background begins to glow, and their wakes in turn stir up even more light. If contact flashing occurs within a layer of dense particles, the cumulative effect of this bioluminescent

activity can look like heat lightning rippling through a cloudy summer night. Whatever the motivation for contact flashing among simpler organisms, more highly developed animals of the midwater region seem well adapted to the situation.

Midwater Attackers

Fish such as hake, as well as some squids, are fast-moving, wide-ranging predators, but they often linger near *Ventana,* attracted to the lights of the ROV. It may be that they misinterpret the illuminated waters as an indication that moving prey are present. Perhaps they are conditioned by the daily excursions of sunlight-shunning species that venture near the surface only at night. Such vertical migrations must be light-provoking events, as these animals pass through resident layers of contact flashers. But the potential for movement-induced bioluminescence probably inhibits overall activity, keeping the midwater environment relatively static. Avoiding unnecessary light shows that would give away their position may be the reason mobile animals seem often to remain "parked" in one position much of the time.

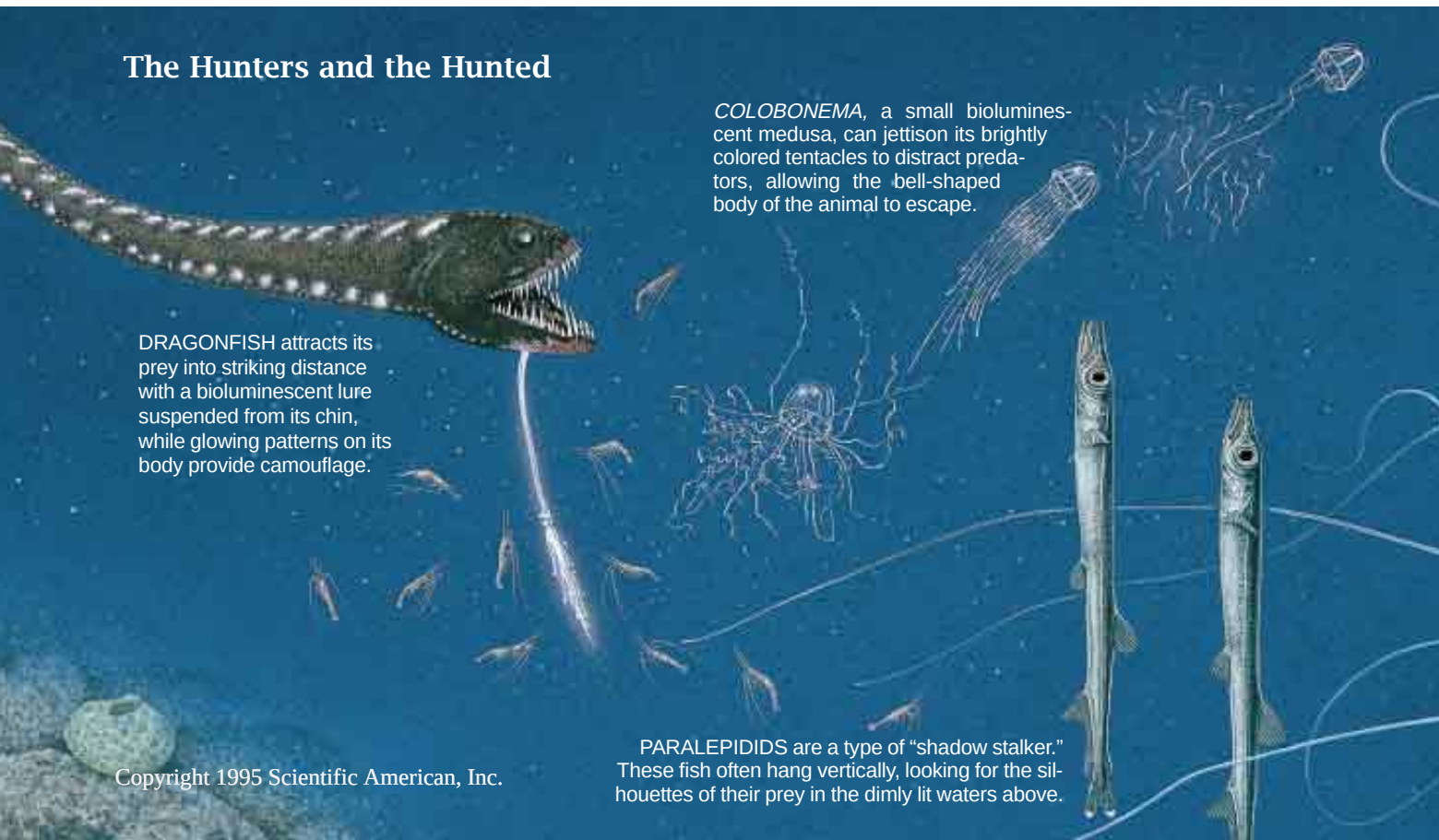
Even some predators stay largely motionless. For instance, paralepidids—slender, speedy fish with bodies that look as though they are made of quicksilver—spend the daylight hours standing on their tails, with their sharp snouts thrust upward and their large eyes staring into the waters above. My colleagues and I believe they are searching for silhouettes of their prey against the weakly luminous backdrop. The hatchetfish *Argyropelecus* is another shadow stalker; it has a heavy keel to keep its body horizontal and to stabilize a pair of tubular eyes positioned on top of its body so that its view remains directed upward. *Argyropelecus* lives between about 300 and 600 meters below the surface, where the sunlight must be sufficient to cast perceptible shadows. But a close relative, *Sternoptyx,* lives at depths too great to employ this tactic and has smaller, normally shaped eyes aimed out to the sides.

Further evidence indicates that the weak sunlight of the midwaters is strong enough to guide predators: a diversity of animals living at these depths are transparent. Such a form of appearance (or rather, disappearance) is good protection in this monochromatic, low-light environment. Another optical defense mechanism is red body pigment; this color absorbs the available blue-green light and reflects nothing, a kind of "visual stealth" strategy.

It is not surprising that such optical ploys can work effectively. The visual regime in the midwaters is a bit like the scene from a low-light video surveillance camera. The range of color is narrow; sensitivity is high, but resolution is low; and the directionality of light imparts a flatness to perceptions. To the unaided human eye, the visual field amounts to a coarse pattern of silhouettes and shadows. Within this light-limited milieu there appear to be only four basic shapes: streaks, blobs, strings and spots. Each of these phantoms characterizes a certain kind of subject. Streaks correspond to fishes and squids. Rounded or amorphous blobs are usually gelatinous creatures such as medusae and ctenophores or the weblike feeding structures built from mucus by appendicularians. Stringy material is typically sinking mucus or the tails of siphonophores. Spots can be tiny zooplankton or particles of diffuse organic matter called marine snow.

Within this framework we see a common behavior pattern employed by a variety of creatures. When startled or threatened, some animals change their apparent shape, usually from elongate to rounded. Fishes such as eelpouts curl up into circles and hang motionless in the water. I believe this behavior is a form of mimicry: the animals adjust their appearance to resemble unpalatable objects. From *Deep Rover* I have seen hake strike at fleeing fish while ignoring those that had curled up nearby. The balled-up fish probably resembled medusae—creatures of relatively low nutritional value that deter predators with stinging tentacles. Not all marine biologists agree with this hypothe-

The Hunters and the Hunted



COLOBONEMA, a small bioluminescent medusa, can jettison its brightly colored tentacles to distract predators, allowing the bell-shaped body of the animal to escape.

DRAGONFISH attracts its prey into striking distance with a bioluminescent lure suspended from its chin, while glowing patterns on its body provide camouflage.

PARALEPIDIDS are a type of "shadow stalker." These fish often hang vertically, looking for the silhouettes of their prey in the dimly lit waters above.

sis, but the observation that this behavior is rarely seen at greater depths (where there is insufficient light for the formation of even rough images) supports the argument for the utility of shape-changing. Such behavior has certainly fooled me at times.

Light for the Blind

Most gelatinous animals, such as medusae, lack eyes and thus cannot form images of any kind. Yet some of these creatures are clearly sensitive to the lights of *Ventana,* even at a distance, showing a mild dislike for the brightness. My colleagues and I are accumulating evidence that suggests this sensitivity to light may regulate the animal's depth during the day. Changing light levels are known to control the morning and evening migrations of fishes and krill, and it would now seem possible that even eyeless creatures may somehow perceive the sun's presence above them.

We documented one example of such light sensitivity during an encounter with an animal called *Bathyphysa.* This bizarre creature, which is about two meters long, has appeared in front of *Ventana*'s cameras only once, while the vehicle was cruising 500 meters below the surface. When the ROV approached it, the stem of the animal was vertical, with its gas-filled "pneumatophore" uppermost. The stem of the *Bathyphysa* had a mane of elongate, serial stomachs (so-called gastrozooids), each with a probing mouth at its end, and all were writhing like snakes. Several five- to 10-meter-long feeding tentacles radiated out from a round, contracted part of the stem at its center. The stem was exceptionally elastic, a trait that seemed to be explained when we discovered the animal's escape response. Sensing the lights of the ROV, this creature began a series of pounding contractions and relaxations of the upper stem that had the effect of driving the animal downward. In concert with these pulsations, gastrozooids were cast off and left to drift away, one at a time. The result was a determined descent, although a fairly slow and taxing one.

Such episodes suggest that eyeless creatures might well be able to sense even low-level light. In any case, it is clear that they can generate it. *Colobonema,* for example, is a beautifully iridescent little medusa that has a "bell" that is about the size of a coin. In the lights of the ROV, muscle bands in the bell have a blue-green metallic sheen. The medusa's tentacles show a deep blue along their length and brilliant white at the tips.

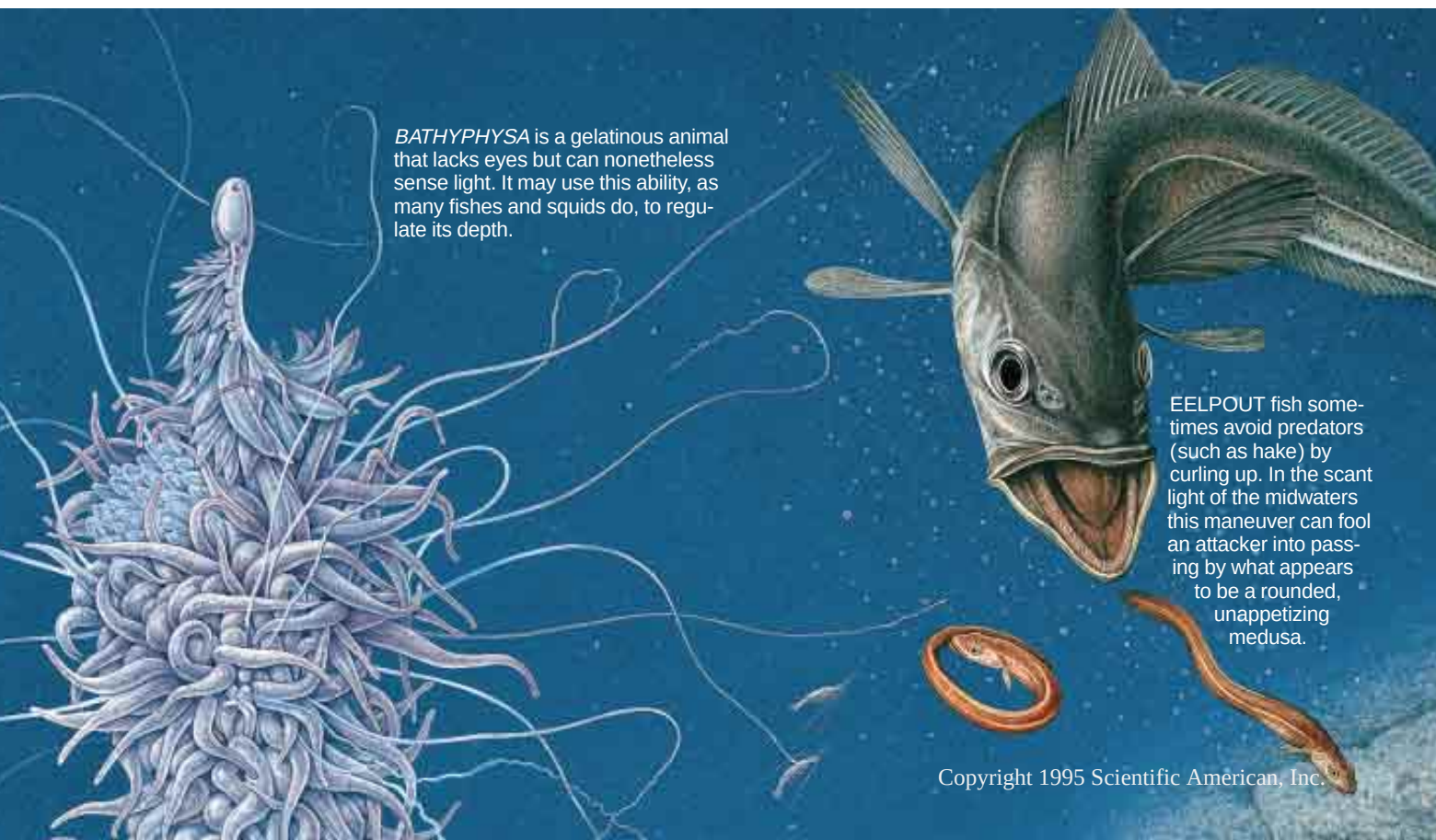
A fully developed individual has 32 tentacles arrayed uniformly around the base of the bell. Often, however, specimens show fewer appendages set in tiers of different lengths. This appearance is perhaps explained by the animal's behavior: when startled, *Colobonema* darts away, leaving a group of bright, swirling tentacles in its wake. From *Deep Rover* I have observed that the release is occasionally preceded by ripples of luminescence pulsing rapidly through the bell. The many tentacles are then dropped as the bell goes dark and zigzags away into the surrounding blackness.

Occupants of the Oxygen Minimum

One of the characteristic features of the Pacific Ocean near Monterey Bay is a zone that is depleted in dissolved oxygen. Just below the sea surface, oxygen concentrations are close to saturation (that is, the water holds as much oxygen as can possibly be dissolved), but deeper in the ocean, oxygen content diminishes. At about 700 meters of depth, oxygen concentration falls to a value that is only one thirtieth of that near the surface. Below this level is a sharp transition from relatively clear water to a milky layer of very small particles. The milky layer shows a moderate amount of oxygen, and at 1,000 meters the concentration rises further. Within the zone of lowest oxygen near 700 meters resides a unique group of animals that have adapted to meet the physiological challenges of near-anoxia.

One of the most curious inhabitants of the oxygen minimum is the archaic

ROBERTO OSTI



BATHYPHYSA is a gelatinous animal that lacks eyes but can nonetheless sense light. It may use this ability, as many fishes and squids do, to regulate its depth.

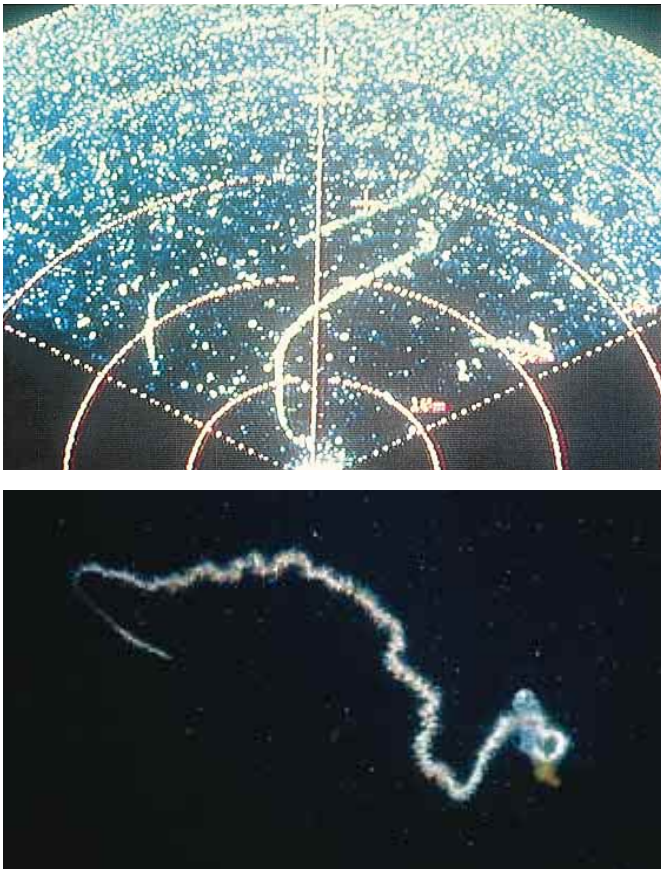
EELPOUT fish sometimes avoid predators (such as hake) by curling up. In the scant light of the midwaters this maneuver can fool an attacker into passing by what appears to be a rounded, unappetizing medusa.

cephalopod *Vampyroteuthis infernalis,* a distant cousin to octopus and squid. A big *Vampyroteuthis* has the size and shape of a soft football. Its body is velvety brown with large eyes that glow like blue opals in the ROV lights. Near the tip of the stubby, conical mantle are two rounded fins and two large light organs with irislike shutters. *Vampyroteuthis* has eight arms like an octopus, but they support a broad web between them. In addition to having suckers, the arms bear a series of paired, fingerlike protrusions, called cirri, that project inward. *Vampyroteuthis* also has two additional appendages: long, elastic sensory filaments that withdraw into pockets between the third and fourth arms on each side.

This creature can be regarded as a living fossil, a modern-day representative of the cephalopods that preceded the evolutionary split into eight- and 10-armed groups. *Vampyroteuthis* propels itself with jets of water expelled from its siphon and by flapping its stubby fins. At the center of the webbed arms is a dark, hooked beak. We do not yet know what this animal eats, but it substantially reduces its own chances of being consumed by living in an inhospitable, anoxic part of the ocean.

My colleagues and I have discovered that this strange animal has a bioluminescent organ at the tip of each of its arms. *Vampyroteuthis* somehow uses these light sources by swinging its webbed arms upward and over the mantle, which turns the suckers and cirri outward and changes the animal's likeness from a football into a spiky pineapple with a glowing top.

This maneuver covers the animal's eyes, but the webbing between tentacles is apparently thin enough for it to see through. We have observed this transformation frequently but remain at a loss to explain exactly what function this unusual behavior might serve.



MONTEREY BAY AQUARIUM RESEARCH INSTITUTE

***APOLEMIA*, an elongate gelatinous creature (*bottom*), may be regarded as either a colonial animal or a superorganism. A sonar scan of such "living drift nets" (*top*) has semicircular reference lines at 10-meter increments and shows that some of these organisms can extend up to 40 meters, making them among the longest animals known.**

Technology-Driven Exploration

The present length of *Ventana*'s umbilical tether has permitted us to explore a volume of water one kilometer deep with a visual resolution that extends from about one centimeter to several hundred meters. Although this span covers the ranges of a large portion of the region's midwater species, there are still many measurements we cannot yet make. But this situation is changing. Future technical development by engineers at our institute should allow us to probe even deeper. Soon new optical and acoustic sensing systems will let us examine larger volumes from greater distances and so allow us to assess the distribution of midwater animals even more thoroughly.

We expect eventually to have autonomous probes that will leave time-lapse cameras in place so that we can track slowly moving animals around the clock for days at a time. Fast-swimming robotic vehicles will follow mobile animals, allowing us better to observe their feeding and migration patterns. The possibilities for investigation seem endless. Hence, despite the numerous discoveries already made, we must consider our undersea investigations to have just begun—the ocean's depths are so vast, and there is so much more to explore.

The Author

BRUCE H. ROBISON developed his curiosity about the ocean early, growing up on the beach in southern California. After receiving a B.S. from Purdue University and an M.A. from the Virginia Institute of Marine Science, he returned to his home state to attend Stanford University, where he completed a Ph.D. degree in 1973. Robison then spent two years in postdoctoral training at the Woods Hole Oceanographic Institution in Massachusetts before taking a position at the University of California, Santa Barbara. In 1987 he joined the fledgling Monterey Bay Aquarium Research Institute in Pacific Grove, Calif., where he is currently a senior scientist and science department chair. Robison's research in deep-sea ecology has carried him throughout the Pacific, to the Atlantic and to the great Southern Ocean surrounding Antarctica. He led the first team of scientists trained as submersible pilots and has long been active in promoting advanced undersea vehicles for oceanographic research.

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The Trebuchet

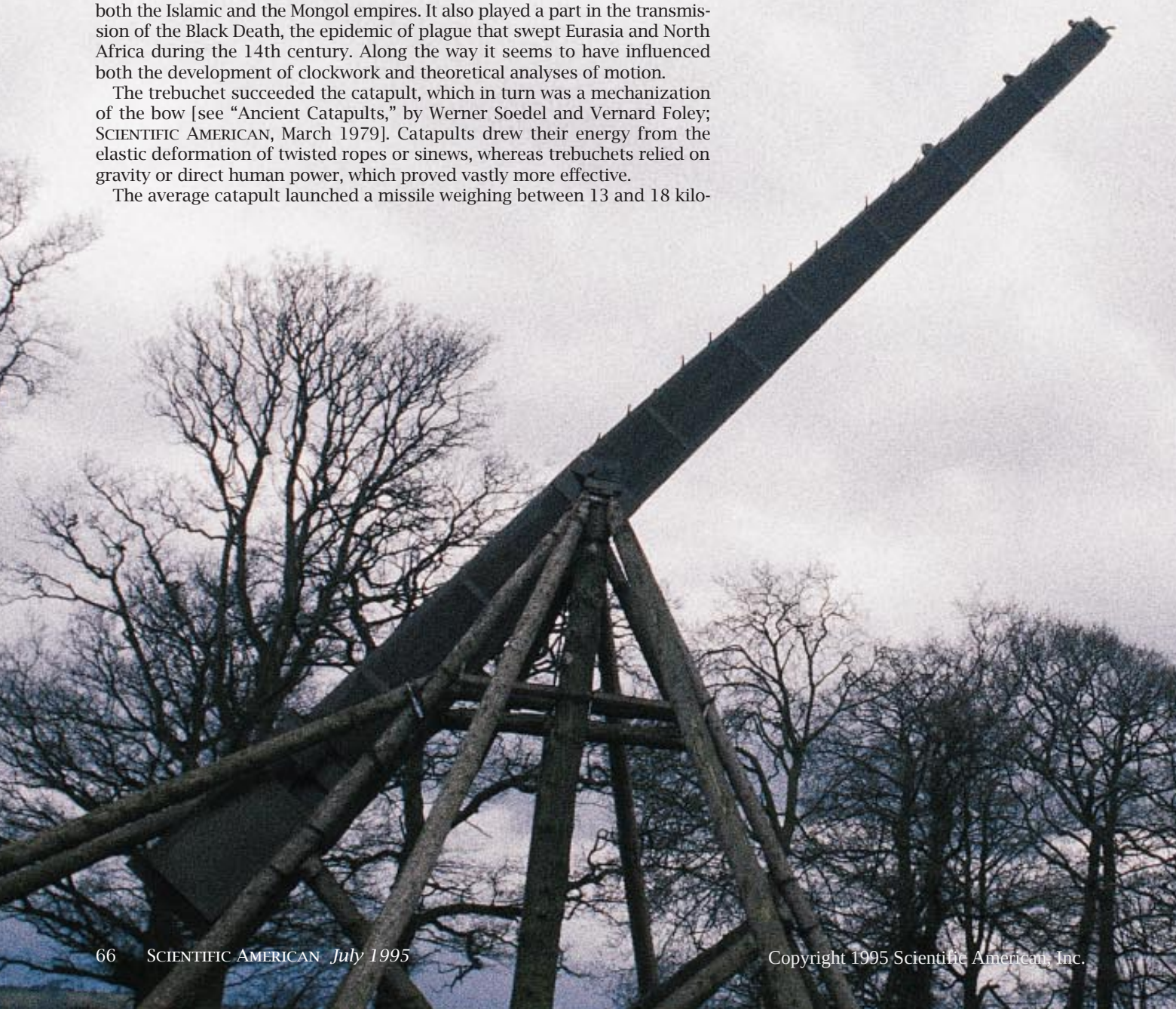
Recent reconstructions and computer simulations reveal the operating principles of the most powerful weapon of its time

by Paul E. Chevedden, Les Eigenbrod, Vernard Foley and Werner Soedel

Centuries before the development of effective cannons, huge artillery pieces were demolishing castle walls with projectiles the weight of an upright piano. The trebuchet, invented in China between the fifth and third centuries B.C.E., reached the Mediterranean by the sixth century C.E. It displaced other forms of artillery and held its own until well after the coming of gunpowder. The trebuchet was instrumental in the rapid expansion of both the Islamic and the Mongol empires. It also played a part in the transmission of the Black Death, the epidemic of plague that swept Eurasia and North Africa during the 14th century. Along the way it seems to have influenced both the development of clockwork and theoretical analyses of motion.

The trebuchet succeeded the catapult, which in turn was a mechanization of the bow [see "Ancient Catapults," by Werner Soedel and Vernard Foley; SCIENTIFIC AMERICAN, March 1979]. Catapults drew their energy from the elastic deformation of twisted ropes or sinews, whereas trebuchets relied on gravity or direct human power, which proved vastly more effective.

The average catapult launched a missile weighing between 13 and 18 kilo-



grams, and the most commonly used heavy catapults had a capacity of 27 kilograms. According to Philo of Byzantium, however, even these machines could not inflict much damage on walls at a distance of 160 meters. The most powerful trebuchets, in contrast, could launch missiles weighing a ton or more. Furthermore, their maximum range could exceed that of ancient artillery.

Recovering Lost Knowledge

We have only recently begun to reconstruct the history and operating principles of the trebuchet. Scholars as yet have made no comprehensive effort to examine all the available evidence. In particular, Islamic technical literature has been neglected. The most important surviving technical treatise on these machines is *Kitab aniq fi al-manajaniq* (*An Elegant Book on Trebuchets*), written in 1462 C.E. by Yusuf ibn Urunbugha al-Zaradkash. One of the most profusely illustrated Arabic manuscripts ever produced, it provides detailed construction and operating information. These writings are particularly significant because they offer a unique insight into the applied mechanics of premodern societies.

We have made scale models and computer simulations that have taught us a great deal about the trebuchet's operation. As a result, we believe we have uncovered design principles essentially lost since the Middle Ages. In addition, we have found historical materials that push back the date of the trebuchet's spread and reveal its crucial role in medieval warfare.

Historians had previously assumed that the diffusion of trebuchets westward from China occurred too late to affect the initial phase of the Islamic conquests, from 624 to 656. Recent work by one of us (Chevedden), however, shows that trebuchets reached the eastern Mediterranean by the late 500s, were known in Arabia and were used with great effect by Islamic armies. The

MODERN RECONSTRUCTION of a medieval siege engine hurls a piano across the English countryside. This trebuchet, patterned after ones used in Europe and the Middle East, has lofted objects weighing as much as 500 kilograms. Its largest forebears could toss more than a ton. (The 60-foot-high reconstruction was built in Shropshire by Hew Kennedy and Richard Barr.)

GUGLIELMO GALVIN

technological sophistication for which Islam later became known was already manifest.

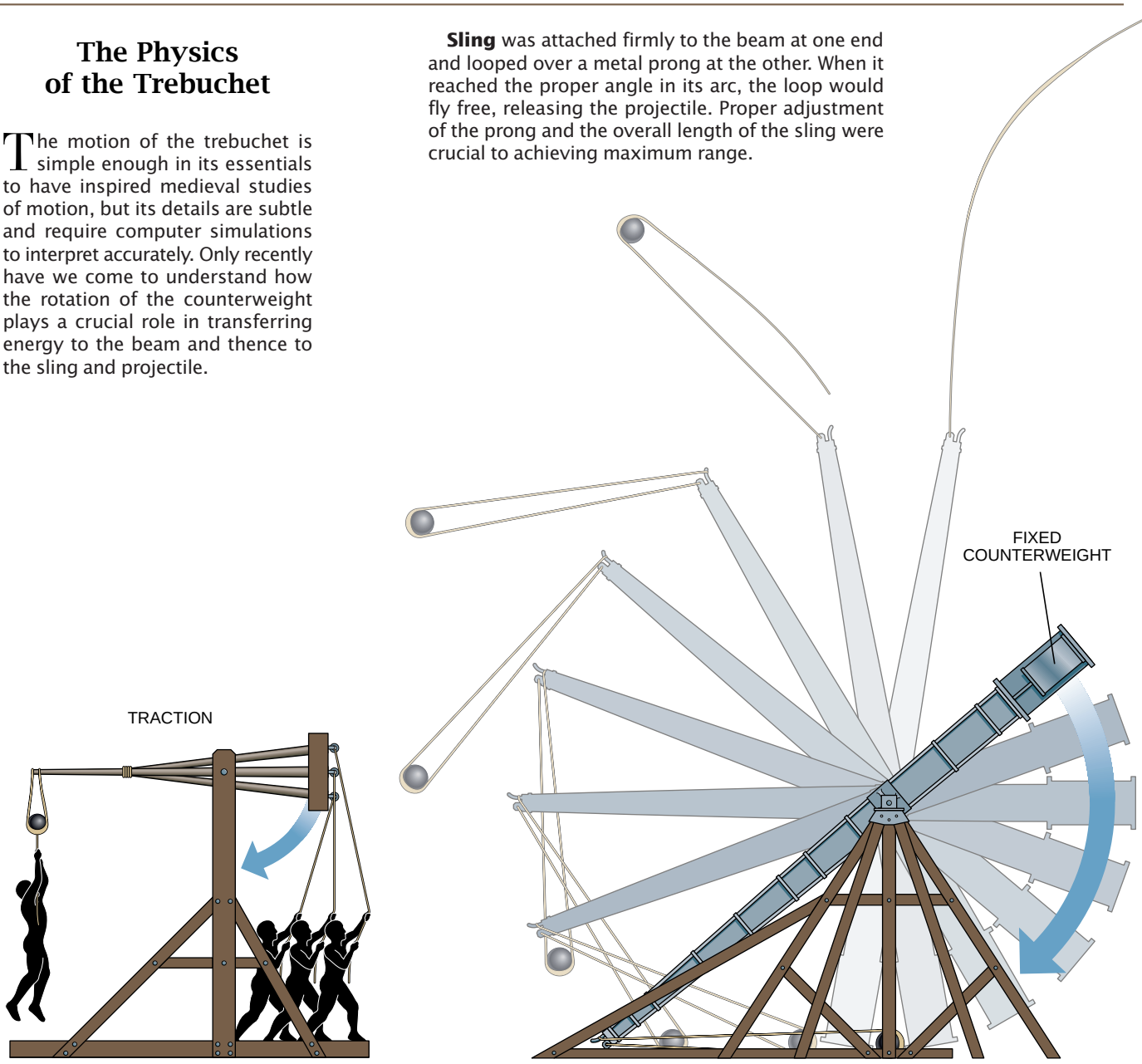
The Mongol conquests, the largest in human history, also owed something to this weapon. As a cavalry nation, the Mongols employed Chinese and Muslim engineers to build and operate trebuchets for their sieges. At the investment of Kaffa in the Crimea in 1345–46, the trebuchet's contribution to biological warfare had perhaps its most devastating impact. As Mongol forces besieged this Genoese outpost on the Crimean peninsula, the Black Death swept through their ranks. Diseased corpses were then hurled into the city, and from Kaffa the Black Death spread to the Mediterranean ports of Europe via Genoese merchants.

The trebuchet came to shape defensive as well as offensive tactics. Engineers thickened walls to withstand the new artillery and redesigned fortifications to employ trebuchets against attackers. Architects working under al-Adil (1196–1218), Saladin's brother and successor, introduced a defensive system that used gravity-powered trebuchets mounted on the platforms of towers to prevent enemy artillery from coming within effective range. These towers, designed primarily as artillery emplace-

The Physics of the Trebuchet

The motion of the trebuchet is simple enough in its essentials to have inspired medieval studies of motion, but its details are subtle and require computer simulations to interpret accurately. Only recently have we come to understand how the rotation of the counterweight plays a crucial role in transferring energy to the beam and thence to the sling and projectile.

Sling was attached firmly to the beam at one end and looped over a metal prong at the other. When it reached the proper angle in its arc, the loop would fly free, releasing the projectile. Proper adjustment of the prong and the overall length of the sling were crucial to achieving maximum range.



Earliest trebuchets were powered by crews pulling on ropes rather than by counterweights. Crews of as many as 250 men pulled to send projectiles 100 meters or more. In this example of a small traction machine, the sling-holder's weight flexed the beam and increased the range.

Addition of counterweights increased the power of the trebuchet. The elimination of the pulling ropes made possible another innovation: by placing a trough under the trebuchet beam to hold the projectile, engineers could lengthen the sling and increase the range even further. The sling rotates faster after the shot is airborne, so its length controls the launch angle.

ments, took on enormous proportions to accommodate the larger trebuchets, and castles were transformed from walled enclosures with a few small towers into clusters of large towers joined by short stretches of curtain walls. The towers on the citadels of Damascus, Cairo and Bosra are massive structures, as large as 30 meters square.

Simple but Devastating

The principle of the trebuchet was straightforward. The weapon consisted of a beam that pivoted around an axle that divided the beam into a long and short arm. The longer arm terminated in a cup or sling for hurling the missile, and the shorter one in an attachment for pulling ropes or a counterweight. When the device was positioned for launch, the short arm was aloft; when the beam was released, the long end swung upward, hurling the missile from the sling.

Three major forms developed: traction machines, powered by crews pulling on ropes; counterweight machines, activated by the fall of large masses; and hybrid forms that employed both gravity and human power. When traction machines first appeared in the Mediterranean world at the end of the sixth century, their capabilities were so far superior to those of earlier artillery that they were said to hurl "mountains and hills." The most powerful hybrid machines could launch shot about three to six times as heavy as that of the most commonly used large catapults. In addition, they could discharge significantly more missiles in a given time.

Counterweight machines went much further. The box for the weight might be the size of a peasant's hut and contain tens of thousands of kilograms. The projectile on the other end of the arm might weigh between 200 and 300 kilograms, and a few trebuchets reportedly threw stones weighing between 900 and 1,360 kilograms. With such increased capability, even dead horses or bundled humans could be flung. A modern reconstruction made in England has tossed a compact car (476 kilograms without its engine) 80 meters using a 30-ton counterweight.

During their heyday, trebuchets received much attention from engineers—indeed, the very word "engineering" is intimately related to them. In Latin and the European vernaculars, a common term for trebuchet was "engine" (from *ingenium,* "an ingenious contrivance"), and those who designed, made and used them were called ingeniators.

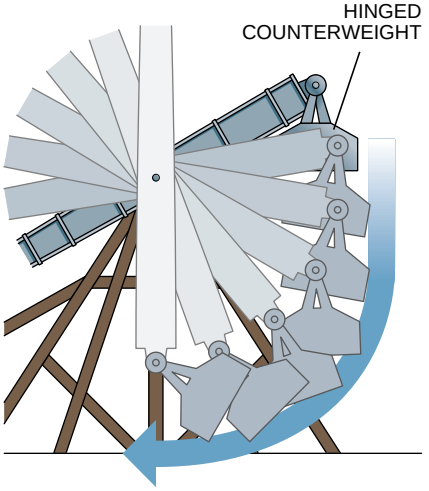
Engineers modified the early designs to increase range by extracting the most possible energy from the falling counterweight and to increase accuracy by minimizing recoil. The first difference between counterweight machines and their traction forebears is that the sling on the end of the arm is much longer. This change affects performance dramatically by increasing the effective length of the throwing arm. It also opens the way for a series of additional improvements by making the angle at which the missile is released largely independent of the angle of the arm. By varying the length of the sling ropes, engineers could ensure that shot left the machine at an angle of about 45 degrees to the vertical, which produces the longest trajectory.

At the same time, so that more of the weight's potential energy converts to motion, the sling should open only when the arm has reached an approximately vertical position (with the counterweight near the bottom of its travel). Observations of the trebuchet may have aided the emergence of important medieval insights into the forces associated with moving bodies.

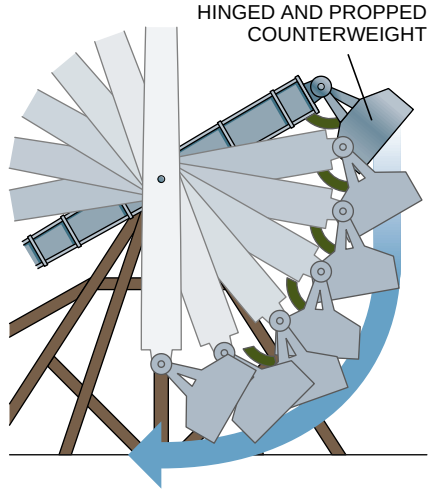
Swinging Free

The next crucial innovation was the development of the hinged counterweight. During the cocking process, the boxes of hinged counterweight machines hang directly below the hinge, at an angle to the arm; when the arm of the trebuchet is released, the hinge straightens out. As a result of this motion, the counterweight's distance from the pivot point, and thus its mechanical advantage, varies throughout the cycle.

The hinge significantly increases the amount of energy that can be delivered through the beam to the projectile. Medieval engineers observed that hinged



Hinged counterweight machines added yet another increment to the range by improving the efficiency with which the trebuchet converted gravitational energy to projectile motion. The center of gravity of the weight fell straight down during the first phase of acceleration; as the hinge straightened, the rotation of the weight around its center of gravity added to the energy transferred. Continued rotation helped to slow the beam as the projectile was released, reducing strain on the mechanism. The smoothness of the trebuchet's action meant it did not have to be repositioned after each shot and so could discharge more missiles in a given time.



Propped counterweights allowed engineers to squeeze even more energy out of the counterweight. By propping up the counterweight at an angle before firing, they gave it slightly farther to fall. This innovation also increased the distance between the center of gravity of the counterweight and the pivot around which the trebuchet beam rotated.

—Vernard Foley

JARED SCHNEIDMAN DESIGN

COURTESY OF PAUL E. CHEVEDDEN

CAIRO CITADEL (*top*) was remodeled at the turn of the 13th century to accommodate the most powerful trebuchets then in use, the counterweight machines. The earlier wall, with its small, half-round towers (*foreground of picture, blue circles on plan*), was augmented by a series of much more massive towers (*red*) that supported counterweight machines used to prevent enemy artillery from getting within range. An illustration from *An Elegant Book on Trebuchets* (*bottom left*) shows both a counterweight trebuchet and a traction machine mounted on the top of a tower.

IAN WORPOLE. SOURCE: K.A.C. CRESWELL

TOPKAPI PALACE MUSEUM *Istanbul*

counterweight machines, all else being equal, would throw their projectiles farther than would fixed-weight ones. Our computer simulations indicate that hinged counterweight machines delivered about 70 percent of their energy to the projectile. They lose some energy after the hinge has opened fully, when the beam begins to pull the counterweight sideways.

Although it exacts a small cost, this swinging of the counterweight has a significant braking effect on the rotating beam. Together with the transfer of energy to the sling as it lifts off and turns about the beam, the braking can bring the beam nearly to a stop as it comes upright. The deceleration eases the strain on the machine's framework just as the missile departs. As a result, the frame is less likely to slide or bounce. Some pieces of classical-era artillery, such as the onager, were notorious for bucking and had to be mounted on special compressible platforms. The much gentler release of the trebuchet meant that engineers did not have to reposition the frame between shots and so could shoot more rapidly and accurately. A machine of medium size built by the Museum of Falsters Minder in Denmark has proved capable of grouping its shots, at a range of 180 meters, within a six-meter square.

Capturing the Trebuchet's Lessons

Later engineers attempted to capture the great power that trebuchets represented. Some of these efforts are made visible in historical records by the proliferation of counterweight boxes in the form of the mathematical curve called the saltcellar, or salinon. The counterweight boxes of the more elaborate trebuchets took this shape because it concentrated the mass at the farthest distance from the hinge and also reduced the clearance necessary between the counterweight and the

frame. The same form reappeared on later machines that incorporated pendulums, such as pendulum-driven saws and other tools.

Most attempts to extend the trebuchet's principles failed because the counterweight's power could not be harnessed efficiently. Success came only in timekeeping, where it was not the trebuchet's great force but rather its regular motion that engineers sought. Pendulums were a dramatic step forward in accuracy from earlier controller mechanisms.

Although the pendulum is usually associated with the time of Galileo and Christiaan Huygens, evidence for pendulum controllers can be traced back to a family of Italian clockmakers to whom Leonardo da Vinci was close. Indeed, da Vinci explicitly says some of his designs can be used for telling time. His drawings include a hinge between the pendulum shaft and bob, just as advanced trebuchets hinged their counterweights, and show notable formal resemblances to fixed counterweight machines as well. In the case of earlier clockwork, there is a marked similarity both in form and in motion between the saltcellar counterweight and a speed controller called the strob. The strob oscillates about its shaft just as the counterweight does before quieting down at the end of a launch.

Trebuchets also appear to have played a role in the greatest single medieval advance in physical science, the innovations in theoretical mechanics associated with Jordanus of Nemore. The key to Jordanus's contribution is his concept of positional gravity, a revival in the Middle Ages of the idea of a motion vector, or the directedness of a force. Jordanus held that for equal distances traveled, a weight was "heavier," or more capable of doing work, when its line of descent was vertical rather than oblique. In particular, he compared cases in which the descents were linear with those that followed arcs. Eventually this understanding led to the notion that work is proportional to weight and vertical distance of descent, no matter what path is taken.

The connection is clear. Engineers knew that machines with hinged counterweights, in which the weight descends essentially straight down during the first, crucial part of the launch cycle, would throw stones farther than would their fixed counterweight equivalents, in which the mass travels in a curve.

Other aspects of Jordanus's work may show military connections as well. The suspension of the hinged counterweight, with the constantly changing leverage of its arm, may have spurred Jordanus's related attempts to analyze the equilibrium of bent levers and to emphasize that it was the horizontal distance between the mass on a lever arm and its fulcrum that determined the work it could do. Observations of the differing distances to which fixed and hinged counterweight machines could throw their stones may have helped Jordanus in his pioneering efforts to define the concept of work, or force times distance.

Jordanus's observations are usually studied as an example of pure physics, based on the teachings of earlier natural philosophers, such as Archimedes. The closeness of his mechanics to trebuchet function, however, suggests that engineering practice may have stimulated theory. Closing the circle, Galileo later incorporated such Jordanian ideas as virtual displacement, virtual work and the analysis of inclined planes to support such newer mechanics as his famous analysis of the trajectory of cannon shot.

Galileo's theoretical innovations came only after the replacement of trebuchets by cannon, a process that took nearly two centuries and was not fully accomplished until metallic shot replaced stones. The last instance of trebuchet use comes from the New World, at the siege of Tenochtitlán (Mexico City) in 1521. As ammunition was running critically low, Cortés eagerly accepted a proposal to build a trebuchet. The machine took several days to build, and at the first launch the stone went straight up, only to return and smash it. In view of the tremendous power of these devices, and the finesse required to make them function properly, would-be replicators should take careful note.

LOWER SAXONY STATE AND UNIVERSITY LIBRARY *Göttingen*

COUNTERWEIGHT TREBUCHET was a mainstay of medieval artillery. This illustration from Conrad Kyeser's *Bellifortis* shows the dimensions of the main beam (46 feet for the long arm, eight for the short) and some of its other parts. The text, left incomplete at Kyeser's death in 1405, does not describe the machine in detail.

The Authors

PAUL E. CHEVEDDEN, LES EIGENBROD, VERNARD FOLEY and WERNER SOEDEL combine engineering and history in their studies of the trebuchet. Chevedden, a historian specializing in premodern siege tactics and fortifications, teaches at Salem State College in Massachusetts. He received his Ph.D. from the University of California, Los Angeles, in 1986. Eigenbrod, an associate professor of mechanical engineering technology at Purdue University, teaches statics, dynamics and finite-element analysis. He spent 24 years in industry before going to Purdue. Foley, an associate professor at Purdue, specializes in the history of technology and science. This is his fifth article for *Scientific American.* Soedel is a professor of mechanical engineering at Purdue, with a strong interest in mathematical models and simulations of machinery. He reports that his idea of a good time is to sit in the garden and read history books.

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Cookstoves for the Developing World

Traditional wood, charcoal and coal stoves are used in hundreds of millions of homes. Their redesign can have a dramatic effect on energy usage, the environment and community health

by Daniel M. Kammen

Half the world's population of nearly six billion people prepare their food and heat their homes with coal and the traditional biomass fuels of dung, crop residues, wood and charcoal. The procurement and consumption of these fuels define the character of everyday life in many developing countries.

In rural areas, women and children may spend several hours a day collecting wood for cooking or making charcoal, tasks that contribute to deforestation and soil erosion. Worse, the choking smoke from indoor wood fires causes respiratory disease—mainly pneumonia—which is the leading health hazard in developing nations and annually kills four to five million children worldwide.

Living in the city provides no refuge. The urban poor frequently spend a significant fraction of their income on the purchase of charcoal and wood. Combustion of biofuels contributes to the hazy pall that hangs over the cities of the developing world. Carbon dioxide, methane and other greenhouse gases from cooking fires may also foster global warming.

Since the energy crisis of the 1970s, international aid organizations have targeted the improvement of traditional cooking practices as a simple and affordable way to address the environmental, economic and energy issues posed by the home fire. Several hundred projects spread throughout dozens of countries have promoted the "improved" cookstove—a more efficient adaptation of the metal or clay implements on which many of the world's families cook their daily meals. These efforts range from national initiatives that have introduced more than 120 million stoves into homes in rural China to village training programs in East Africa in which small groups of women learn to build and maintain their own stoves.

Cookstove programs follow closely the model for technology development and adoption established by the late British economist E. F. Schumacher in his 1973 classic *Small Is Beautiful*. Schumacher made a compelling case for "appropriate technologies" that were affordable and could be produced and maintained locally. Unfortunately, the enthusiasm of many of Schumacher's early followers concealed a meager technical know-how or simple naïveté. Virtually every developing country can point to examples of dilapidated wind pumps or photovoltaic power systems that either did not work or could not be repaired with local materials.

Modernized woodstoves were often too bulky or saved fuel only when used under ideal conditions seldom found in the field. Cookstove training courses were sometimes offered only to men, even though women perform more than 90 percent of the cooking duties in most developing countries.

Over the past decade government programs, development assistance groups and community-based organizers have undertaken a thorough review of the requirements for successful dissemination of cookstove technology. A new generation of stove programs is now implementing these hard-won lessons. This effort encompasses everything from an examination of stove thermodynamics and materials science to market research and grass-roots educational campaigns.

Cookstoves in Kenya

A case history that traces the progress of stove development from early misstep to ultimate acceptance can be found in East Africa. Almost one million households now cook with the

DIMITRY SCHIDLOVSKY

OPEN FIRE (*left*) used for cooking in millions of rural homes transfers heat to a pot poorly. As little as 10 percent of the heat goes to the cooking utensil; the rest is released to the environment.

GEORGE MULALA

COOKSTOVE SMOKE is ubiquitous in Kenya, where wood, charcoal and other biomass fuels are used for cooking and heating. Particulates in smoke are a major contributor to respiratory disease, the leading cause of illness in developing nations.

Kenya ceramic *Jiko*. The *Jiko*—the word means "stove" in Swahili—consists of a metal casing with a ceramic lining that helps to direct 25 to 40 percent of the heat from a fire to a cooking pot. The traditional metal stove that the ceramic *Jiko* replaces delivers only 10 to 20 percent of the heat generated to a pot, whereas an open cooking fire may yield efficiencies of as little as 10 percent.

The first improved stoves began to appear in the early 1980s and were designed by aid groups such as UNICEF and CARE-Kenya. The response from stove users was mixed at best. The designers, mainly natives of the U.S. and Europe, two havens of consumerism, had forgotten the first thing about marketing. Field testing was all too brief, sometimes with pathetic results. In one of the first models, the stove's opening did not match the size of most pots.

Even more fundamental problems plagued some of the early prototypes. Designers acted as if it would be an elementary exercise to improve the efficiency of the common metal stove, a deceptively simple canlike enclosure into which charcoal or wood is fed and ignited. In fact, after much trial and error, it turned out that an extensive investigation of stove physics and engineering design was needed. This analysis revealed that the largest loss of heat from the fire, about 50 to 70 percent, occurs from radiation and conduction through the metal walls. Makers of some of the first stoves took measures to deliver more of the fire's energy directly to the pot. They sometimes accomplished their job a little too well.

The design for one early improved *Jiko* model emerged after an aid group named the Kenya Renewable Energy Development Program sponsored a research trip to Thailand to inspect an improved stove—the Thai bucket. The resulting *Jiko* design had inward-sloping metal walls, like the Thai stove, as well as an insulating liner made of ceramic and a mica called vermiculite. The liner was cemented from the top to the bottom of the inner surface walls. It caused excessive amounts of heat to be retained inside the tapered vessel. Metal fatigue resulted from exposure to the trapped hot gases, which caused structural segments to crack.

An initial round of field tests did not provide enough feedback to stop this first-generation improved *Jiko* from reaching the

METAL STOVE (*left*), a traditional cooking implement, directs only 10 to 20 percent of the heat to a pot. From 50 to 70 percent of the heat is lost through the stove's metal sides, and another 10 to 30 percent escapes as carbon dioxide, carbon monoxide, methane and other flue gases.

KENYA CERAMIC *JIKO* (*left*) increases stove efficiency by addition of a ceramic insulating liner (the brown element), which enables 25 to 40 percent of the heat to be delivered to the pot. From 20 to 40 percent of the heat is absorbed by the stove walls or else escapes to the environment. In addition, 10 to 30 percent gets lost as flue gases, such as carbon dioxide.

market, where it received an equivocal response from purchasers. Various governmental and international aid groups, however, continued to work with a loose consortium of craftspeople, called *Jua Kali,* or "Hot Sun," to try to rectify the problems.

Better stove designs gradually came about during the mid-1980s. At that time, a number of academics began to publish serious analyses of optimal stove combustion temperatures and of the insulating properties of the ceramic liner materials. One of the most notable contributions to enhanced design came through the responses of several women's organizations that had formed around such issues as community health and protection of the environment. These groups were part of a feminist movement spreading throughout the developing world. In Kenya, it was women who suggested recasting the metal bucket design, with its unstable narrow base, into an hourglass shape.

That alteration prevented the new stove from tipping over, a constant danger when food was vigorously stirred in the Thai-influenced, bucketlike implement. It also meant that the insulating liner need extend only from the upper lip to its narrowest circumference at the stove's middle—and the tapered shape let the liner rest stably cemented to the upper metal walls without falling into the stove's bottom cavity. Because the liner covered only half the stove's interior, it did not cause the overheating and consequent cracking that had plagued the early versions.

These design changes, along with extensive training programs established by aid groups and women's organizations, caused dramatic gains in acceptance for the more efficient stoves. Schools, churches and businesses were among the first owners and helped to spark the interest of individual buyers. Today hundreds of *Jua Kali* manufacturers provide stoves to some 20,000 purchasers every month.

Benefits of the *Jiko*

The ceramic *Jiko* has had a considerable impact on household finances. Typical savings of 1,300 pounds of fuel a year frees up about $65 per household—up to a fifth of the annual income for urban dwellers. Women have benefited in that they control a disproportionately small share of family income yet are the primary purchasers of fuel. The Kenya ceramic *Jiko* has improved their lot in important ways. Many have invested the savings from reduced fuel purchases in small businesses or school fees for their children.

Currently more than half of all urban households in Kenya own the ceramic *Jiko,* and purchasers range from the poor to the affluent. The concentration of demand in urban areas points up another difficulty with the early stove programs, which commonly targeted users in the countryside. Programs outside the cities, where more than 70 percent of the Kenyan population lives, seemed justified because they met the needs of the poorest segment of society. But the $2 to $5 stove price proved too high for many households that had the option of collecting their own firewood and cooking over open fires. For city dwellers, who sought ways to cut their unavoidable fuel costs, more efficient stoves held a greater allure.

Establishing an infrastructure for stove production has begun to benefit the masses who live outside the city. Village residents have little ability to pay for a ceramic *Jiko* that may cost up to $5. But they may be willing to spend something less than that amount, some observers reasoned. After all, there are undeniable benefits for an implement that will diminish the drudgery of collecting wood for hours on end and that will reduce the acrid smoke in cooking huts. The smoke can cause exposure to particulates at 20 times the level that the World Health Organization considers a serious health risk.

Success of the ceramic *Jiko* in Nairobi and Mombasa did not go unnoticed by many of the women's groups that had organized in rural areas. An alliance developed between leading government and aid organizations in Nairobi and women's groups, most notably *Maendeleo ya Wanawake* (literally "Women's Development"). From these efforts has come a simplified and affordable variant of the ceramic *Jiko.*

The *Maendeleo* stove borrows the insulating element from the ceramic *Jiko* without the metal outer covering. The ceramic liner is set down in the middle of the open fireplace; it is then reinforced with mud and stones. A pot placed atop the stove heats almost as quickly as one on a Kenya ceramic *Jiko.* Indoor smoke is reduced considerably through more efficient combustion. Further, a *Maendeleo* stove is usually placed near a wall of the hut so that smoke can climb along the wall and exit more easily.

The *Maendeleo* stove costs as little as 80 cents; more than 100,000 of them have been disseminated so far. This rural success story helped to spawn a third-generation cookstove, the *Kuni Mbili* ("two-stick") stove, which has a larger firebox to accommodate wood instead of the charcoal typically used in urban settings.

The Kenyan program has been emulated in a number of other African countries, where the improved stoves continue to gain popularity. Variants of the Kenya ceramic *Jiko* have made their way to Tanzania, which has more than 54,000 stoves; Sudan, which has 28,000; Uganda, which has 25,000; and Zambia and Burundi, each having from 5,000 to 10,000.

Chinese and Indian Programs

Higher efficiency cookstoves have been adopted throughout the developing world. China has by far the world's most extensive program, with more than 120 million stoves in place—seven out of 10 rural households own

METAL COOKSTOVE: Traditional cookstove, produced by local artisans, has a metal skin that lets heat escape easily. Efficiency: 10 to 20 percent. Cost: $0.25 to $10. Number disseminated: hundreds of millions.

KENYA CERAMIC *JIKO:* This metal stove with a ceramic liner has achieved great popularity both within Kenya and in neighboring countries. Efficiency: 25 to 40 percent. Cost: $2 to $5. Number disseminated: nearly one million.

MAENDELEO: This ceramic insulating liner can serve as an inexpensive stove when placed in an open fireplace and reinforced with mud and stones. Efficiency: 15 to 35 percent. Cost: $0.80 to $1.20. Number disseminated: more than 100,000.

KUNI MBILI: A variation on the ceramic *Jiko,* this stove has a large firebox to hold wood sticks instead of charcoal, making it more suited for rural cooking. Efficiency: 25 to 40 percent. Cost: $2 to $5. Number disseminated: more than 20,000.

CHINESE IMPROVED COOKSTOVE: Brick and mortar stoves with chimneys are used to burn wood, straw, rice husks and coal. Efficiency: 20 to 40 percent. Cost: $8 to $9. Number disseminated: more than 120 million.

INDIAN *CHULA:* Efficient clay fireplaces, called *Chulas,* have been installed in rural homes in India. Efficiency: 10 to 40 percent. Cost: $8 to $10. Number disseminated: more than eight million.

DIMITRY SCHIDLOVSKY

these units. The longtime isolation of that huge country has, until recently, made it less influential than Kenya as a model for other developing countries.

The Chinese stoves, which burn wood, crop residues and coal, consist of a brick and mortar construction with a chimney that fits in the central living area of a home. An insulating material, such as ash and mortar, is packed around the circular cast-iron opening, which holds a wok.

Even the centralized Chinese government recognized that a successful stove program could not be mandated from Beijing and must meet local people's needs. Besides conducting stove research, the government confined itself to clearing away bureaucratic hurdles, giving local energy offices the responsibility for technical training and setting standards for manufacturing production. Most important, people made their own decisions to buy the stoves: no direct subsidies were supplied to purchasers by the government.

In contrast, a program in India, in which the government subsidized 50 percent of the cost of the eight million stoves distributed, resulted in half the stoves lying unused. The government ignored important regional differences in cooking habits. Respondents to follow-up inquiries often complained that the stove did not really save energy or get rid of smoke. Fortunately, reforms by the government and the launching of new research programs during the past five years have begun to correct these problems.

The lessons of improved stove programs can serve as the basis for a more radical shift away from traditional cooking technologies—fuel use can be eliminated by harnessing the energy of the sun. The solar oven, an idea reported a century ago in *Scientific American,* is essentially a greenhouse for cooking food. It consists of an insulated box made of wood, metal, plastic or cardboard whose open top is covered with one or two plates of glass.

DANIEL M. KAMMEN

SOLAR OVEN, shown in Kenya, cooks food in a glass-covered box where pots are placed.

Trapping Sunlight

Solar oven designs are as varied as cookstoves, but a "box cooker," as it is known, typically incorporates walls with a reflective coating, such as aluminum sheet or foil, and a metal floor plate to absorb sunlight. The energy is then reradiated within the box as infrared heat, which does not escape because it is blocked by the glass. Pots on the bottom metal plate can heat several liters of water or food to more than 300 degrees in under an hour.

The ovens are mostly used for crockpot-style cooking. They allow for slow simmering, baking and roasting in covered pots. On a sunny day, rice, stews, chicken or bean dishes will be fully cooked in two to five hours.

Solar-box ovens will never compete with the microwave oven in speed of preparation, and they must be supplemented with a wood cookstove for a rainy day. But they require no fuel except the sun's rays—and they emit no health-damaging smoke. By using the technology, some households in Africa, Latin America and elsewhere have reduced their cooking-fuel expenditures by 50 percent.

As with the early stove programs, acceptance rates are still modest: only 20 to 40 percent of the Kenyan families who adopted some 2,500 solar ovens early on continue to use them. The cost of the stoves—$20 to $40 apiece—remains too high for many households. Yet the *Jua Kali* artisans who have mastered mass production of the ceramic *Jiko* might also be able to make large numbers of solar ovens, which could halve the price. The cost of the ceramic *Jiko* dropped markedly, from $12 to as little as $2, once the stoves were mass-produced. In many places, a manufacturing base has begun to emerge that could bring costs down. Women's groups, artisans and several large-scale commercial industries in more than 100 countries are making solar ovens in a diverse range of styles. (Besides Kenya, China and India each have more than 100,000 in use.)

Cookstove projects boast a record of accomplishment that may serve as a model for the development of an array of renewable-energy projects, such as wind-energy systems and photovoltaic electrical generators. The halting first steps of the appropriate technology movement are now being translated into solid research and a more pragmatic execution. These programs may become a realization of Schumacher's vision: for one out of every two people worldwide, modifications in their means of cooking offer enormous promise for improvements in health and economic well-being.

The Author

DANIEL M. KAMMEN is assistant professor and co-chairperson of the Science, Technology & Public Policy Program of the Woodrow Wilson School of Public and International Affairs at Princeton University. His research focuses on energy resource management, technology policy, and gender and environmental issues. Kammen received his bachelor's degree from Cornell University and his Ph.D. from Harvard University, both in physics. Before moving to Princeton, he did postdoctoral work at the California Institute of Technology in neurobiology and renewable-energy engineering and at Harvard in global change studies. Kammen directs a field training program on renewable energy and development in partnership with the African Academy of Sciences and the University of Nairobi.

Further Reading

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J. Robert Oppenheimer: Before the War

Although Oppenheimer is now best remembered for his influence during World War II, he made many important contributions to theoretical physics in the 1930s

by John S. Rigden

Fifty years ago this month, on July 16, 1945, an unearthly blast of light seared the predawn sky over the desert in New Mexico. The witnesses of this event included many of this century's most distinguished physicists. As they watched the boiling glare through their welding goggles, a sober reality bore into them: the nuclear age had begun. The chief witness—the person who had directed the atomic bomb project from its inception—was J. Robert Oppenheimer.

Oppenheimer was a rare individual. His intellectual acuity, diverse interests, frail physique and ethereal personality made him a man of legendary proportions. After World War II Oppenheimer became a public figure, known for leading the physicists who built the atomic bomb at Los Alamos Laboratory. His success as the director of the Manhattan Project provided him with a base of influence, and, for a time, he enjoyed the authority and power that were his.

Then, in June 1954, amid the anticommunism paranoia of McCarthyism, the U.S. Atomic Energy Commission (AEC) concluded that Oppenheimer had defects in his character and deemed him a national security risk. Albert Einstein and others at the Institute for Advanced Study in Princeton, N.J., where Oppenheimer was then director, declared their support for him. In October the trustees of the institute reelected him to another term as director, a position he then held until a year before his death in February 1967. Still, after the AEC's actions, Oppenheimer's slight frame became the depiction of a broken man.

Few historians have written about the Oppenheimer who invigorated American theoretical physics a decade before the war, which is unfortunate for two reasons. First, Oppenheimer became a physicist at the rarest of times, when the theories of quantum mechanics and nuclear physics were being formed, revising a great deal of traditional thought in the field. Second, although he is sometimes characterized as an underachiever, Oppenheimer had in fact made many significant contributions to several major areas of physical research before taking his post at Los Alamos.

Oppenheimer built the foundation for contemporary studies of molecular physics. He was the first to recognize quantum-mechanical tunneling, which is the basis of the scanning tunneling microscope, used to reveal the structure of surfaces atom by atom. He fell just short of predicting the existence of the positron, the electron's antiparticle. He raised several crucial difficulties in the theory of quantum electrodynamics. He developed the theory of cosmic-ray showers. And long before neutron stars and black holes were part of our celestial landscape, Oppenheimer showed that massive stars can collapse under the influence of gravitational forces.

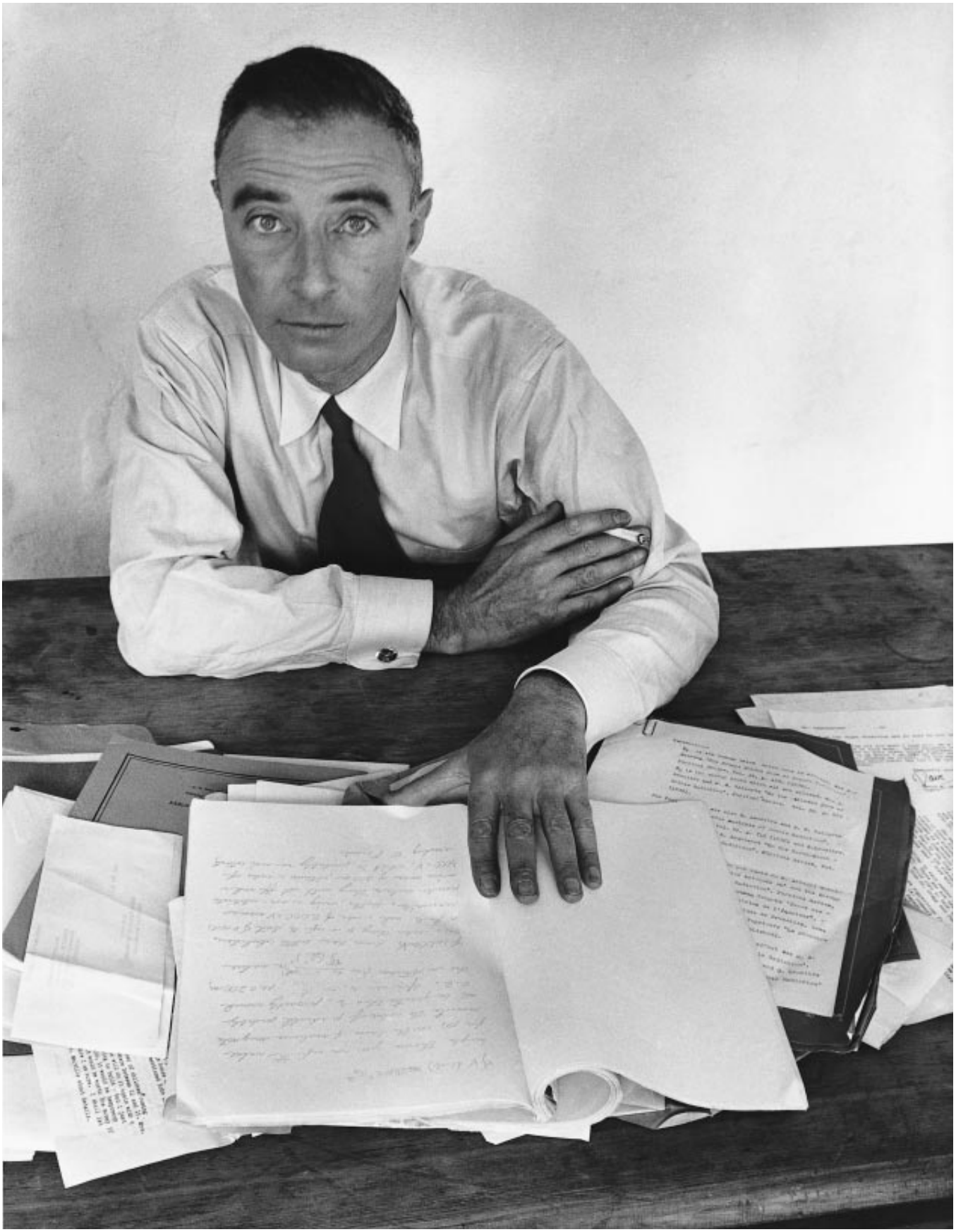
To Physics from Chemistry

Like many physicists of his era, Oppenheimer studied chemistry first. "Compared to physics," he said, "[chemistry] starts right in the heart of things." As a freshman at Harvard University he realized that "what I liked in chemistry was very close to physics." So that spring, he submitted a reading list to the physics department and was granted graduate standing. He enrolled in many physics classes, but because his interests and coursework were very diverse, he claimed later to have received only "a very quick, superficial, eager familiarization with some parts of physics." He wrote: "Although I liked to work, I spread myself very thin and got by with murder; I got A's in all these courses which I don't think I should have."

Whether that was true or not, Oppenheimer did gain valuable experience working in Percy W. Bridgman's laboratory—a privilege granted to him by virtue of his advanced standing. In the 1920s American physics was dominated by experimentalists such as Bridgman, who was among the first to investigate the properties of matter under high pressure and built much of the apparatus needed to do so. Thus, from his student experiences, Oppenheimer did not distinguish between experimental and theoretical physics, the latter being largely a European activity. "I didn't know you could earn your living that way [as a theoretical physicist]," he once said, looking back on his undergraduate days.

For this reason, as his graduation in 1925 grew near, he aspired to work under Ernest Rutherford, one of the greatest experimentalists of the century, at the Cavendish Laboratory in Cambridge, England. Rutherford had conducted the first trials to reveal that atoms contained extremely small, heavy cores, or nuclei. He was, however, unimpressed with Oppenheimer's credentials and rejected his application. Oppenheimer next wrote to Joseph John Thomson, another renowned experimentalist at the Cavendish. Thomson accepted Oppenheimer as a research student and put him to work in a corner of the laboratory, depositing thin films on a base of collodion. "I am having a pretty bad time," he wrote to a high school friend on November 1, 1925. "The lab work is a terrible bore, and I am so bad at it that it is impossible to feel that I am learning anything."

The ensuing winter was a dark time for Oppenheimer, but with the coming of spring, new possibilities became ap-



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Oppenheimer, 1904–1967

parent. Rutherford, who took to Oppenheimer in person, introduced him to Niels Bohr when Bohr visited the Cavendish; through Patrick M. S. Blackett, a physicist at the Cavendish, he met Paul Ehrenfest of the University of Leiden. He also became friends with the influential Cambridge physicists Paul A. M. Dirac and Ralph H. Fowler. All these men were theoreticians and helped to broaden Oppenheimer's view of the field. Fowler was particularly perceptive. He advised Oppenheimer to learn Dirac's new quantum-mechanical formalism and apply it to band spectra, a melding of old and new knowledge as yet untackled.

Oppenheimer became absorbed in the problem and over the next few years developed the modern theory of continuous spectra. This work not only led to his first paper, it also marked the beginning of his career as a theoretical physicist. When Max Born visited the Cavendish in the summer of 1926 and suggested that Oppenheimer pursue graduate studies at the University of Göttingen, a center for theoretical physics, Oppenheimer readily accepted the plan. "I felt completely relieved of the responsibility to go back into the laboratory," he said to the philosopher Thomas S. Kuhn in a 1963 interview.

It was at Göttingen that Oppenheimer first became aware of the problems perplexing European physicists. "The science is much better [here]," he wrote to his friend Francis Furgusson in November 1926. At that time, Born, Werner Heisenberg and Pascual Jordan were all in Göttingen, formulating the theory of quantum mechanics. Born, a distinguished teacher, made Göttingen as good a place as any to learn the intricacies of the new theory. Oppenheimer learned fast. In December 1926, only four short months after he had applied to Göttingen, he sent an article, "On the Quantum Theory of Continuous Spectra," to the leading German physics journal *Zeitschrift für Physik*. This paper was in fact an abridged version of what would be his dissertation. After receiving his doctorate from Göttingen in March 1927, he spent the next two years, one in the U.S. and one in Europe, as a National Research Council Fellow.

During this period, Oppenheimer profited a great deal from his association with prominent European physicists of the day. "They gave me some sense and…some taste in physics," he told Kuhn. Still, the theoretical problems he investigated were primarily of his own choosing. Later, in the 1930s, perhaps because of his own laboratory experience, Oppenheimer worked closely with experimentalists, many of whom acknowledged that he understood their data better than they did.

Atoms and Molecules

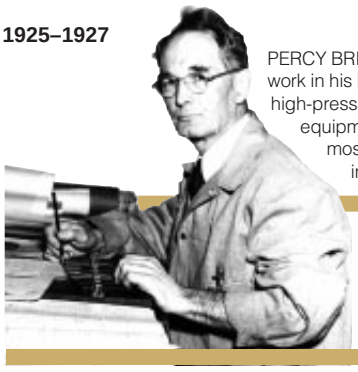
The atom, once found to emit discrete spectra during transitions between energy states, gave the first indication that the physics of preceding centuries was inadequate. Thus, atoms and molecules provided a natural testing ground for the new theory of quantum mechanics and for Oppenheimer in 1927. His first major contribution was finding a way to simplify the analysis of molecular spectra. By interpreting spectra, physicists determine the structure and properties of molecules. But an exact quantum-mechanical description of even a simple molecule is complicated by the fact that the electrons and nuclei of the atoms making up that molecule all interact with one another.

Oppenheimer recognized that because of the great disparity between the nuclear and electronic masses, these interactions could be largely ignored. The massive nuclei respond so slowly to mutual interactions that the electrons complete several cycles of their motion as the nuclei complete a small fraction of their own. While on a vacation, Oppenheimer wrote up a short paper on the topic and sent it to Born. Born was aghast at the brevity of Oppenheimer's draft and churned out a 30-page paper, showing in detail that the vibration and rotation of the nuclei could be treated separately from the motion of the electrons. Today the Born-Oppenheimer approximation is the starting point for physicists and chemists engaged in molecular analysis. Later on, Oppenheimer determined the probability that one atom captures the electron of another atom. In keeping with the Born-Oppenheimer approximation, he showed that the probability is independent of the internuclear potential between the two atoms.

Oppenheimer in fact discovered an-

The Shaping of a Scientist

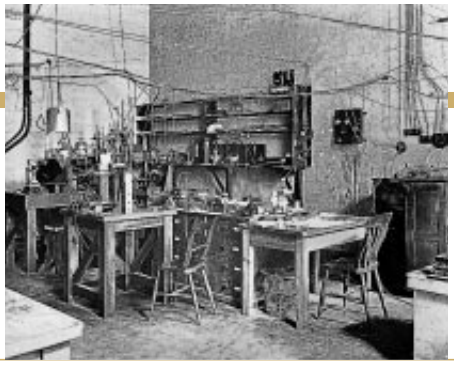
1925–1927



AP/WIDE WORLD PHOTOS

PERCY BRIDGMAN (*left*) asked Oppenheimer as an undergraduate to work in his laboratory at Harvard University. Bridgman was a pioneer in high-pressure physics during the 1920s and, in fact, built much of the equipment needed to carry out his studies. His hands-on approach most likely influenced Oppenheimer's decision to pursue a career in experimental physics after graduating in 1925.

1925 **1926** **1927**



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CAVENDISH LABORATORY in Cambridge, England (*right*), was home to Oppenheimer for a year after he left Harvard. There he had hoped to work in Ernest Rutherford's laboratory (*left*), but Rutherford, one of the great experimentalists of the century, was unimpressed with Oppenheimer. Instead Oppenheimer assisted another renowned physicist at the Cavendish, Joseph John Thomson (*above*).

other quantum-mechanical behavior, called tunneling, in 1928. Tunneling occurs under many theoretical conditions. An electron, for example, can escape from confines that normally sequester it if it behaves like an infinitesimal billiard ball. The time-honored example of tunneling is that which takes place when a nucleus expels an alpha particle during radioactive decay. Inside a uranium nucleus, both nuclear and electrostatic forces will restrict the motion of an alpha particle. Classically, it has no way to leave the nucleus. Quantum-mechanically, though, the alpha particle can tunnel through the surrounding barrier and slip away.

During the summer of 1928 physicists George Gamow and, independently, Edward U. Condon and Ronald W. Gurney first explained radioactive disintegration by means of tunneling. Textbook writers of today acknowledge this fact, but they also imply that these scientists actually discovered the phenomenon, which is not true. Several months earlier, in March, Oppenheimer had submitted a paper to the *Proceedings of the National Academy of Sciences* that considered the effect an electric field has on an atom. Classically, an atom can be dissociated only by an intense electric field. In the quantum view, however, a weak field can separate an electron from its parent atom because the electron can tunnel through the barrier that binds it. Oppenheimer showed that a weak electric field could dislodge electrons from the surface of a metal. Gerd Binnig and Heinrich Rohrer of the IBM Zurich Research Laboratory developed the scanning tunneling microscope based on this principle in 1982, 54 years after Oppenheimer had discovered it [see "The Scanning Tunneling Microscope," by Gerd Binnig and Heinrich Rohrer; SCIENTIFIC AMERICAN, August 1985].

Particles and Fields

Oppenheimer spent his final months in Europe, from January to June 1929, with Wolfgang Pauli at the Swiss Federal Institute of Technology in Zurich. After this apprenticeship, Oppenheimer's interests turned away from applications of quantum mechanics to more basic questions of physics. The timing for such a shift was perfect. That spring he received offers from the California Institute of Technology and the University of California at Berkeley; in both places, physical research was aimed at the forefront of basic questions. Robert A. Millikan, who coined the term "cosmic rays" in 1925, was at Caltech, and Ernest O. Lawrence, who invented the cyclotron in 1930, was investigating nuclear physics at Berkeley. Oppenheimer accepted both positions, typically spending the fall term at Berkeley and the spring semester at Caltech. At both schools he attracted outstanding students who helped to bring American physics into the ranks of the world's best.

One of the most heated controversies of the early 1930s was over a theory proposed by Dirac. On January 2, 1928, the editor of the *Proceedings of the Royal Society* received a manuscript from Dirac entitled "The Quantum Theory of the Electron." This paper, along with a second part published a month later, was probably Dirac's most significant accomplishment. The relativistic wave equation he devised to describe the electron thrilled physicists in that it yielded the particle's spin and correct magnetic moment. Yet this paper also raised vexing issues. Heisenberg wrote to Pauli in July 1928 that the "saddest chapter of modern physics is and remains the Dirac theory." The principal problem with Dirac's wave equation was that it gave solutions corresponding both to positive energy states and to an infinite number of negative energy states. In such a situation, quantum mechanics predicts that electrons can jump into these negative energy states, and so all electrons could end up there. Accordingly, ordinary electrons should not exist.

To avoid this difficulty, Dirac imagined that these negative energy states were occupied by an infinite number of electrons. If a few of these states were unoccupied, however, they would appear as positive holes in the negative sea of charge. In March 1930 Dirac published a paper asserting that these positive holes were protons. But Oppenheimer, who read Dirac's paper before publication, argued in a letter to *Physical Review,* printed the same month, that they were not. He pointed out that

1928–1930

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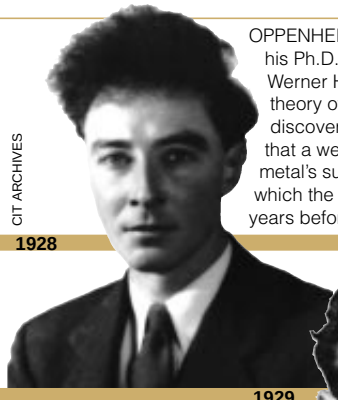
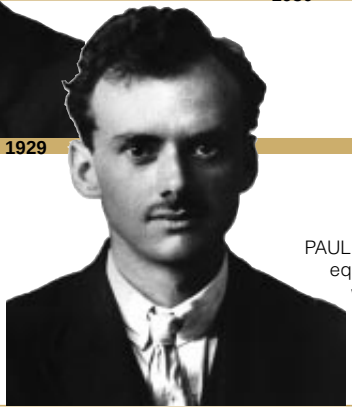


CIT ARCHIVES

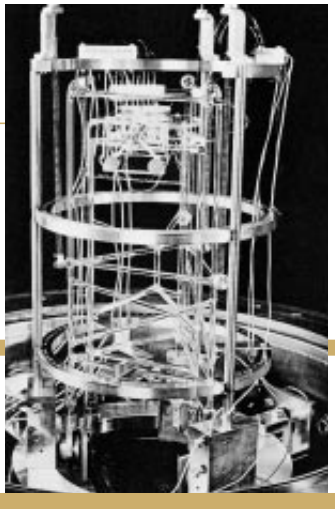
OPPENHEIMER is shown here in 1928, one year after receiving his Ph.D. from the University of Göttingen, where Max Born, Werner Heisenberg and Pascual Jordan were formulating the theory of quantum mechanics. That same year Oppenheimer discovered quantum-mechanical tunneling by demonstrating that a weak electric field could dislodge electrons from a metal's surface. In doing so, he described the principle on which the scanning tunneling microscope (*right*) is based—54 years before its invention.

1928 **1929** **1930**



UPI/BETTMANN

PAUL A. M. DIRAC (*left*) devised a relativistic wave equation to describe the electron in 1928. His work, though accurate in many ways, raised several vexing issues. Oppenheimer made insightful criticisms of Dirac's theory and, in constructing his arguments, fell just short of predicting the existence of the positron.



GERD BINNIG AND HEINRICH ROHRER

if the positive holes in Dirac's theory were protons, then electrons and protons would annihilate one another, meaning that ordinary matter would have a lifetime of approximately 10^{-10} second. He further made note that the positive particles posited by Dirac's theory needed to have the same mass as an electron. In fact, these positive holes were positrons, the electron's antiparticle, but in 1930 this particle was unknown and unanticipated. In contesting Dirac, though, Oppenheimer fell just short of predicting its existence.

Even after the Caltech physicist Carl Anderson's discovery of the positron in 1932, positron theory resulting from Dirac's work was plagued with problems. Oppenheimer and other physicists working on quantum electrodynamics (QED) had many doubts about the basic theory. In 1930, for example, Oppenheimer showed that when the QED theory published that same year by Heisenberg and Pauli was applied to the interactions between electrons, protons and an electromagnetic field, the displacement of spectral lines was infinite. Oppenheimer's skepticism about QED was kept alive throughout the 1930s by anomalies in his cosmic-ray work caused by the muon and other high-energy particles unknown at the time. Had Oppenheimer had an experimental result on the hydrogen atom obtained by his student Willis E. Lamb only after the war, it is conceivable that he would have resolved the troubling problem of infinities.

In 1931 Oppenheimer attempted to find an equation for the photon that would be an analogue to Dirac's equation for the electron. He failed in this effort but in the process demonstrated the basic difference between particles of half-integral and integral spins, which later constituted the basis for Pauli's formal proof of the connection between spin and statistics.

Creation and Destruction of Matter

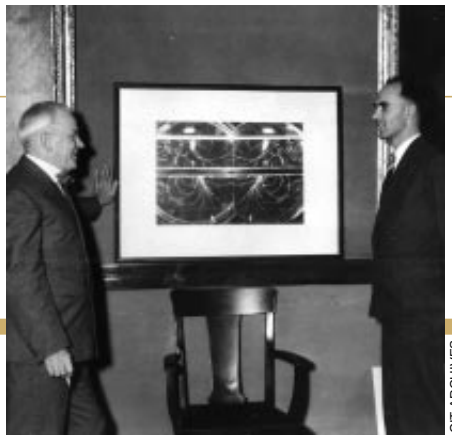
According to quantum mechanics, both the annihilation and the creation of matter—subject to the conservation laws of energy and momentum—are possible. A gamma ray, for example, can give rise to an electron and a positron in a process called pair production. Oddly, Oppenheimer did not originate the idea of pair production, but along with his student Milton S. Plesset, he did provide the first correct description of it in 1933. Working with his postdoctoral student Wendell H. Furry a year later, Oppenheimer developed electron-positron theory essentially in its modern form. They showed that the observed charge of the electron is not the true charge and, in doing so, anticipated the phenomenon called charge renormalization, which helped to explain some of the earlier difficulties surrounding infinities in QED.

In the 1930s most of the high-energy physics experimentation was happening in the earth's atmosphere. There energetic particles (in the billion-electron-volt range) having cosmic origins bombarded atmospheric atoms. It was during a cloud-chamber study of such cosmic radiation in 1932 that Anderson first discovered the positron. If a metal plate of, say, lead is placed in a cloud chamber, a single cosmic-ray track incident on the plate from above the surface can give rise to a number of tracks emanating from a point on the plate's lower surface. Oppenheimer and his student J. Franklin Carlson showed that these cosmic-ray "showers," commonly consisting of photons, electrons and positrons, are produced by a cascade of electron-positron pair productions. The thickness of the lead plate can, of course, be varied. If the primary cosmic ray was either a photon or an electron, Oppenheimer and Carlson noted that a lead plate 20 centimeters thick absorbed all the resulting radiation for the energy ranges experimentally observed.

Additional data revealed, however, that penetration exceeded depths that could be attributed to either photons or electrons. They concluded that "there is another cosmic-ray component." A few months later groups at Caltech and at Harvard simultaneously discovered a new particle. Oppenheimer and his

1931–1933

ROBERT A. MILLIKAN is shown below in 1932 with a self-recording electroscope he built in the basement of his home to detect cosmic rays. Millikan, who coined the term "cosmic ray" in 1925, was one of Oppenheimer's colleagues at the California Institute of Technology. It was during a cosmic radiation experiment at Caltech in 1932 that Carl Anderson discovered the positron. He is pictured with Millikan and an image of the telltale tracks (*right*).



CIT ARCHIVES

1931 **1932** **1933**

AP/WIDE WORLD PHOTOS

ERNEST O. LAWRENCE, seen standing with Oppenheimer (*right*), invented the cyclotron at the University of California at Berkeley in 1930. There both men studied nuclear physics.

AP/WIDE WORLD PHOTOS

Berkeley colleague Robert Serber immediately equated this particle with one the Japanese physicist Hideki Yukawa had predicted to explain nuclear forces. The newly discovered particle in fact turned out to be the muon. The pion—Yukawa's prediction—came later.

Away from Caltech at Berkeley, Oppenheimer's research revolved around the accelerator. When James Chadwick discovered the neutron in 1932, the proton-electron theory of the nucleus was abandoned, and the modern proton-neutron model took its place. During the spring of 1933 Lawrence first began accelerating deuterons, consisting of a single neutron and proton, and using them to bombard heavy nuclei. Deuterons, he found, disintegrated nuclei more effectively than did protons. In no time at all, Lawrence and his coworkers observed alpha particles coming out of target nuclei.

Then they came on a puzzling result: when high-energy deuterons hit any nucleus whatsoever, the target would give off protons within a narrow energy range. In fact, deuterons contaminating Lawrence's apparatus accounted for the mystery: the protons he witnessed all resulted from deuterium fusion. But before this explanation emerged, the observation stimulated questions about deuterium-induced reactions. At Berkeley, Oppenheimer and his student Melba N. Phillips showed that when a deuteron collides with a heavy nucleus, that nucleus can capture the neutron in the deuteron, liberating the proton. The theory Oppenheimer and Phillips formulated for this reaction, now named after them, accounted exactly for Lawrence's strange results.

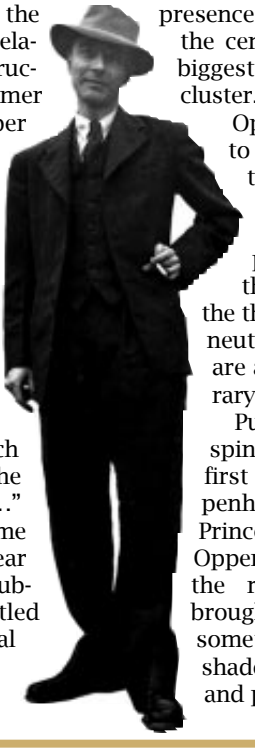
Neutron Stars and Black Holes

Now accepted as end points in stellar evolution, neutron stars and black holes were both postulated on theoretical grounds during the 1930s. Oppenheimer and two of his students, George M. Volkoff and Hartland S. Snyder, were in the vanguard of this development. Oppenheimer and Volkoff together became interested in another worker's suggestion that once a sufficiently massive star had exhausted its source of thermonuclear energy, a neutron core could be formed. To test whether this scenario was possible, Oppenheimer and Volkoff set out to establish the difference between a gravitational treatment of the process, based on Newton's theory, and one consistent with Einstein's general relativity.

The Oppenheimer-Volkoff equation, which gives the pressure gradient within the star, revealed that the pressure increased more rapidly moving deeper into the stellar core than would be expected from a Newton-based calculation. Thus, the Oppenheimer-Volkoff theory, based on general relativity, predicted stronger, and more accurate, gravitational forces than did Newtonian theory. Oppenheimer and Volkoff also performed the first detailed calculations establishing the structure of a neutron star, thereby laying the foundation for the general relativistic theory of stellar structure. Just before Oppenheimer and Volkoff published a paper on this work in 1939, Oppenheimer sent a letter to George E. Uhlenbeck, a theoretical physicist at the University of Michigan, who, with his colleague Samuel A. Goudsmit, discovered the electron's spin. He wrote, "We have been…working on static and nonstatic solutions for very heavy masses…old stars perhaps which collapse to neutron cores. The results have been very odd…."

The results in fact became even stranger. Later that year Oppenheimer and Snyder published a classic paper entitled "On Continued Gravitational Contraction." They noted that when a massive star has exhausted its internal source of nuclear energy, its ultimate fate is determined by how much mass it can shed, either through radiative expulsion or by rapid rotation and flying apart. After all avenues for ejecting mass have been traversed, the core that remains is bound together by the gravitational force. If there is no thermonuclear energy to act as an equilibrating counterforce, the core will continue to collapse.

As this collapse takes place, the light radiating from the core becomes increasingly redshifted, meaning its wavelength lengthens; further, the path along which this light can escape into space becomes increasingly narrow until the path closes on itself, leaving behind a source of gravitational attraction shut off from external observation. In constructing this description, Oppenheimer and Snyder provided the first calculation revealing how a black hole can form. In May 1994 compelling evidence was observed through the eye of the *Hubble Space Telescope* for the presence of a massive black hole in the center of the galaxy M87, the biggest and brightest in the Virgo cluster.



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Oppenheimer's contribution to physics throughout the century was broad, deep and lasting. The Born-Oppenheimer approximation, the penetration of electrons through potential barriers, the theory of cosmic-ray showers, neutron stars and black holes are all a vital part of contemporary physics.

Pulsars, now recognized as spinning neutron stars, were first seen in 1967, the year Oppenheimer died of cancer in Princeton. Had he lived longer, Oppenheimer might have enjoyed the recognition this discovery brought to his prewar physics, something that had been overshadowed by his wartime work and postwar fame.

The Author

JOHN S. RIGDEN received his Ph.D. from Johns Hopkins University in 1960. He is currently director of the physics programs at the American Institute of Physics. Recently he served as director of the Development of the National Science Education Standards Project at the National Academy of Sciences. From 1978 to 1988 he was the editor of the *American Journal of Physics*. In addition to editing a collection of articles entitled *Most of the Good Stuff: Memories of Richard Feynman,* he has written two books, *Physics and the Sound of Music* and *Rabi: Scientist and Citizen.*

Further Reading

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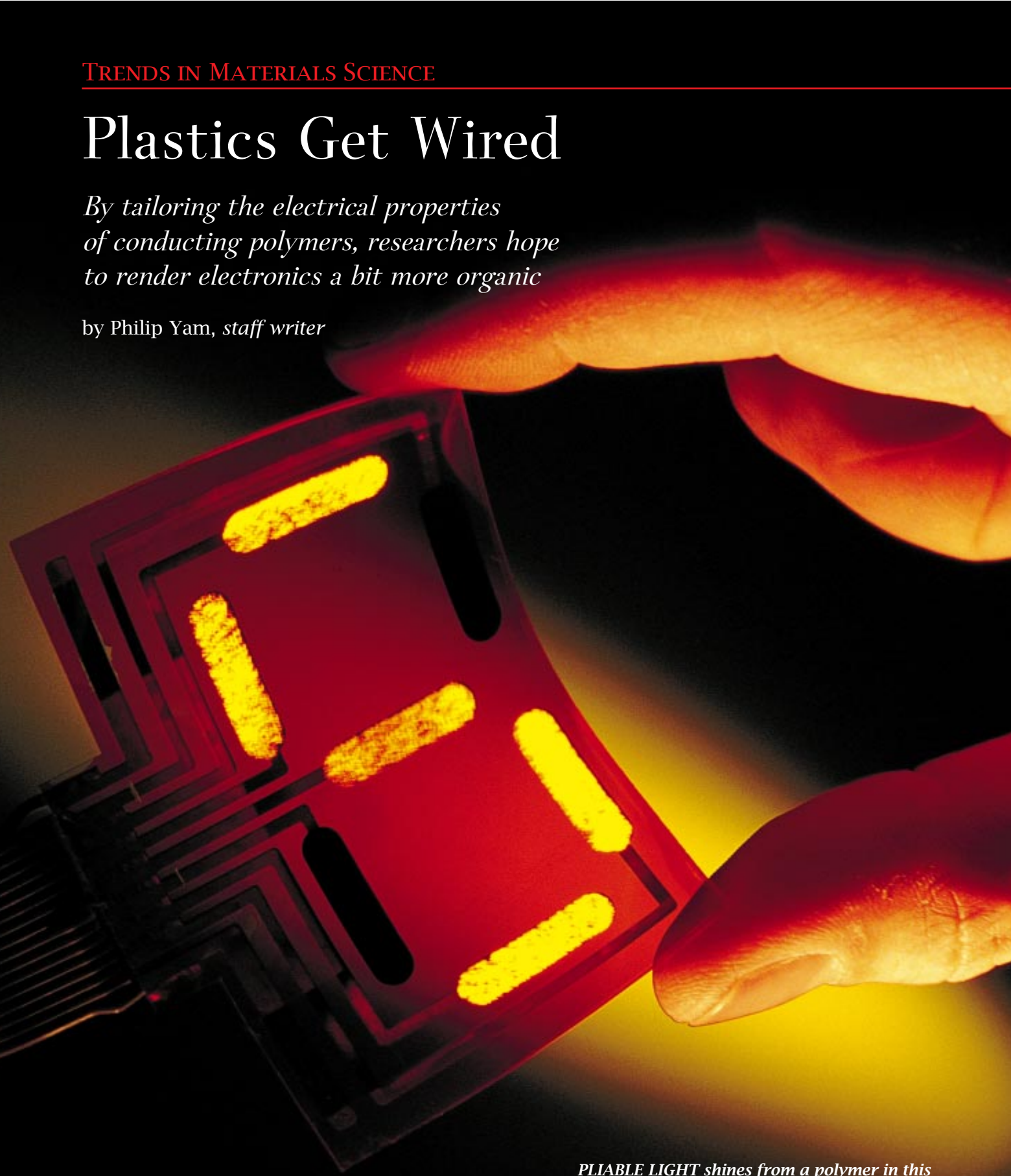
Plastics Get Wired

By tailoring the electrical properties of conducting polymers, researchers hope to render electronics a bit more organic

by Philip Yam, *staff writer*



***PLIABLE LIGHT** shines from a polymer in this alphanumeric display made by UNIAX Corporation in Santa Barbara, Calif. Organic light-emitting diodes, or LEDs, should find applications soon and may form the basis of future lightweight screens.*

Like many technological advances, the innovations in the field of conducting polymers began by accident. While attempting to make an organic polymer called polyacetylene in the early 1970s, Hideki Shirakawa of the Tokyo Institute of Technology mistakenly added 1,000 times more catalyst than the recipe called for. What he produced was a lustrous, silvery film that resembled aluminum foil but stretched like Saran Wrap—something that sounds more like a new and improved way to keep leftovers fresh than a potential breakthrough in materials science.

The substance appeared so unusual that when Alan G. MacDiarmid spied it, he wondered if it would be a candidate for his goal of making "synthetic metals"—nonmetallic substances that could transmit electricity. In 1977 Shirakawa joined MacDiarmid and Alan J. Heeger in their laboratory at the University of Pennsylvania to investigate this form of polyacetylene. After mixing in some iodine, the group found that the material's conductivity subsequently jumped by a factor of several million.

Many investigators see broad marketing opportunities now

Durable, cheap, manufacturable and flexible, conducting polymers inspired visions of a future of transparent circuits, artificial muscle and electronic displays that conveniently roll up under the arm. Researchers have auditioned various demonstration devices, including components that could be useful for new displays, such as plastic transistors and light-emitting diodes (LEDs). Although such a future is about as dreamy as it gets, many investigators see broad marketing opportunities possible now—in antistatic coatings, electromagnetic shielding, lights for toys and microwave ovens, among others. Perhaps mundane, such applications are nonetheless promising enough that universities are collaborating with corporations, and scientists have initiated start-ups.

Although the pace of technological innovation has been impressively brisk, whether the materials will make an impact on commerce remains unclear. Firms are unlikely to invest in new equipment if the devices perform only marginally better than existing instruments. Polymer-based batteries, for instance, have a longer shelf life than do conventional ones, but they have penetrated the market only in a limited way. Flat-panel displays and LEDs made of organic substances face entrenched competition from existing inorganic liquid crystals and semiconductors.

Still, optimism pervades the field. Because plastic and electrical devices have become integral parts of the modern world, researchers are confident that at least some profitable uses will emerge. Conducting polymers constitute a radically novel market area, points out Ray H. Baughman of Allied-Signal in Morristown, N.J., who predicts confidently, "Fortunes are going to be made."

Polymers, the constituents of familiar plastic materials and synthetic fibers, are large organic molecules built out of smaller ones linked together in a long chain. Generally, they are insulators, because their molecules have no free electrons for carrying current. To make these substances conductive, workers exploit a technique familiar to the semiconducting industry: doping, or adding atoms with interesting electronic properties. The added atoms either give up some of their spare electrons to the polymer bonds or grab some electrons from the bonds (and thereby contribute positive charges called holes). In either case, the chain becomes electrically unstable. Applying a voltage can then send electrons scampering over the length of the polymer.

Since the Pennsylvania group's work, several kinds of polymers have been found to conduct electricity when doped. Besides polyacetylene, there are polypyrrole, polythiophene and polyaniline, to name just a few of the most commonly studied. Although investigators do not understand the precise physical mechanisms that enable polymers to conduct, the purity and particularly the arrangement of polymer chains seem to be crucial. By stretching polyacetylene, for instance, workers now routinely make the material conduct 50,000 amperes per volt per centimeter, up from 60 in the first reports. Some workers even managed to make polyacetylene conduct about one quarter as well as copper.

Such developments are "extremely important for the whole conducting field," MacDiarmid says. "They exemplify how dedicated improvement in chemical and molecular structure can lead to enormous advances in the physical and electrical properties." Moreover, the degree of conductivity is readily adjusted. "You can control the quality of the metallic state by controlling the structural order of the polymer," notes Arthur J. Epstein of Ohio State University.

Although other polymers are more conductive, polyaniline is emerging as the material of choice for many applications. As one of the oldest of synthetic organic polymers, its properties are well known. The substance—which resembles the plastic used in 35-millimeter photographic film—is easily made, it is stable in air and its electronic properties are readily customized. Most important, polyaniline is cheap—the most inexpensive conducting polymer around. It can also assume diverse incarnations, including thin films and patterned surfaces.

Polyaniline, which conducts up to about 500 amperes per volt per centimeter, will not replace copper wiring, however. "We won't be as good as copper; we won't be as cheap as copper," admits Andy Monkman of the University of Durham in England. Copper conducts 100,000 times as much current and costs half as much. Still, polyaniline's electrical performance is more than adequate for some applications, he insists: "The kinds of things we are going to replace are those that are complicated to manufacture, like braids on cable." Braids impart flexibility, permitting coaxial cable to wind around your living-room end table, for example, to reach the cable television box. But weaving copper wire into braids is a slow, laborious task, Monkman explains. If workers could extrude polymer braids and lay the insulation over the cable in a single step, the speed of the manufacturing would rise 10-fold, and the cost would plummet. The University of Durham has a three-year make-or-break deal with a cable company. "There will be a product, or there will never be a product," he says ruefully.

That Annoying Static Cling

Although conducting organics could find uses in virtually anything that relies on electricity, solid-state electronics probably offers the greatest number of opportunities. At the moment, observes Marie Angelopoulos of the IBM Thomas J. Watson Research Center, "the largest market is electrostatic dissipation." Such charges are well known to wreak havoc on digital devices: estimates of electrostatic damage to electronic equipment alone exceed $15 billion in the U.S., she notes.

Contemporary protective packaging, which relies on ionic salts or resins filled with metals or carbon, has some shortcomings. The conductivities of ionic materials tend to be low and unstable; metal is expensive and heavy; and carbon pos-

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es a contamination hazard because bits of it can slough off during shipment. Polymers should be easier to handle and be able to dissipate electrostatic charges more efficiently. As a bonus, polyaniline coatings also happen to be highly transparent. Angelopoulos hopes to see IBM's polyaniline solution, named PanAquas, marketed before the end of the year.

The dissipative abilities of polymers also make them ideal for electromagnetic shielding. Such protection is necessary to keep electrical signals among components from overlapping—the reason airlines request that portable electronics be turned off during takeoff and landing. (The shielding would not benefit those concerned about the potential health effects of power lines, because the frequencies of the fields are much lower than these screens can block.) Incorporated into the plastic cases of electronic equipment, the polymers can guard against spurious signals, Epstein remarks. Conventional screening materials rely on impregnated bits of carbon or metal, which could harm the mechanical properties of the base material at any points that bend. Although proposals relying on polymers are still more costly than present solutions, conducting polymers could be adulterated with other substances, such as nylon, to reduce the expense.

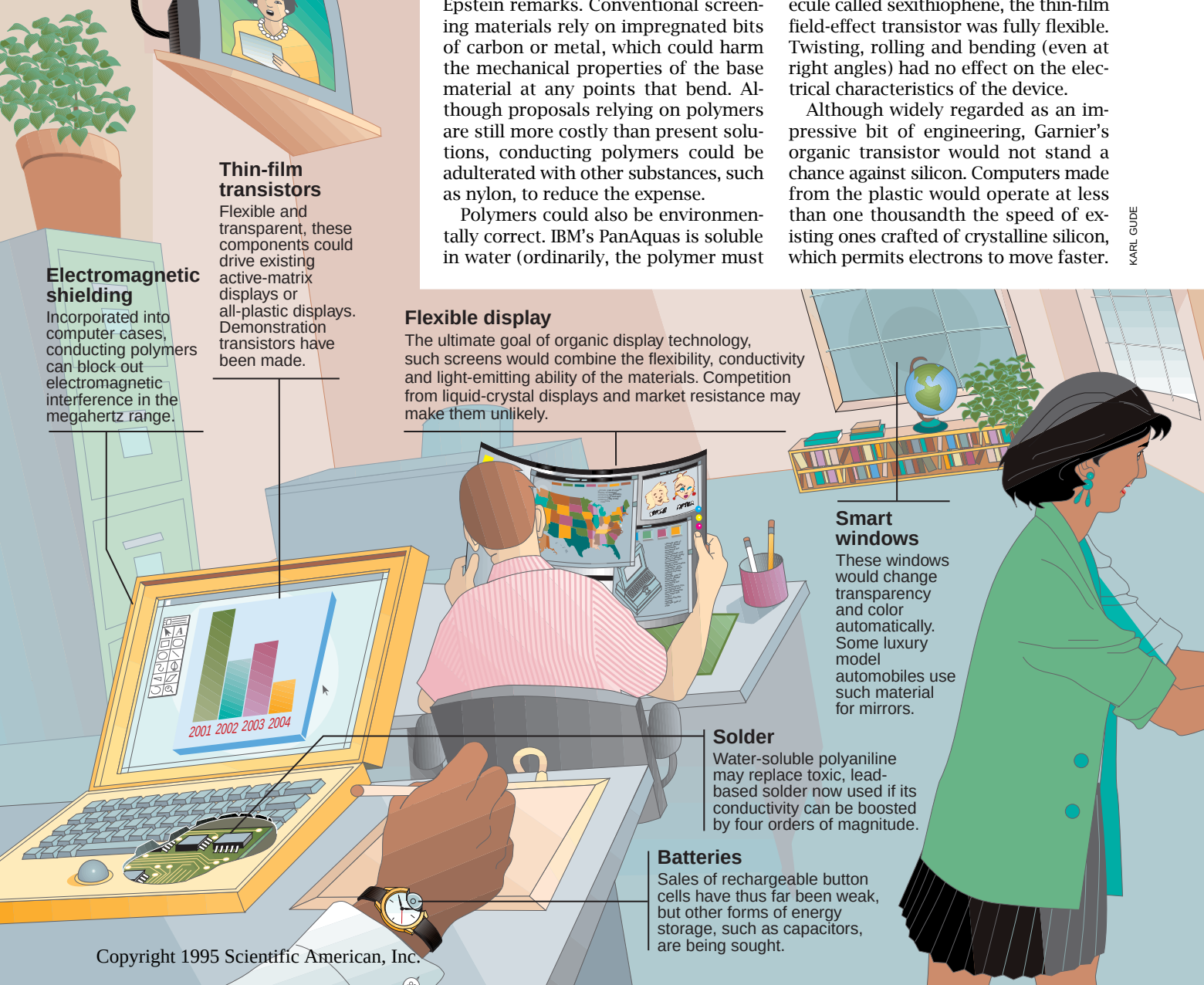
Polymers could also be environmentally correct. IBM's PanAquas is soluble in water (ordinarily, the polymer must be processed with organic solvents). If Angelopoulos and her colleagues could increase the conductivity of the water-soluble polyaniline, the material could replace the lead-based solder used to connect electronics parts on a substrate. MacDiarmid explains that outdated equipment poses an environmental hazard and an economic nuisance: "In many parts of Europe the manufacturer must remove all lead-containing material from discarded printed circuit boards, which is one hell of a job."

The All-Plastic Transistor

The ultimate achievement in electronics application, however, would be a component fabricated out of polymers. Using ordinary circuit-printing techniques, Francis Garnier of the CNRS Molecular Materials Laboratory in Thiais, France, did just that, creating the first all-polymer circuit element: a transistor. Constructed around a short-chain molecule called sexithiophene, the thin-film field-effect transistor was fully flexible. Twisting, rolling and bending (even at right angles) had no effect on the electrical characteristics of the device.

Although widely regarded as an impressive bit of engineering, Garnier's organic transistor would not stand a chance against silicon. Computers made from the plastic would operate at less than one thousandth the speed of existing ones crafted of crystalline silicon, which permits electrons to move faster.

KARL GUDE



But there is an application that does not need fast electronics: video displays. Currently amorphous silicon (that is, silicon in its noncrystalline form) is used in such circuitry because it is much less expensive to process than crystals are and can be laid on different substrates, such as glass. Garnier's transistor runs at just about the speed of circuits made from amorphous silicon, and he feels the requisite video-rate performance is easily within reach.

An organic semiconducting transistor would be a boon to manufacturers of liquid-crystal displays (LCDs), the approach that dominates research into flat-panel technology. Existing screens seal liquid crystals, made from various kinds of organic substances, between two glass plates; a fluorescent tube illuminates the crystals from behind. In so-called passive displays, the pixels (cells containing the liquid crystals) are controlled by voltages applied along all the rows and columns. In active-matrix displays, which offer greater contrast and resolution, each pixel is individually controlled by a thin-film transistor.

Therein lies the cost. A 20-inch, full-color active-matrix display contains more than two million pixels. Unfortunately, a few malfunctioning ones are sufficiently distracting to the sensitive human eye to ruin the image. "The percentage of flat panels rejected is very high," Garnier states. That failure rate drives up the price of the displays that make it to market.

Organic circuits might ease the strain on corporate wallets because they should be easier to make, especially in large sizes. The circuitry can be fabricated at lower temperatures and is less sensitive to the presence of impurities during processing, which should lower production costs. Moreover, organics could make it possible to create entirely new types of displays. Manufacturers should be able to tune the properties of the polymers, controlling their flexibility and even their transparency. See-through electronics would permit a direct-view, heads-up display on windshields and helmets, obviating the need to reflect images onto a viewing glass, as is now done.

Shines in the Dark

Conducting organics could also be used as the light sources in displays, not just in the controlling circuitry. Indeed, lightweight, robust displays have been one of the most widely publicized, pie-in-the-sky applications. But as a first step researchers are aiming for a more modest, albeit lucrative, use—light-emitting diodes. These little glowing indicators decorate innumerable electronic gizmos and are worth $400 million in the U.S., according to the 1994 figures of the Electronic Industries Association in Arlington, Va.

At present, LEDs are constructed from an inorganic semiconducting material, often gallium arsenide. Two layers, each

doped to have different electrical characteristics, are interconnected and act as positive and negative electrodes. When electricity passes through the materials, one electrode gives off electrons, the other, positively charged holes (spaces that electrons would normally occupy). The negative and positive charges meet at the junction of the substances, where they combine and give off light. The color of the light depends on the properties of the semiconductor and dopant; those producing red and green light are the easiest to make.

Organic LEDs promise to make the manufacture of these lights much cheaper, mostly by reducing the number of contacts and interconnections. Conventional LEDs must be spliced together to be used in displays on such devices as microwave ovens, alarm clocks and videocassette recorders. Each LED cannot be crafted larger than the gallium arsenide crystal wafers can be grown, and modern technology limits the size to no more than about six inches, measured diagonally. To make a large display, then, LEDs must be individually mounted and wired—a difficult task considering that one reasonably sized letter in a typical display takes 35 LEDs. In contrast, organic films can be laid over practically unlimited extents. In addition, the starting materials for organics are more economical than those for conventional LEDs.

Ching W. Tang and his colleagues at Eastman Kodak are by far leading the way in bringing organic-based LEDs to market. (The rather undescriptive term for the approach they have adopted—"small molecule"—distinguishes it from work using much longer polymers.) In 1987 Tang reported that a small crystalline organic molecule of 8-hydroxyquinoline aluminum (Alq) would give off green and orange light. Since then, workers found they could elicit all colors from the spectrum by varying the thin-film organic layer. Moreover, the organic LEDs can, in lumens per watt, burn as efficiently as a household bulb and can last 10 times longer—more than 10,000 hours.

"The efficiency is extremely attractive. With [components that have] a 10,000-hour lifetime," Tang says, "you can seriously consider display applications, particularly in portable devices." At the moment, small-molecule LEDs are not ready to replace liquid-crystal displays in flat screens—their performance is still too poor. Yet it is adequate for dot-matrix displays in electronic organizers and microwave oven panels, for instance, and that will do for now. Tang expects small-molecule LEDs to pop up in such applications in the next year.

High-end displays are not completely out of reach. Plastic light emitters may serve as backlights for liquid-crystal displays. This past March, Junji Kido and his co-workers at Yamagata University built a polymer diode that combined three different organic layers (each one emitting red, green or blue light) to yield a white radiance. Still, the diode glowed at most with only about one quarter the intensity of a standard room fluorescent lamp and had an efficiency of only about 0.5 lumen per watt, compared with the 15 to 20 lumens per watt of typical backlights.

One solution for increasing the brightness and efficiency may be an alternative architecture. Last year Ananth Dodabalapur and his Bell Laboratories colleagues constructed electroluminescent devices by sandwiching layers of Alq and inert material between two reflecting surfaces. Structured this way, the layers conform to the physics of a Fabry-Perot cavity—the basic structure of most lasers. The emissive Alq sends out light that bounces back and forth, amplifying until it leaks out one end. (This microcavity has yet to yield true lasing.)

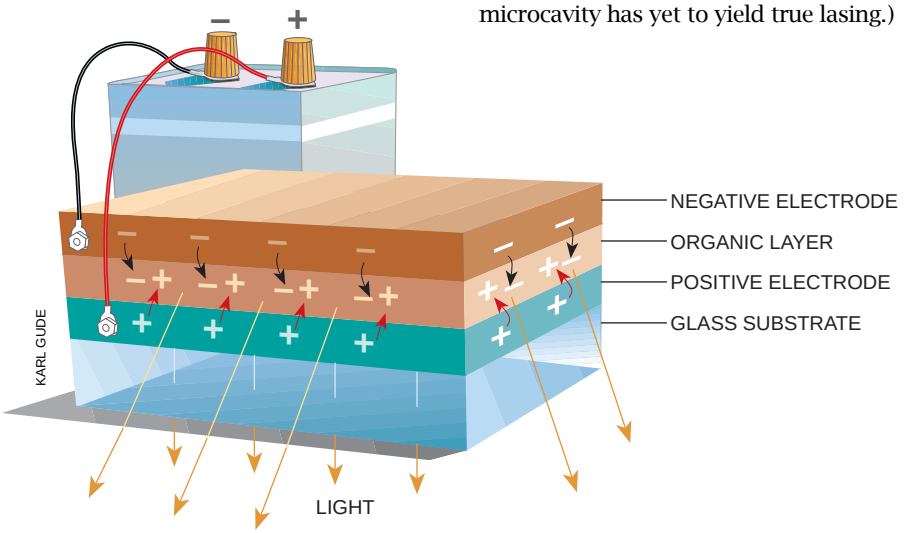
The Alq emits in all colors, although it is strongest in the green part of the spectrum. But by varying the thickness of one of the inert layers, the workers could filter out the extraneous wavelengths and make the microcavity LED produce light in all colors, even white. Also, because the light emerges from only one end of the cavity, more of it reaches the viewer, unlike the light from conventional diode structures, which leaks wastefully in all directions.

The potentially higher efficiency may also boost the longevity. Current that is not transformed into light becomes waste heat, which hastens a diode's demise. Because a microcavity LED would require less current for the same amount of light, it should in principle last longer.

Polymer Lights

Other investigators are trying to develop LEDs made from polymers instead of small organic molecules. The most widely used polymers are poly-*p*-phenylenevinylene, or PPV for short, and its derivatives. Richard H. Friend of the Cavendish Laboratory of the University of Cambridge and his associates discovered the green-yellow glow of PPV in 1990. By combining that material with electrodes made from other polymers or from flexible metal backings (like the foil that keeps supermarket nachos fresh), researchers have produced flexible LEDs that give off 2.5 lumens per watt. Driven at 10 volts, the light is about as bright as the fluorescent lamp in a liquid-crystal display. By varying the chemical makeup of PPV, they have also teased the full range of colors out of the devices.

So far, however, polymer LEDs have plenty of drawbacks. "Lifetime issues are clearly key to making this curiosity into a business," remarks Heeger, now at the University of California at Santa Barbara. Most polymer LEDs burn for only a few hundred hours, when 2,000 to 10,000 hours is desirable. The main cause is inefficiency. The polymer LEDs convert no more than 4 percent of the current sent through them into light; the rest is transformed into waste heat. Hence, the diode can shine quite brightly, but the high voltage necessary to achieve that intensity comes at the price of faster breakdown.



FLEXIBLE LED consists of an organic substance sandwiched between electrodes. A voltage applied to the LED sends negative and positive charges from the electrodes to the organic layer, where they combine and give off light.

Improved processing might extend PPV's life; during manufacturing, unwanted reactions can create defects on the polymer chain, which interfere with PPV's ability to glow. Shelf life is also a drawback; at the moment, PPV diodes last only several months in storage because they are unstable in air, reacting with oxygen and water vapor. Better packaging might help.

Still, polymer LEDs are close to being sufficiently bright and efficient for some limited applications. Heeger states that his company, UNIAX Corporation in Santa Barbara, "has identified serious market opportunities" for their flexible LEDs and expects the first products out in the middle of 1996. Cambridge Display Technology, which Friend helped to found, also expects to have something marketable within a year. Like small-molecule organic LEDs, the polymer LEDs will probably first be used in low-level performance areas, such as lights in toys, watches and promotional novelties.

Even if lifetime issues are resolved, polymer LEDs may never really see the light of day, not so long as the small-molecule, Alq-based LEDs surpass them in performance. Japan has focused virtually all its attention on the small-molecule lights. What keeps hope alive in the polymer crowd is the potential for cheaper manufacturing. Polymer LEDs extracted from solutions of chemicals may be easier to make than small-molecule LEDs, which are vacuum-deposited onto substrates.

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POLYMER SHEETS made of polyaniline appear as a lustrous pink (*left*) until doped with iodine, which makes the substance conduct and colors it blue (*right*). Weigong Zheng of the University of Pennsylvania prepared the material.

Who Wants Wallpaper That Glows?

Whether any new kind of LED, small molecule or polymer, emerges on a large scale depends on manufacturability. "Almost certainly at a cost, anything can be done," Friend notes. "The question is whether these things are going to be cheap." More to the point, existing technology is quite adequate. As indicator lights, conventional LEDs cost only pennies. As backlights, standard fluorescent lights are excellent sources, remarks Lewis J. Rothberg of Bell Labs. For polymer products, he says, "the competition is going to be harsh."

The color capability of organics could also be irrelevant. Why would you need a rainbow of hues if you just want to know if your amplifier is on? More broadly, does a market for a large, roll-up display truly exist? That question still has no clear answer. "People have a vision of carrying around a view graph," Rothberg says. "I don't know if the public is going to want that."

There is some justification for skepticism. The first commercial products incorporating conducting polymers were actually made a few years ago. In the late 1980s the Japanese companies Bridgestone and Seiko commercialized a rechargeable button-cell battery that used polyaniline for one electrode and lithium for the other. Milliken and Company, a textile manufacturer based in South Carolina, developed Contex, a fabric that consists of common synthetics interwoven with the conducting polymer polypyrrole. It just so happened that the conductivity of the resulting fabric was perfect for "spoofing" radar—that is, interfering with detection by making it appear that the signals were going right through empty space. It has an advantage over the military's existing radar camouflage nets, which rely on incorporated carbon fibers, in that it has no gaps in its signal absorption.

Yet sales of these early products proved disappointing. Although the polymer-based battery had a longer shelf life than did lead-acid or nickel-cadmium cells, the technology never took off. Heeger explains that the advantage, though real, was not substantial enough to convince investors to set up completely new manufacturing plants. Commercialization of Contex was perhaps even more discouraging. "We were approved as a vendor for the A-12 bomber," remarks Hans H. Kuhn of Milliken, "but the bomber was never built." While sobered—"I was much more of an optimist three or four years ago"—Kuhn is hoping that the army's interest in camouflage nets could revive appeal in the material.

Even conducting polymers that have loyal customers may not be financially worthwhile for a big corporation. Before IBM's PanAquas antistatic spray coating, Allied-Signal offered an analogous product named Versacon—the main difference being that Versacon was a dispersible powder rather than a solution and therefore may not have been as effective or as transparent. At the time, several companies considered Versacon advantageous and incorporated it into such products as paints and coatings. Yet Allied has abandoned production; the volume of sales was simply too low. "The major problems for wide applications remain cost and reliability," says Epstein of Ohio State.

That does not faze the pioneers of conducting polymers, especially because possibilities beyond electronics are conceivable. Epstein has a patent on a technique that uses the polymers to form "hidden joints." Polyaniline in powder form can be sprinkled on two pieces of plastic that need to be joined. The conducting powder can absorb the energy from ordinary microwave ovens to heat and fuse two other pieces of plastic together, making the two as strong as a single piece.

Baughman and MacDiarmid have made plastic electromechanical mechanisms. Two polymers with different conductivities would change their linear dimensions when current flows through them, much as the metallic strips in thermostats do under varying temperatures. The polymers would undergo more dramatic changes in size using much less electricity than conventional piezoelectric or electrostatic actuators, Baughman says. More than just high-tech tweezers, several microactuators coupled together could function as artificial muscle.

Certainly there is no shortage of imagination, and such immediate uses as the dissipation of static charge and the shielding of electromagnetic fields are clearly viable. But stiff competition from present-day devices and marketing considerations may jeopardize hopes of having a portable roll-up display to take on the commute to work. The newspaper may have to do for a while.

Election Fever in Blockvotia

The National Assembly of Blockvotia had just counted the votes for the Palmgreasing Slushfund Bill, and President Freebie Perks was not pleased. His secretary, Penelope, was doing her best to calm him down.

"Penny, you told me that four of the six districts were in favor, including the biggest. How did we lose?"

"It's the weighted voting system, sir. Each district has assigned to it some number of votes that is roughly proportional to its population. Here's a table showing the details. The total number of votes is 31, so any coalition that has 16 votes, or one more than half of that total, can decide the outcome.

"Sheepshire, Fiddlesex, Slurrey and the Porkney Isles voted for the bill. Four districts of six, as I said, including the biggest. But they have only 15 votes. The two who voted against have 16."

"The presidential election is coming up next month, and I don't want a repeat. If we got the Boundary Commission to give Sheepshire one more vote and Candlewick one fewer—"

Penny shook her head. "I wouldn't recommend that, sir. Richfolk and Candlewick both favor your reelection. Sheepshire is wavering, and the other three are opposed. Richfolk and Candlewick can block a coalition formed by the other four, but not if you take a vote away from either one of them."

There was a knock on the door, and Charlie Hogg, the representative from the Porkneys, stormed in.

"Mr. President, your so-called democratic voting system is a farce. The Porkneys have no power!"

"But you have one vote, in proportion to your population. Slurrey, which has a larger population, also has one vote. You actually have more power than Slurrey."

"Nope. The outcome of any vote is decided entirely by the three largest districts. At least two of them will vote the same way, and their combined votes will be at least as great as those possessed by Richfolk and Candlewick, the second and third largest districts. That's 16 votes—a majority. You would get the same result in any vote even if the three smallest districts had none to cast!"

"I see. But what can I do about it?"

"Give us another vote! Then at least the three smallest districts could join with Sheepshire to produce a tie. If you gave Slurrey a second vote, too, we could form a winning coalition."

"I get it. The total number of votes would then be 33," Penny said. "So 17 or more would win. A coalition of Fiddlesex, Slurrey, the Porkneys and Sheepshire could force a win."

"Yes! Any one of the smallest three districts could swing the vote."

The Boundary Commission liaison officer, Gerry Mander, walked in. "Gerry, can the Boundary Commission redraw the districts so that Slurrey and the Porkneys get an extra vote?" Perks asked.

Mander shook his head. "Might swing it for Slurrey. But the Porkneys are islands."

"My constituents won't be pleased," Hogg growled.

"No. But, as you said, that will have no effect, because your district is powerless," the president chirped. "Don't make threats you can't keep, Hogg."

"You can't be happy that three districts alone can put you out of office. There must be something you can do."

"I could give two votes to Sheepshire."

"But extra votes for the biggest district can't possibly help the smallest one gain a share of power!" Hogg wailed.

"On the contrary," Perks said. "If Sheepshire has two more votes, you get a share of the power."

"Yes," Penny said, looking over the numbers. "The same coalition musters 17 votes out of 33; again each of the three smallest districts can claim to hold the balance of power."

"That's weird," Hogg said. "You give more power to Sheepshire, and some of it miraculously rubs off on us."

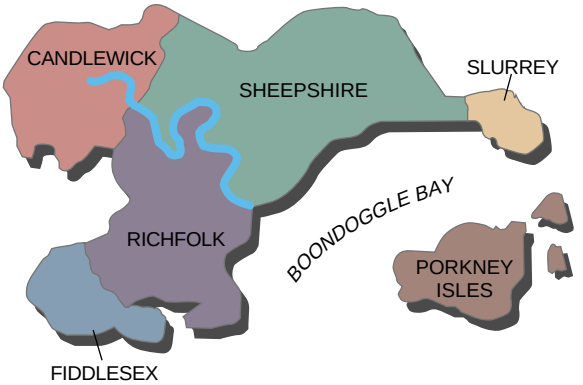
"No, Hogg, we don't give them more power—we give them more votes," Penny sighed. "As you argued, those aren't the same at all."

"Oh, but wait," Perks said. "If power isn't votes, what is it? I need to know. Power wins elections."

"I think you need the Banzhaf power index, sir," Penny said. "In 1965 lawyer and activist John F. Banzhaf III proposed a way to measure the power held by each member in a weighted voting system. The idea is that a representative can exercise power either by joining a losing coalition and turning it into a winning one or by leaving a winning coalition and turning it into a losing one."

"Aren't those the same thing?"

"That's correct, sir. When you join one coalition, you leave another formed by everybody else. So we need only to consider one case—say, creating a winning



JOHNNY JOHNSON

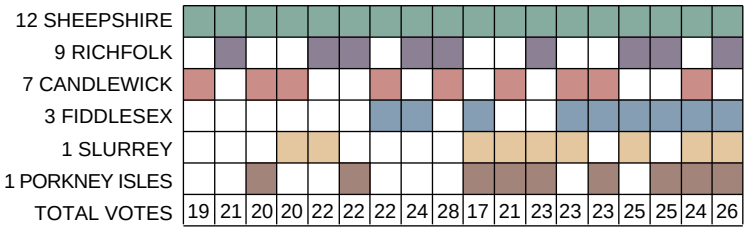
MAP OF BLOCKVOTIA shows the size of the various districts. The charts list the current voting weights and two additional possibilities.

VOTING WEIGHTS FOR THE DISTRICTS OF BLOCKVOTIA	
DISTRICT	NUMBER OF VOTES
SHEEPSHIRE	10
RICHFOLK	9
CANDLEWICK	7
FIDDLESEX	3
SLURREY	1
PORKNEY ISLES	1

AMENDED VOTING WEIGHTS	
DISTRICT	NUMBER OF VOTES
SHEEPSHIRE	10
RICHFOLK	9
CANDLEWICK	7
FIDDLESEX	3
SLURREY	2
PORKNEY ISLES	2

THIRD-CHOICE VOTING WEIGHTS	
DISTRICT	NUMBER OF VOTES
SHEEPSHIRE	12
RICHFOLK	9
CANDLEWICK	7
FIDDLESEX	3
SLURREY	1
PORKNEY ISLES	1

COALITIONS IN WHICH SHEEPSHIRE IS PIVOTAL IN A [17; 12, 9, 7, 3, 1, 1] VOTING SYSTEM



POWER INDEX of Sheepshire in the above voting system is 18, reflecting the number of coalitions in which it plays a pivotal role. Ideally, the power index should be made nearly equal among all districts, as was done in Tompkins County, New York, in 1982.

BOARD OF REPRESENTATIVES, TOMPKINS COUNTY, NEW YORK, 1982

MUNICIPALITY	POP.	WEIGHT	POWER INDEX	POWER/ POP.
LANSING	8,317	404	4,747	0.571
DRYDEN EAST	7,604	333	4,402	0.579
ENFIELD & NEWFIELD	6,776	306	3,934	0.581
ITHACA WARD 3	6,550	298	3,806	0.581
ITHACA WARD 4	6,002	274	3,474	0.579
ITHACA SOUTHEAST	5,932	270	3,418	0.576
ITHACA WARD 1	5,630	261	3,218	0.572
ITHACA WARD 2	5,378	246	3,094	0.575
ITHACA NORTHEAST	5,235	241	3,022	0.577
GROTON	5,213	240	3,006	0.577
CAROLINE & DANBY	5,203	240	3,006	0.578
ITHACA WARD 5	5,172	238	2,978	0.576
ITHACA WEST	4,855	224	2,798	0.576
ULYSSES	4,666	214	2,666	0.571
DRYDEN WEST	4,552	210	2,622	0.576

JOHNNY JOHNSON

coalition. Suppose that a certain representative plays a pivotal role in a coalition: it will win with her and lose without her. The Banzhaf power index for any particular representative is the number of different coalitions in which she plays just such a role.

"Our original voting system was a [16; 10, 9, 7, 3, 1, 1] system. The vote needed for a majority is 16; the districts have weights of 10, 9, 7, 3, 1 and 1. The Porkneys could play a pivotal role only in those coalitions having exactly 16 votes. If the group had more votes, it would make no difference if the Porkneys defected. If it had fewer, it wouldn't be a winning coalition. But there are no such coalitions and so the Porkneys' power index is 0. With the president's new proposal, we have a [17; 12, 9, 7, 3, 1, 1] system. The Porkneys are pivotal in any coalition that contains them and has precisely 17 votes. There are exactly two, so the Porkneys' power index is 2."

"And Sheepshire?" Perks asked.

"Sheepshire has 12 votes, so it plays a pivotal role in any coalition it joins having between 17 and 28, or 17 – 1 + 12, votes. You can list those coalitions by trial and error. There are 18 of them, so Sheepshire's power index is 18."

"Their population would be 12 times ours, but their power would be only nine times greater," Hogg exulted.

"Is there a better method than trial and error?" Mander asked.

"Well, it's best done by computer for large systems," Penny said. "For small systems such as our own, however, there's a nice graphic method. Suppose the system is [3; 2, 1, 1]. That is, there are three voters: A, B and C. A has two votes, B and C have one, and three makes a majority.

"First, you draw a lattice diagram that shows all the possible coalitions and links them by an edge if they differ by just one member. Label each edge with the member they do not have in common. Then mark every pivotal edge (*red*)—where the total vote changes from being below the majority to being equal to it or above it. The power index of any given member is the number of pivotal edges bearing its label. Here member A appears on three pivotal edges and so has a power index of 3; B and C appear on one pivotal edge each, having a power index of 1. The lattice diagram is a cube. The lattice diagrams for bigger systems get messy. The one for four members is kind of nice, though."

"I'd be happy if everyone had a power index roughly in line with their population," Hogg said.

"It's not so easy," Penny said. "Let me show you how it worked out for the Board of Representatives of Tompkins County, New York, in 1982. The power index was almost exactly proportional to the population."

"We could try to do something similar here," Hogg suggested.

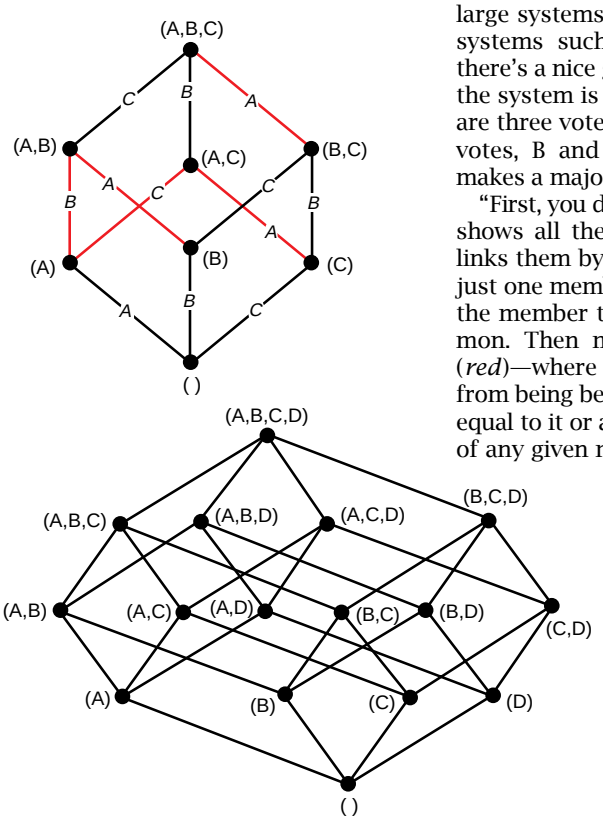
"Maybe," the president said slowly. "Do you have any studies of the power index of the U.S. president, Penny?"

"Yes, sir. He has a power index 40 times greater than that of a senator and 175 times greater than that of a member of the House of Representatives."

"That sounds wonderful."

"But the U.S. legislative body as a whole holds roughly two and a half times more power than the president."

Freebie Perks stared at her for a moment, then he looked Hogg firmly in the eye. "I think we'll stick to the present system."



JOHNNY JOHNSON

***LATTICE DIAGRAMS show a three-member voting system* (top) *and a four-member system* (bottom).**

FURTHER READING

ONE MAN, 3,312 VOTES: A MATHEMATICAL ANALYSIS OF THE ELECTORAL COLLEGE. John F. Banzhaf III in *Villanova Law Review,* Vol. 13, pages 304–346; Winter 1968. Rebuttals in Vol. 14, pages 86–96; Fall 1968.

GAME THEORY AND RELATED APPROACHES TO SOCIAL BEHAVIOUR: SELECTIONS. Edited by Martin Shubik. R. E. Krieger, 1975.

FOR ALL PRACTICAL PURPOSES: INTRODUCTION TO CONTEMPORARY MATHEMATICS. Second edition. Edited by Lynn Arthur Steen. W. H. Freeman and Company, 1991.

REVIEWS

Beauty in the Beast

Review by Mel Sunquist and Fiona Sunquist

INTO AFRICA, by Craig Packer. University of Chicago Press, 1994 ($24.95).

Craig Packer is engrossed by the social evolution of animals. Together with his wife, Anne Pusey, he has spent parts of the past 20 or so years working in Africa, watching baboons, chimpanzees and lions in an effort "to solve fundamental problems about how cooperation can arise in a sea of self-interest." Against the wildly dissimilar backgrounds of the open Serengeti plains and the dripping, disease-ridden forests of Gombe, Packer, a professor at the University of Minnesota, wrestles with the basic question of "Why be social?" Why *do* lions and chimps live in groups? Why bother to cooperate?

To answer these questions, Packer works with well-studied populations. He builds up a detailed knowledge of each animal's personal history—who is related to whom, who breeds and who does not, and how many young survive to have families of their own. To maintain continuity in the data, he or his students must return to the study site every year, conduct a census of adults and record the identity and parentage of new offspring.

In *Into Africa,* Packer deftly uses his latest trip as a framework on which to hang the story. Traveling with Packer is like birdwatching with Roger Tory Peterson or going into a kitchen with Craig Claiborne as your guide. The enjoyment comes not just from the insights into the lives of lions and chimpanzees but in getting to know Packer as a person. He shares impressions, motivations, fears, gossip and background rarely offered by biologists. He reveals himself to be engrossed more by the questions than by the animals themselves; he views baboons, chimpanzees and lions as "abstractions, like well-defined characters in a good novel."

The drive into the Serengeti Research Institute sets the park starkly in context. We see the Serengeti not just as a vast, wild grassland teeming with animals but as a 5,000-square-mile protected area embedded within a larger African civilization of hunting reserves, small towns, markets, agriculture and tourist lodges. Two million hungry people live within 50 miles of the park's western boundary, in a landscape where lines of snares and pit traps dot the riverbanks. This is not the Serengeti we think we know from television specials.

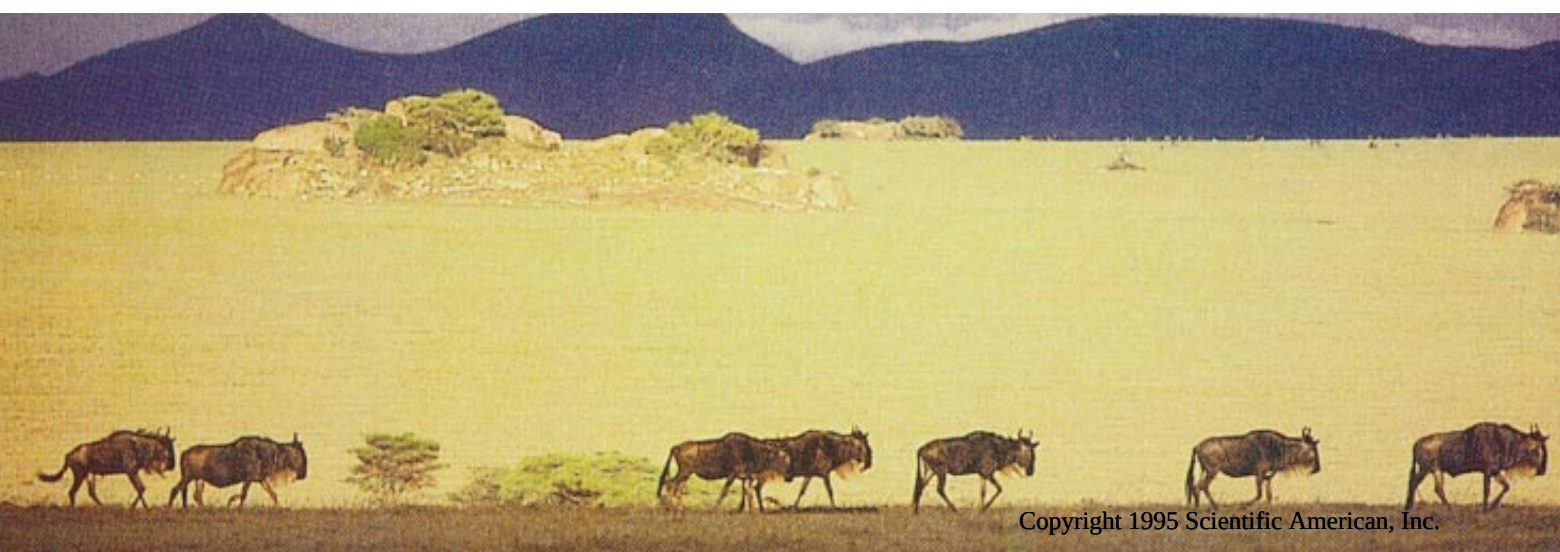
As Packer drives his graduate students around the study site, we, too, become immersed in the sights and sounds of the Serengeti. Later he explains how he began to unravel the Gordian knot of problems that surround the issue of cooperative hunting. While puzzling over the generally dismal show of cooperation displayed by hunting lions in the Serengeti, Packer tries to enter the mind of a selfish animal on a group hunt. "Think of a doubles match where your partner is the top seed at the tournament, and you are a rank amateur," he writes. "When the ball comes over the net, what are you going to do? Charge around and run yourself ragged, or hang back and force your talented partner to cover most of the court?" Among the selfish lions of the Serengeti, the answer is to hang back—as long as someone else is taking the mortal risk, don't bother to get up!

The lions of the Serengeti spend most of the year at the animal equivalent of a Christmas dinner table. Elsewhere in Africa, where prey is much scarcer, lions often do hunt cooperatively. These conflicting observations, once a source of argument, now fit neatly into the theory that animals hunt cooperatively only when they have to.

After a couple of weeks with the lions, Packer heads for Gombe, the site of Jane Goodall's three-decade-long study of chimpanzees. Compared with the "big sky" splendor of the Serengeti, Gombe is a dark, sodden place full of snakes, biting insects and steep hillsides covered with tangled vegetation. Fieldworkers constantly battle the elements just to move around, let alone follow baboons or chimpanzees and collect data. On one occasion, Packer and another researcher are caught in a tropical downpour: "The storm finally breaks free, and we can only brace ourselves, there is no place to hide. The air is white with rain; we stand facing the ground to keep from choking. The baboons sit like Buddhas with their eyes closed."

Returning after several years' absence, Packer scans the faces of the children and grandchildren of the baboons he studied years ago and re-

ABUNDANT PREY, such as these wildebeest, make hunting comparatively easy for the lions of the Serengeti.



marks regretfully that there is no easy, objective way to recognize these animals. Unlike lions, they cannot be identified by whisker rows and spots, then catalogued in a card index file; their faces must be learned and stored in the minds of human observers.

Recollecting his student days at Gombe two decades earlier, Packer regales us with the highs and lows of living and working in this famous 12-square-mile patch of forest. In the early 1970s, when research at Gombe was at its peak, as many as 18 graduate students lived, played and worked there. Although field conditions were arduous and the hours incredibly long, a sense of community prevailed—"the Gombe spirit," as Goodall called it. Remarkable scientific discoveries took place there, including the first observations of cannibalism among chimps and chimpanzee warfare—male groups invading, attacking and cooperating to pin down and kill an opponent.

There were also hauntingly bad times at Gombe. A female graduate student died, probably having fallen off a cliff while following a group of male chimpanzees. One terrible night 40 armed men stormed the camp and kidnapped an administrator and three Stanford University students. Those events resulted in major procedural changes. In place of the graduate students, Tanzanian fieldworkers now do most of the chimp following but not just as uninvolved day laborers. They discuss their day in the forest in excited detail, relating new moves by the chimps and talking about who did what to whom. The spirit of discovery and teamwork remains. Gombe should be a model for long-term field studies everywhere.

Apart from longing for more photographs and a detailed map to follow Packer's journey, one closes *Into Africa* with a sense of satisfaction. Not only have we explored a part of the world that must rank high on the agenda of every armchair traveler, but we have ventured behind the scenes of the television specials on animal behavior to experience what it is like to be there, doing the research. We have come to know our guide and have enjoyed being with him despite, or perhaps because of, his driven, worried and intestinally challenged companionship. Packer has done what few have been able to do. He has put a face on a real wildlife biologist.

MEL SUNQUIST is an associate professor in the department of wildlife ecology and conservation at the University of Florida. FIONA SUNQUIST is a science writer and roving editor for International Wildlife.

Crowd Control

Review by Virginia Deane Abernethy

CRITICAL MASSES: THE GLOBAL POPULATION CHALLENGE, by George D. Moffett. Viking, 1994 ($26.95).

The author's journalistic background forms the touchstone of this in-depth exploration of the perils of overpopulation. George D. Moffett's skillful weaving of facts and anecdotes vividly conveys the population-driven environmental, social, political and economic disintegration that is occurring worldwide; unfortunately, he also credulously repeats some of the bankrupt conventional wisdom about how to confront the current situation. The book's greatest strength derives from the extensive interviews he has conducted with men and women from all walks of life. These quotes and paraphrases open a window on the calculus underlying survival strategies and family-size decisions in diverse settings ranging from Cairo to Thailand to Guatemala.

The comments elicited by Moffett support my own findings (which I have set out in *Population Politics* and elsewhere) that a sense of limited environmental resources and of deteriorating economic opportunity strongly encourages people to exercise reproductive and marital caution. In Cairo, he writes, "housing shortages have forced thousands of couples to delay marriage, sometimes for years." In Thailand, "Sam Ruang would like to have one more child, but he understands that that is beyond his means." In Mexico a 32-year-old mother of two defends her use of contraceptives to the village priest, saying that "'things are difficult here. A majority of people are having hard times. Jobs are hard to come by.'"

A further brake on fertility comes from the new pattern of international lending, in which loans are tied to the important contingency that the recipient governments implement austerity measures. Moffett observes that the Mexican government "has turned adversity to good account, communicating the message that because of the country's protracted economic crisis, more children means less for everyone." When the Kenyan government eliminated subsidies for education, "faced with the need to shoulder the costs of education alone, many parents have responded by embracing family planning and having fewer children."

Drawing on his own extensive research and scientific background, Moffett writes that "the inverse relationship between living costs and childbearing is found throughout the developing world." That conclusion is congruent with a recent report on acceptance rates of contraceptives among the Yoruba in Nigeria. John Caldwell, a respected demographer, stated that "two-thirds of all respondents claimed that the major force behind marriage postponement and the use of contraception to achieve it was the present hard economic conditions." Many of Caldwell's informants also perceived that as local crowding increased, children seemed more susceptible to dying, and they viewed this connection as a deterrent to frequent childbearing, counter to what is often assumed.

The policy implications are not arcane. On the contrary, they are all too clear but do not sit well with the interventionist-internationalists (a cabal well represented in the media), who espouse the 50-year-old demographic transition model, which justifies blanket foreign aid aimed at increasing personal wealth. Unfortunately, the journalist in Moffett quickly retreats from his rich data in favor of the conventional tenets. He is soon laying out the need for economic development and reporting that half of a successful family-planning policy entails "continuing efforts to alleviate poverty and raise living standards." Yet by Moffett's own account, it is perception of the fact and threat of *declining* living standards that have induced countless people to limit family size.

Indeed, the data suggest—but well-meaning people are loath to state—that past government subsidies of food, housing, health care and education (made possible by international development aid) were counterproductive precisely because they fostered images of abundance and prosperity. I have found that fertility stays high and may in fact rise under such circumstances. History provides numerous examples of fertility rising in response to expansion of the ecological niche, whether as a result of innovative technology, improved crops, new sources of income, escape through migration, or a populist political change that promises to redistribute wealth.

It is telling that those few of Moffett's informants who remain comfortable with large family size are the very ones who still perceive a frontier of opportunity. Guatemalan Lopez Alala, for example, was a pioneer logger in the Petén region, a virgin forest opened to settlement in the early 1970s. He and his fellow families average nearly eight children each. Lopez anticipates that his children's families will be of similar size and expects also that "the forest will be there for them to clear." Who but the willfully blind would not speculate that

Lopez's grand procreative strategy might be linked to his optimism?

Every time Moffett mentions the "demographic transition model" as a prescription for slowing population growth, it chills the blood: cash infusions that subsidize consumption seem only to fuel high fertility. The larger part of his recommendations are sound, however. In the excellent chapter called "A World Population Plan of Action," he describes the importance of getting contraceptive services to impoverished peoples and hard-to-reach constituencies, a challenge that often involves overcoming the concerted objections of entrenched religious entities. Moffett rightly cites improved employment opportunities for women as another promising strategy for limiting family size. Case studies show that women who work in the cash economy, however menially, recognize the cost of time spent raising children and so are more willing to limit the number of offspring.

But Moffett and others are also ready—too ready, in my opinion—to spend scarce resources on women's education and health care. Although these services are desirable in themselves, the evidence linking them to lower fertility is correlational and open to multiple interpretations. Nevertheless, health and education were part of the mainstream credo of the International Conference on Population and Development held in Cairo last September.

With the caveats given, Moffett's book can be recommended for those who want a lively and provocative introduction to the world population crisis. It is a challenge for the reader to sort out real data from rote repetition of demographic transition theory. The problem is important enough, one hopes, to spur policymakers and informed citizens to consult a wider reference list.

VIRGINIA DEANE ABERNETHY is professor of psychiatry and anthropology at the Vanderbilt University School of Medicine and author of Population Politics: The Choices That Shape Our Future *(Plenum Press, 1993).*

LOIS LAMMERHUBER *Matrix*

***PACKED MARKET** reflects the huge population of Cairo. Would economic development really slow population growth, as is commonly assumed?*

Road to Nowhere

Review by Joseph I. Silk

THE PHYSICS OF IMMORTALITY: MODERN COSMOLOGY, GOD, AND THE RESURRECTION OF THE DEAD, by Frank J. Tipler. Doubleday, 1994 ($24.95).

The dividing line between science and science fiction is surprisingly soft. One might hope that scientists would strive to maintain the division from their side. Recent books suggest otherwise. Not long ago we had Kip Thorne taking the theory of general relativity via *Black Holes and Time Warps* into the uncharted territory of time machines. Now, in *The Physics of Immortality,* Frank J. Tipler, a professor of mathematical physics at Tulane University, vigorously attempts to drag relativity through the doors of the church.

Tipler takes us one large step further than Thorne does beyond the pale of scientific respectability. He uses big bang cosmology to prove the existence of God, specifically a loving God who will resurrect us all to eternal life. Tipler claims that theology is simply a subbranch of physics and that God is what he defines as the Omega Point: the end point to our universe, when the future big crunch will provide an inexhaustible supply of energy (from the release of gravitational energy liberated by the collapse of the cosmos). Armed with that energy and a corresponding ability to store information, a supercomputer of the future—also known as God—will attain unlimited power, resurrect the dead and bestow all sorts of blessings on humanity.

Most cosmologists are prepared to accuse Tipler of the direst crime, perpetrating a hoax of Piltdown Man proportions. Yet the reading public seems eager to embrace Tipler's theology. Even Wolfhart Pannenberg, an eminent German theologian, has spoken out in its defense. To provide a veneer of sophistication, Tipler appends many pages of mathematical notes, which generate an almost impenetrable aura of erudition. Immortality, he purports to prove, is an inevitable consequence of general relativity and quantum theory. When Tipler starts using physics to prove the existence of God, the scientist tunes out. But is dabbling with God any more insidious than musing about time travel? And where does Tipler go wrong, if indeed he is guilty of the alleged crime?

Other researchers have already softened up the God-seeking audience. Physicists far more mainstream than Tipler have equated God with such fundamental entities as a set of equations or the Higgs boson, an undiscovered elementary particle. European countries are pouring billions of dollars into the Large Hadron Collider for the Higgs search. Particle physicists flock around "theories of everything" (which aim to explain the very basis of existence) like moths around a flame.

Even observational cosmologists have entered the God stakes. George Smoot, the leader of the National Aeronautics and Space Administration team that discovered fluctuations in the cosmic microwave background, described his achievement as seeing "the face of God." Paul Davies, seldom far from the forefront of cosmology, has already written two books in which he identifies God as a quantum cosmologist. Never one to be bashful, Stephen W. Hawking declared God unnecessary. Hawking proposes that the universe has no boundary in space or time, rendering a divine Creator superfluous.

Tipler takes a very different, personal tack that carries him into uncharted territory light-years beyond Davies, Hawk-

ing and their ilk. Tipler's theology, for instance, embraces not just cosmic structure but human sex: thanks to the Omega Point, "it would be possible for each male to be matched not merely with the most beautiful woman in the world, not merely with the most beautiful woman who has ever lived, but…with the most beautiful woman whose existence is logically possible." In this process, our bodies can acquire the most desirable characteristics, and unrequited love is certain to be requited. This astonishing vision, we are told, stems directly from application of Einstein's theory of general relativity.

Tipler's bold assertions test the limits of how far science can take us in the ageless quest for an omniscient and omnipotent deity. Physics is far from confronting consciousness. For now, biologists laugh at the notion that quantum gravity could provide vital clues to the origin or evolution of life. Yet Tipler envisages a supercomputer of the future that will be able to resurrect human beings in full: our memories of passion, our thoughts of beauty, our dreams and desires. I concede that one must remain open-minded regarding any predictions about the capabilities of supermachines billions of years in the future, but I cannot really believe what Tipler describes.

THE GRANGER COLLECTION

GOD PRESIDES over the Ptolemaic universe in Martin Luther's bible. In a twist on traditional theology, Frank J. Tipler wants to build a modern God from the laws of physics.

My confidence in Tipler's grand predictions is not strengthened by the gaping holes in his more specific assertions. Consider the claim that he has made elsewhere, and repeats in *The Physics of Immortality,* that the universe cannot be teeming with life, because if it were we would have already found artifacts of ancient alien civilizations in the solar system. This fallacious argument ignores the likelihood that any advanced civilization capable of colonizing the galaxy would have developed the ability to hoodwink and hide from any terrestrial simpletons they encountered.

The assertion that our fate in a collapsing universe will enable us to unlock the gates of heaven is equally flawed, for a simple reason. When the universe was one minute old, it was about as hot and dense as the center of the sun. We are quite confident of this description because of the remarkable success that the big bang theory has had in predicting the abundances of the light elements, which were synthesized in the first few minutes. In the distant future, if the universe does ultimately collapse, it would return it to a similarly hot, dense state. No room there for any supercomputer or for any recognizable being. Sex would not be much fun at 100 million kelvins. It seems that Tipler has constructed hell rather than heaven.

Can this man actually believe what he writes? Or is he the Don Quixote of modern physics, tilting at imaginary windmills? Even these questions are almost beside the point. Tipler's illustrious predecessors in cosmology have presented hypotheses in which they allegedly did not believe. Tipler's real crime is to have cheapened physics by bringing it down to the level of a religious cult.

This pandering does a disservice to science. It may sell books, but it alienates philosophers, if not theologians. Reductionism does not work any longer, even in physics. Nor does physics begin to tap the depths and complexity of biological structures. Life is likely to involve far more than a set of equations. I would contend that as many mysteries may reside in the uncertain boundaries at critical phase transitions as in the physical regimes amenable to algorithmic computation. One has to go beyond physics to comprehend the full complexities of nature.

Physics, for good reason, was born, and still resides in some circles, as natural philosophy. Physics and philosophy enrich each other, in a relationship that deserves to be more than a mere relic from the amateur inquirers of that bygone era. Why should modern physicists give a hoot about philosophical issues? The reason, as I see it, is to keep the science in perspective, a notion that Tipler has lost.

Older, established physicists often have turned their thoughts toward religion. Steven Weinberg writes that "the more the universe seems comprehensible, the more it also seems pointless," which runs counter to Einstein's more optimistic philosophy, shared by many scientists, "God is subtle, but He is not malicious." Davies insists that "science offers a surer path to God than religion." And Hawking offers his dream: "Then we shall all, philosophers, scientists and ordinary people, be able to take part in the discussion of the question of why it is that we and the universe exist. If we find the answer to that, it would be the ultimate triumph of human reason—for then we would know the mind of God."

Such thoughts complement theology and are not a substitute; Tipler, however, takes the search for a science of God to a ridiculous extreme. Humility in the face of the persistent, great unknowns is the true philosophy that modern physics has to offer.

JOSEPH I. SILK is professor of astronomy and physics at the University of California, Berkeley, and author of A Short History of the Universe *(Scientific American Library, 1994).*

ESSAY by Anne Eisenberg

Rest and Relaxation on the Net

He's probably playing a MUD, that teenager who once spent rapt hours reading Robert Heinlein. MUDs (from Multi-User Dimension and, earlier, Multi-User Dungeon) are adventure games that operate on computer networks. At least 300 MUDs run on the Internet, set anywhere from Camelot (you wake up alone in a dark forest) to the future (your planet is being attacked by Romulans). The games combine role playing and problem solving with what is called a chat feature—players can type messages to one another that appear on-screen within seconds. MUDs lack the visceral graphics of arcade games; in fact, they have no graphics whatsoever. MUDs are, as they say in the computer industry, text-based, meaning that only words, not exploding spaceships or slain dragons, appear on the monitors. The action plays out not in images but in the imagination.

MUDs fascinate college students, who log on late in the evening to chat and play through the night. ("When you get tired of talking, you can always go back to killing," one student explained.) MUDs and their many variations, such as MUSHs, MOOs and MUCKs, are examples of the thousands of on-line entertainments collectively known as Net games. A multitude of users stands ready to play these games, poised for the next round of chess, LambdaMOO (the most popular MUD), the World Wide Web pop culture scavenger hunt, trivia court, e-wrestling and I Ching.

Innocents who have confined themselves to the occasional hand of solitaire on the PC are just beginning to discover how seductive Net games can be. In the elastic space of the Internet, a world of insidious habits awaits—a fact well known to researchers who must shoo postdocs deeply engrossed in Netrek tournaments away from the Silicon Graphics workstations. (Netrek is an on-line evolution of *Star Trek*. It is martial, addictive and so complex it requires two hands to play: one for the mouse, the other for the dozens of keystroke commands needed for a blood-stirring dogfight. Netrek is graphical, not text-based, the better to spot the twinkling green spaceships of invading Klingons warping onto the high-resolution monitor.)

Net games can be a vast time sink. In a version of Netrek called Paradise, for instance, a typical player's age—the term for the amount of time actually clocked by a Netrekkie during competition—is two to three weeks. (Procrastinating doctoral candidates will, of course, have far higher stats.)

From their beginnings, interactive games have fascinated the technically minded. In 1962, inspired by science fiction writer E. E. "Doc" Smith, a young programmer named Steve Russell created Spacewar, a game designed to run on a Digital Equipment Corporation PDP-1 computer. Players faced their

STEWART BRAND

SPACEWAR TOURNAMENT in 1962 presaged the rise of modern Net games.

toggle switches and cathode-ray tube displays and never looked back. Within weeks, the game—an addictive combination of strategy, reflexes and life-or-death combat—propagated through the Arpanet, an early computer network.

Hackers created and passed on refined versions of the game from one research center to the next. Stewart Brand, best known as the founder of the *Whole Earth Catalogue,* recorded the experience of watching several hundred people "ruining their eyes, numbing their fingers, joyously slaying their friends and wasting their employers' valuable time." As companies switched from batch computing to workstations, electronic tournaments invaded the business world. A computer scientist remembers the excited whisper of a colleague when their company first bought Imlacs: "It's a workstation. *You can play games on it.*"

Scientists tend to be a playful lot, so it comes as no surprise that they are drawn to gaming on the Net. In *Naturalist,* E. O. Wilson credits "bright minds at play" for most scientific achievements. That love of play is probably also responsible for untold hours lost in the Bermuda Triangle of on-line games. In the years since the appearance of Spacewar, the Arpanet has grown into the Internet; parents who once banned TV have switched to banning modems; and Brand—who dubbed the midnight Spacewar gatherings in 1962 as "a crystal ball of things to come"—has turned out to be absolutely right.

You do become a wonderful typist. In Genocide, for instance, one of the most complicated and fast-moving MUDs, a player who wishes to remain among the living must fend off a dozen competitors at a time, each of them sending lines of text that must be read and rebutted instantly. Those who thrive in this and in other Net game worlds must be both fast and accurate on the keyboard. To save time, players learn aliases—standard, shortened forms of their game's lexicon. *K* is usually for kill, of course; *ki* is for a more romantic moment ("Kiss whom?" the screen will prompt politely if you are not specific). *Cac* may represent cackle (the screen will read, "You throw back your head and cackle with insane glee"). Choose *n* and see, "You head boldly north for the deserted monastery." Once inside, try *lo* (look) to check out the mysterious books on the refectory table.

The abbreviations on the chat lines that accompany MUDs tend toward the starkly phonetic. "See" has become *c,* "you" has turned into *u,* and "ex-" (as in "expert") has reduced itself to *x*. Among younger players, numbers replace letters when writers want to show off their Net savoir faire: *l* becomes 1, *e* becomes 3 (a laterally reversed E). Using this orthography, "elite," a word of highest praise among youthful gamers, becomes *3133t*. College-age players who learn aliases to increase their combat speed scorn complicated coinages like *3133t* that may slow their response time. Besides, one of them explained to me on-screen, "It's kid stuff." Then he signed off to his friend on the MUD with characteristic élan. *Bi,* he typed. *C u l8r.*

ANNE EISENBERG (aeisenb@duke.poly.edu) is a professor, writer and occasional game player at Polytechnic University in Brooklyn, N.Y.