SCIENTIFIC AMERICAN

AUGUST 1995
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A new theory of AIDS latency.

What causes tornadoes.

The comet collision: one year later.

***Diving's greatest dangers** often come from the air, not the water.*

SCIENTIFIC AMERICAN

August 1995 Volume 273 Number 2

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Recollections of a Nuclear War
Philip Morrison

On the 50th anniversary of the bombings of Hiroshima and Nagasaki, this celebrated physicist and author reflects on the nuclear age. As a member of the Manhattan Project, he saw fission grow from a frightening promise in the lines on a chalkboard into the most awesome weapons ever seen; as one of the first Americans to enter Japan after the blasts, he witnessed the devastation firsthand.

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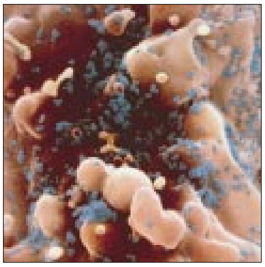
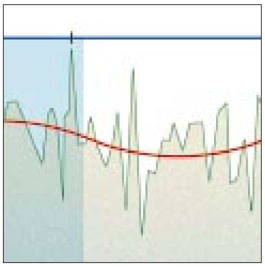
Tornadoes
Robert Davies-Jones

The terrifying funnels that wreak havoc on the ground are only the bottommost layer of a complex cyclonic phenomenon. Using an arsenal of ground- and air-based instruments, meteorologists have begun to identify the atmospheric conditions that create towering vortices of winds. But when a twister unexpectedly changes direction, the storm hunters can become the hunted.

58 

How HIV Defeats the Immune System
Martin A. Nowak and Andrew J. McMichael

Strangely, most people infected with the human immunodeficiency virus (HIV) do not acquire symptoms of AIDS for about a decade. According to a new theory, this latency may result from fierce competition between the proliferating, mutating virus and the body's defenses. For years these forces are matched at a standoff, but when the variety of mutants is finally overwhelming, the immune system collapses.

66 

The Benefits of Background Noise
Frank Moss and Kurt Wiesenfeld

Everyone who has strained to hear a faint radio signal through a haze of static knows how much of a problem background noise can be. But that is not always the case: because of "stochastic resonance," random background fluctuations can sometimes amplify weak signals. Nervous systems take advantage of this effect; now engineers and physicists are building better sensors with it, too.

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The Physiology of Decompression Illness
Richard E. Moon, Richard D. Vann and Peter B. Bennett

When scuba divers ascend after being down too deep for too long, they may suffer an agonizing episode of decompression illness. Bubbles in the blood cause its varied symptoms, as has long been known. Only recently, however, have physiologists discovered where those bubbles come from and precisely why they have these punishing effects. Their findings may soon make diving safer.

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Frog Communication
Peter M. Narins

Loudly croaking frogs may sound like a chorus, but the opposite is true: they are each trying to make themselves heard above the din. To that end, they employ a remarkable set of acoustic adaptations enabling them to fit their calls into split-second silences and to produce 80-decibel calls without deafening their own ears.

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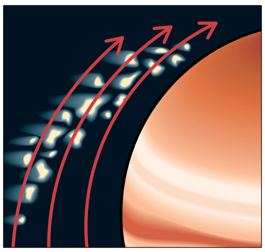

Comet Shoemaker-Levy 9 Meets Jupiter
David H. Levy, Eugene M. Shoemaker and Carolyn S. Shoemaker

The impact of this comet with our solar system's largest planet was unforgettable, an event probably not to be repeated for millennia to come. One year later the astronomers who first spotted the comet reflect on their discovery, on the anxious months of anticipation before the collision and on what has been learned since.

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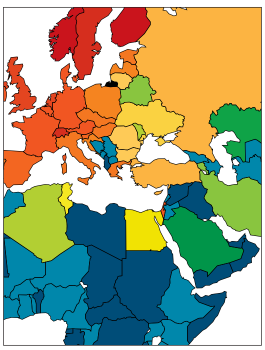

TRENDS IN SCIENTIFIC COMMUNICATION

Lost Science in the Third World
W. Wayt Gibbs, staff writer

Researchers in developing countries find that some of the most frustrating problems they face are in the library, not the laboratory. Results they publish in regional journals are all but invisible to their Northern colleagues; their submissions to more prestigious journals are disproportionately likely to be rejected. Fairness issues aside, good science may be falling through the cracks.

DEPARTMENTS

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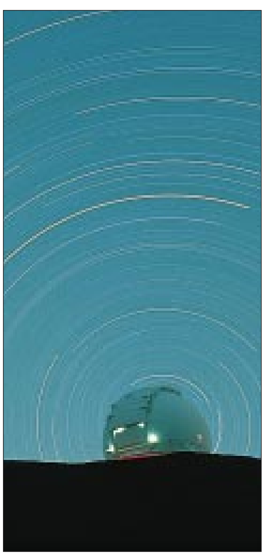

Science and the Citizen

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The velocity of money.

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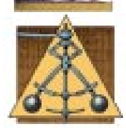

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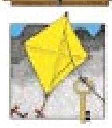

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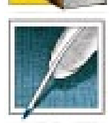

Essay: *Abigail Zuger*
For some patients, AIDS carries macabre benefits.

THE COVER depicts a frightened scuba diver heading for the surface. A minor equipment problem or an encounter with a fearsome-looking (but usually harmless) creature may prompt a rapid ascent. And therein may lie the real danger: if the diver holds his or her breath, for example, pressure can rupture the lungs, and gas can escape into the bloodstream. The embolism can then lead to neurological damage (see "The Physiology of Decompression Illness," by R. E. Moon, R. D. Vann and P. B. Bennett, page 72). Painting by Gregory Manchess.

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LETTERS TO THE EDITORS

Eye on Crime

W. Wayt Gibbs should have provided a reference for the longitudinal study of violence among Philadelphia males discussed in his article "Seeking the Criminal Element" [SCIENTIFIC AMERICAN, March]. The work can be found in *Delinquency in a Birth Cohort,* by M. E. Wolfgang, R. M. Figlio and T. Sellin (University of Chicago Press, 1972).

MARVIN E. WOLFGANG
University of Pennsylvania

I am appalled at the remark attributed to me by Gibbs. He presents me as claiming that forces organized by Peter Breggin coerced me and my colleagues "to ditch plans to collect blood and urine samples." How could that be when we have never had such plans? We have never been impressed with a variety of possible biological markers for criminality and violence. But we maintain an active appraisal of ongoing neurobiological work so that we can modify the design appropriately if a particularly promising mechanism does emerge. Does that sound like ditching plans?

FELTON EARLS
Harvard School of Public Health

Gibbs replies:
In the course of a lengthy interview, I asked Earls whether he and his colleagues could have looked for biological markers for violence by taking blood samples from a study group and storing them until it was possible to identify a subgroup to test. Earls responded that "there is a guy named Peter Breggin who decided that our study was the incarnation of the Federal Violence Initiative. And he and the Association of Black Psychologists and various other groups have been on our case." Earls then described rallies held at state colleges opposing his study and said that the group decided not to collect fluids "because it would simply invite criticism and possible derailing of the study, given the sensitivity of it."

Losing the Green

I read Curtis N. Runnels's article, "Environmental Degradation in Ancient Greece" [SCIENTIFIC AMERICAN, March], with an eerie sense of recognition that similar degradation is happening right here in the U.S. As a range conservationist with the U.S. Department of Agriculture's Forest Service in northern Arizona, I observed in the early 1980s accelerated erosion everywhere, resulting from man-made impacts, particularly grazing. Many U.S. rangelands and forests have suffered irreparably at the hands of political expediency and are destined to suffer even further as public service positions in natural resource management disappear because of impending budget cuts.

JAY K. PAXSON
West Linn, Ore.

Runnels fails to question why anybody would farm in the first place on "steep slopes, at high elevations and in areas where only soils of marginal productivity ever existed." One answer is that ancient farmers chose to live close to settlements for protection. Land scarcity then forced them to cultivate steep-sloped areas. The Nigerian civil war of 1967–1970 provided numerous parallel examples of soil erosion resulting from the concentration of agriculture in areas where peasants fled to escape violent conflict—usually on remote hillsides. Today the prohibitive cost of land again forces the rural poor to cultivate marginal areas. Despite their considerable differences, both conflict and economic inequity often lead to agro-ecological degradation.

KEITH PHILLIP CHILD
Kingston, Ontario

Chasing Infinity

A. W. Moore's otherwise entertaining "A Brief History of Infinity" [SCIENTIFIC AMERICAN, April] was marred by an incorrect definition of infinity. Moore, like Dedekind, proposes that a set is infinite when it is equinumerous with a proper subset of itself. Mathematicians know, however, that under the standard Zermelo-Fraenkel axioms for set theory, we must allow for sets that are neither finite nor equinumerous with any proper subset. Under Moore's definition, such sets are neither finite nor infinite. Admittedly, the historically controversial Axiom of Choice rules out such absurdities. But the accepted definition winds around the absurd and the controversial in simple elegance: a set is infinite when it is not finite.

JOEL DAVID HAMKINS
University of California at Berkeley

Moore replies:
Hamkins is quite right: Dedekind's definition of "infinite" is unsuitable in the absence of the Axiom of Choice. I think his comment actually illustrates a point I tried to make at the end of the article. A suitable definition of infinite depends on context—on what assumptions are being made, on what aims are being pursued and on what the definition is being used for. Even granted the Axiom of Choice, neither Dedekind's definition nor indeed Hamkins's is adequate for capturing certain traditional conceptions of infinity.

I would also like to correct a misstatement in the article: John Duns Scotus was a theologian and philosopher, not a mathematician.

Woman's World?

My one sticking point with Frans B. M. de Waal's "Bonobo Sex and Society" [SCIENTIFIC AMERICAN, March] was the statement concerning the supposed quid pro quo between male and female bonobos when they have sex, after which the female takes food from the male. It seems to me that the female came out ahead on that deal, unless the assumption is made that the female is not as desirous of sex as the male. De Waal seems to engage in a bit of anthropomorphizing—unless he has some special insight into the social psychology of bonobos.

ROGER C. WADE
Metropolitan State College of Denver

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

ERRATUM

The article "Deciphering a Roman Blueprint" [SCIENTIFIC AMERICAN, June] should have indicated that Augustus's mausoleum was erected in 30 B.C., not A.D. 30.

50 AND 100 YEARS AGO

AUGUST 1945

American Telephone and Telegraph Company has worked out elaborate plans for a network of automatic radio relay stations all over the country so that motorists equipped with two-way radio can telephone from their moving cars anywhere in the country to regular telephone subscribers. And when world-wide radiotelephone service is resumed after the war, a person driving along some charming country road in, say, Minnesota could chat with a friend in Java without even stopping the car, assuming, of course, that his credit was good with the telephone company."

"Using a miniature ball bearing as its writing contact and viscous ink, a new writing instrument which rolls the ink onto the surface dry, instead of inscribing it wet with a pen point, has just been announced. It is claimed that the pen cannot leak or drip and that ink cannot be shaken out of it."

"Magnetic studies, one tool of the chemist, are discovering new facts about catalysts, the vitally important 'marrying parsons' in many chemical reactions, Dr. P. W. Selwood, of Northwestern University, said in a recent address. 'From the nature and degree of magnetic attraction or repulsion, it is possible to draw conclusions as to the structure of these chemical compounds, the electrons in the molecules, the presence of impurities, and the mechanism of certain chemical and physical changes.' "

"Two hundred thousand new passenger cars by the end of 1945. Four hundred thousand more in the first quarter of 1946. Such are the latest predictions. The fact that new cars are going into production gives the average car owner a different attitude toward the machine that has seen him through the past few years. He suddenly is conscious of its shabby appearance, its eccentricities, its deficiencies. Suddenly he needs a new car. And what will this new car be like? It is possible that some day entire automobile bodies will be made of some type of plastics material."

AUGUST 1895

Perhaps the oddest pavement ever laid is one just completed at Chino, Calif. The new sidewalk, a thousand feet long, is made mostly of molasses; if the pavement proves all of the success claimed for it, it may point a way for the sugar planters of the South to profitably dispose of the millions of gallons of useless molasses which they are said to have on hand. The molasses is simply mixed with a certain kind of sand to about the consistency of asphalt and laid like an asphalt pavement. The composition dries quickly and becomes quite hard and remains so."

"That glass is porous to molecules below a certain weight and volume has been shown by recent electrolytic experiments. A current was passed through a vessel containing an amalgam of sodium separated by a glass partition from mercury. After a while the amalgam was found to have lost a certain amount of its weight, while the same amount had been added to the mercury. But with potassium, whose atomic weight and volume are high, the glass could not be penetrated."

"In those sciences, such as archaeology, antiquarianism, genealogy and heraldry, where the chief elements of success are infinite patience, conscientious study, a fine memory and broad general culture, women have always manifested signal ability. The latest addition to the list of women of high talent and of genius is Mrs. Nuttall, who has made a special study of ancient Mexican folk lore and 'Mexicology,' if the name may be coined."

The Boston subway for streetcars

"Niagara Falls will probably be the location of a factory for turning out electric men; not mesmerists or svengalis, but automatons that will run by electricity. They have built one up at a plant in Tonawanda; the man clothed in Continental uniform drags a heavy cart about the streets with some ease. Future models of electric men will be run by storage batteries and have a phonograph. The phonograph can expound the virtues of patent medicine or be used for political campaigns."

"Work is now in progress in the city of Boston, on a subway, or underground railroad system, which is designed to do away with congestion, and which it is believed will take care of the traffic adequately. The idea is that by having a tunnel devoted to the railroad alone, and free from all interference of vehicles or pedestrians, schedule time will be made by the cars, which can naturally be run at much higher speeds than is possible on a crowded street."

SCIENCE AND THE CITIZEN

Misreading Dyslexia

Researchers debate the causes and prevalence of the disorder

Dyslexia, the inability to learn how to read, is the most frequently diagnosed learning disability in the U.S. According to the National Institute of Child Health and Human Development, 10 million American children—that is, one in five—suffer from this disorder. Over the past 16 years, diagnoses of dyslexia have tripled, and an estimated $15-billion industry, employing testers, therapists and teachers, has sprung up, as has a profitable educational publishing market. Moreover, the appearance in the past year of at least two major studies ascribing a biological basis to dyslexia has focused unprecedented attention on the issue.

ABRAHAM MENASHE

TUTORING has been shown to be effective in treating many children who have been diagnosed as dyslexic.

At the same time, however, researchers are engaging in a rancorous debate over the causes, the definition and especially the prevalence of dyslexia. No one doubts that a core 1 to 3 percent of poor readers have some brain-based phonological deficit that prevents them from breaking down written and heard words into component sounds. But a growing number of dissenters believe postnatal experience, including inadequate instruction, is the real culprit in most cases.

"There is no evidence that millions of children are dyslexic," maintains Gerald Coles, an educational psychologist at the University of Rochester. "To legitimize the category is unconscionable, because it's unproved. I can cite 50 studies that show even very weak readers can be trained to develop phonological abilities."

Sally E. Shaywitz of Yale University supervised the landmark investigation that was the source for the government's claim that 20 percent of youths are dyslexic. She says dyslexia is an organic disorder afflicting a range of people, from illiterates to lawyers. All of them, she asserts, have trouble understanding "that the word you see on paper is made up of the same number and patterns of sounds as the same word when you hear it." According to this logic, because all struggling readers stumble when figuring out what, say, the word "Germany" sounds like without the "ma," all of them must be dyslexic.

Some educators prefer Shaywitz's definition to the older, narrower one, which identified dyslexia only in those who showed a gap between their IQ scores and their reading scores. But some scientists fear Shaywitz's definition is so broad that it risks being meaningless. And still other researchers object to Shaywitz's strictly phonological-deficit explanation on the grounds that it is too limited.

"She's wrong, and that's the end of it," says Albert M. Galaburda, a Harvard University neuroscientist. "Right now we're studying a woman who is a phonological genius. She can decode auditorially at a fast rate in seven languages. She just can't read. The distinctions we make about the visual and auditory brain are somewhat arbitrary." Galaburda has himself drawn fire for a report, published in August 1994 in the *Proceedings of the National Academy of Sciences,* that dyslexics suffer from abnormally small neurons in a region of the thalamus that processes auditory signals. Critics point out that Galaburda's article was based on autopsies of only nine brains; they also challenge evidence he presents that his subjects were dyslexics. For instance, Galaburda classified one brain as dyslexic based on a reported spelling test given to the subject by a tutor.

Galaburda is not alone in trying to pinpoint some physiological basis for dyslexia. Workers have also hunted for genetic markers. Last year a study of fraternal twins by a group at the University of Colorado linked markers on chromosome 6 to reading disabilities. "The odds of finding that association were 1,000 to 1," says Shelley D. Smith, a geneticist at Boys Town National Research Hospital involved in the study.

Neil J. Risch, a professor of genetics at Stanford University, is not impressed by Smith's claim. "These are fishing expeditions," he says. "There have probably been a dozen findings for such behavioral genetic linkages. Not a single one has been replicated." Indeed, in 1983 a much ballyhooed report by Smith and her colleagues seemed to have located markers for dyslexia on chromosome 15—also at 1,000 to 1 odds. But that statistical correlation disintegrated after the addition of a single family member to the sample.

The brain-biology debate may become somewhat moot. To find out just how many bad readers are products of childhood experience rather than prenatal development, Frank R. Vellutino of the University at Albany undertook a study of some 750 first graders. Of this group, 76 students scored very low on a battery of language tests. After tutoring the group for two years, Vellutino found that only 12 children, or 1.6 percent of the original sample, continued to have severe reading problems—a lower percentage than even the most conservative estimates would predict. The rest were reading at or above grade level.

Stringent selection criteria made his findings particularly valid, Vellutino asserts; his initial group of poor readers had to read at or below the 15th percentile—that is, near the lowest test scores. Other investigators, he charges, have excluded the most severely impaired readers solely because they would not benefit from instruction. "The world is full of those kinds of studies," Vellutino says disdainfully.

And full of all kinds of theories, according to Coles, that should be viewed with great skepticism. "If you trace the history of dyslexia research," he says, "you always find the same pattern. First, there's a paper or two claiming a new explanation for the disorder. Then replication research ultimately repudiates the initial claim." *—Billy Tashman*

It's All in the Timing

Neurons may be more punctual than had been supposed

Neuroscientists have long known that timing plays some role in the brain's processing of information. They don't have many other choices. Neurons resemble digital switches, which are either "on," firing, or "off," quiescent. The electrical spikes that neurons generate in response to signals from other neurons display uniform duration—about one millisecond—and intensity. Information must, therefore, be encoded in the timing of neural spikes.

The question is, How? According to one common view, signals may be encoded in the average rate at which neurons fire over a given period, just as signals in a telephone line are embodied in the rate at which electrons flow through it. But many neuroscientists have assumed that neurons in the cortex, where some of the brain's most sophisticated information processing takes place, are subject to too much noise, too many random processes, for the timing of any single, individual spike to matter much.

Terrence J. Sejnowski of the Salk Institute for Biological Studies in San Diego thinks the capabilities of cortical neurons may have been underestimated. Research by him and others suggests that signals transmitted between neurons in the cortex might actually be timed with exquisite precision. In fact, Sejnowski adds, timing might be vital to the brain's processing of information.

FIELD NOTES

Blast from the Past

This past February, Charles C. Schnetzler, a planetary scientist who spends most of his time in an office at the Goddard Space Flight Center in suburban Maryland, was wondering just how he found himself being tossed about the cab of a truck in the jungles of southern Laos. He truly started questioning the scientific curiosity that had brought him there when his fellow passenger, John F. McHone—a Vietnam veteran who is now a geologist at Arizona State University—explained that, even with a four-wheel-drive, they must not venture off the road. Driving over unexploded ordnance is a real possibility when your field area overlaps the Ho Chi Minh Trail.

Schnetzler's excellent adventure began sanely enough in his office, as he scrutinized satellite images and relief maps of Southeast Asia, looking for circular features that might mark the spot of the long-lost "Australasian Impact." Unlike the dinosaur-killing comet that hit the earth 65 million years ago (spawning global disaster and much belated media coverage), the Australasian collision remains largely unappreciated even though it occurred less than a million years ago, at a time when the genus *Homo* would have been around to see the explosion loft debris over as much as one tenth of the earth's surface.

The Australasian event has baffled geologists for decades because no crater has ever been found. The collision is known only because it scattered its blanket of ejecta—mostly in the form of glassy blobs of formerly molten rock, called tektites—from China to Australia. But where was ground zero? From his knowledge of the size and composition of tektites previously collected, Schnetzler hoped to find the site somewhere in the outback of Indochina. Schnetzler and McHone had already participated in an unfruitful expedition to northeastern Thailand. So this trip to Laos offered them an opportunity finally to make the big find. Schnetzler had located several features on his maps that might reflect a hidden crater, including four circular rings that stood strangely apart from the general lay of the land.

CHARLES C. SCHNETZLER

"TEKS" MARK THE SPOT leading to the missing crater.

As they approached the prospective craters, the scientists noticed local villagers selling something out of large, apparently heavy, sacks. The driver explained offhandedly that these were bags of salt—and he was surprised when his passengers turned glum. Schnetzler suddenly accepted something McHone had suspected: the targets that had looked so much like impact craters from his desk in Maryland must be the remnants of salt domes—geologic structures that result when a layer of deeply buried salt deforms like plastic and erupts at the surface.

So, as with all previous attempts, the recent fieldwork failed to locate the increasingly elusive Australasian crater. But most scientists agree that, in contrast to the case of Bigfoot or the Loch Ness monster, the enigmatic crater does exist. Perhaps next year Schnetzler will find it cloaked with overgrowth, like some ancient temple in the lush jungles of Cambodia—that is, Khmer Rouge permitting. *—David Schneider*

CNRI/SPL *Photo Researchers, Inc.*

NEURONS may not be as "sloppy" and imprecise as some investigators had assumed.

In an experiment described in *Science,* Sejnowski and Zachary F. Mainen, a graduate student at the University of California at San Diego (where Sejnowski also teaches), isolated a section of a rat's cortex in a dish and attached electrodes to the "spike-generation zone" of various neurons. The researchers monitored the spikes emitted by neurons as they were stimulated with electrical signals resembling those received from other neurons in the brain.

Sejnowski explains that if neurons were indeed "sloppy integrators," as some scientists have assumed, their response to identical forms of stimulation would almost certainly show random variation. But Sejnowski and Mainen found that when the stimulus consisted of a pattern of pulses with strong fluctuations—akin, the workers surmise, to a signal generated by a significant sensory input—identical stimulation patterns generated virtually identical firing patterns. The intervals between the spikes in each pattern varied by less than a millisecond.

Although these results do not demonstrate that precise timing plays a role in the brain's functioning, they do show that such timing is possible in the cortex, Sejnowski says. Evidence that punctiliousness is useful as well as possible has been set forth in *Nature* by John J. Hopfield of the California Institute of Technology. He is a pioneer in developing artificial neural networks, which are arrays of amplifiers and resistors that mimic the behavior of real neurons and synapses.

In his paper Hopfield demonstrates that neural networks can respond more rapidly to complex patterns if they encode data not just in the rate of firing but in the relative arrival times of individual spikes. The finding makes intuitive sense, he argues. In the precision-timing approach, data can be conveyed by the arrival of a single spike, whereas if firing rate alone is used, many spikes are required to represent a single piece of information. "It's a more efficient use of the available hardware," Hopfield explains.

Recent studies of the echolocation of bats by a Japanese group show how timing can solve an information-processing problem, according to Hopfield. Ideally, he explains, bats seeking to measure precisely their distance from an insect would emit extremely short but loud chirps of uniform pitch, or frequency. Instead the bat utters a longer chirp that starts at a relatively low pitch and swoops upward; the total energy of such a chirp is greater than the bat could achieve in a much shorter chirp.

So how does the bat achieve high precision with such spread-out chirps? The answer has to do with the fact that different neurons in the bat's auditory cortex respond to different frequencies of sound. When the echoed chirp returns, neurons sensitive to low-frequency sound fire first and those sensitive to higher frequencies an instant later. But time delays in the circuitry of the bat cause these initial signals to feed into the next level of neurons—those involved in distance estimation—at precisely the same time.

Sejnowski thinks that as researchers examine the brain more closely, they are likely to find more evidence that timing is crucial to the mind's operation. Neuroscience, he declares, "is on the brink of appreciating the complexity and potential implications of temporal neural computation." *—John Horgan*

Coming in from the Cold

The long-sought Bose-Einstein condensate turns up

In 1925 Albert Einstein and Indian physicist Satyendra Nath Bose reasoned that if you cooled a dense gas to within a whisper above absolute zero, it would condense into a rather unusual kind of ice cube. The atoms would lose their individual identities and act as an organized whole—much the way photons in laser light march in coherent fashion. In effect, they would become one giant atom.

Now, 70 years later, atomic physicists seem to have succeeded in verifying the prediction. By cooling rubidium atoms to a record-low temperature of less than 10 nanokelvins—10 billionths of a degree above zero—Eric A. Cornell and his colleagues at the National Institute of Standards and Technology (NIST) in Boulder and the University of Colorado managed this past June to create that quantum ice cube, known formally as the Bose-Einstein condensate.

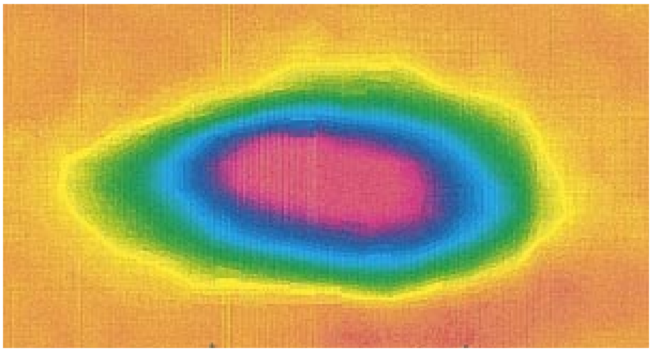
One of the reasons this state of matter has attracted a following of physicists is its mystique: theory says little about it, other than that it exists. "The condensate is unique among all phase transitions," notes Thomas J. Greytak of the Massachusetts Institute of Technology, who leads one of the other groups that have been racing neck-and-neck with Cornell's team in pursuit of the condensate. All other phase transitions—such as steam into water or water into ice—happen because of forces between atoms and molecules, Greytak explains. "But Bose-Einstein condensation is driven only by quantum mechanics."

More specifically, it is driven by Heisenberg's uncertainty principle, which describes the trade-off between knowing a particle's position and its momentum. Because atoms are barely moving when cooled to near zero, the uncertainty principle demands that their positions become virtually unknown. Their wave functions—or the equations that describe the atoms—then spread out and merge. As a result, "you get a large number of atoms occupying the same quantum state," Cornell elaborates. "It's the same basic thing that happens in superconductivity and superfluidity." Yet despite similarity to the resistanceless flow of electricity and liquid, researchers have not been able to deduce the condensate's properties. Even its appearance is a matter of speculation: it might be clear as glass or shiny as metal.

Those unknowns should soon see some answers now that the NIST-Colorado collaboration has created the condensate in the world's chilliest fridge. The group relied on a technique called evaporative cooling. Pioneered in the late 1980s by Greytak and his colleagues at M.I.T., the method suspends atoms between two magnetic fields. Turning the field down a notch and applying a radio-frequency burst cause the magnetic spin of the hotter atoms to flip. That result drives them out of the trap, leaving colder atoms behind. Step by step, the temperature of the collection drops. By 1990 Greytak was able to chill hydrogen atoms to 100 microkelvins with the technique, getting to within a factor of three to five of Bose-Einstein condensation.

But progress froze there because of a hole in the trap. As the remaining atoms jostled about, they bumped into one another. The collisions sometimes reversed the spins of the cold atoms, which would escape through the center of the trap, where the magnetic field is zero. That outcome not only prevented further cooling but also reduced the number of atoms to below the amount needed to form the condensate.

Last year workers devised successful ways to plug the hole. Wolfgang Ketterle of M.I.T. used laser light to keep the cold atoms trapped, and Cornell's group relied on a special kind of magnetic field, which essentially circulated the hole in the trap faster than the atoms could fall out of it. With the escape hatch thus sealed, both teams witnessed remarkable progress. In less than eight months Cornell was able to improve the cooling almost 1,000-fold.


ERIC A. CORNELL ET AL.

30,000 ATOMS at 35 nanokelvins, near Bose-Einstein condensation, are colored to reveal the distribution of atoms across 100 microns, from packed **(red)** *to sparse* **(yellow).**

In fact, evaporative cooling works so well that the condensate may have formed without investigators realizing it. "Our problem has not been going to lower temperatures," Greytak notes. "It has been observing the gas." As the temperature drops, so does the size of the atom cloud, making it hard to study. For conclusive proof, "you have to overshoot by an order of magnitude to be sure," Ketterle asserts.

But Cornell's group, it appears, gets the me-first honors. While scanning the cloud of rubidium atoms with a laser, they found a sharp increase in density in the middle. "It is a much more dramatic signature than we ever expected to get," remarks collaborator Carl E. Wieman of the University of Colorado.

The group has yet to ascertain the condensate's properties, but in principle, the substance can survive about a minute before freezing into rubidium ice—more than enough time to conduct laser experiments, which last milliseconds. The race may be over, but with so little known about the substance, physicists should find plenty more than just cold comfort. *—Philip Yam*

ROGER RESSMEYER *Starlight*

KECK TELESCOPE, shown here in a seven-hour exposure, sits atop Mauna Kea in Hawaii.

What the Keck?

The world's largest telescope quietly transforms astronomy

The cliché that a picture is worth a thousand words may help explain the muted response that has greeted early results from the Keck telescope, the biggest optical telescope ever built. Keck cannot match the sharp views from the orbiting *Hubble Space Telescope;* its main strength lies instead in its tremendous light-gathering ability, a boon for studying the spectra of extremely faint, distant objects. But "spectra are a hard sell, even if you put them in pretty colors," remarks Lennox L. Cowie of the Institute for Astronomy in Honolulu. "So people just end up running a photo of Keck" (*above*).

Since it began full-time operation in 1993 on its perch atop Mauna Kea in Hawaii, Keck has created a stir in the astronomical community. The telescope's huge segmented mirror—10 meters in diameter—speeds the process of exploring the most distant, and hence youngest, parts of the cosmos. "It really blows you away, it is so fast," marvels David Tytler of the University of California at San Diego. Tytler, Cowie and various collaborators are using Keck's talents to home in on basic questions about how galaxies form and evolve and about how much ordinary matter is out there—often with unanticipated results.

One manner in which to weigh the universe is to look at the abundance of heavy hydrogen, or deuterium, in very young objects that are not yet contaminated by nuclear by-products from stars. The big bang model predicts that the amount of such primordial deuterium depends on the total density of normal, or baryonic, matter—the stuff of stars and gas clouds.

When Tytler and his co-worker Xiao-Ming Fan used Keck to look for deuterium, they found a surprisingly weak spectroscopic signal. The results imply that the baryonic density of the universe is much greater than expected. But the observed galaxies and intergalactic material account for only a small fraction of that density. Could scientists be overlooking at least 80 percent of the normal matter out there? "It is really embarrassing," Tytler says. "Astronomers should be able to see ordinary gas."

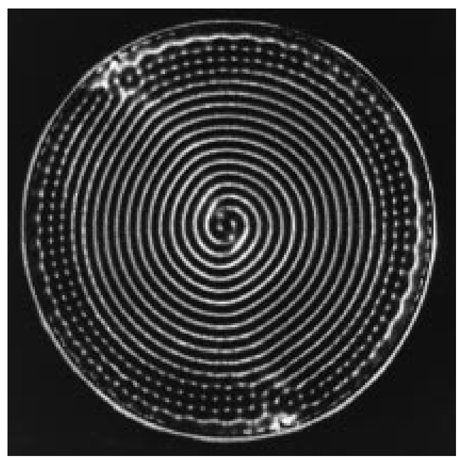
So where is the missing material? Tytler suspects the answer lurks in another set of data from the telescope, which seems to show that the space between galaxies is packed with clouds of nearly invisible, hot gas. These intergalactic wisps may outweigh all the more prominent stars and galaxies.

Cowie and Antoinette Songaila, also at the Institute for Astronomy, have come to a different conclusion—also on the basis of observations from Keck. Using the same principles but different observing techniques, the two found ten times as much deuterium, which suggests that there is no need to search for "missing" baryonic matter. Such disagreements are not unusual as researchers try out various approaches on a new instrument. Both Tytler and Cowie are confident that Keck has the raw power to settle the question in the next few years.

In another set of studies, Cowie, Tytler and their colleagues found traces of carbon in the spectra of very distant gas clouds. Cosmologists believe that, unlike deuterium, all the carbon in the universe was created in stars, so it should serve as an indicator of star formation. Cowie was surprised to find the element in young clouds that were thought to be pristine samples from the big bang.

"We're still thrashing around trying to understand this result," Cowie says. He leans toward a model promoted by Jeremiah P. Ostriker of Princeton University, in which instabilities that arose after the big bang could have triggered star formation before the first galaxies gathered. Tytler favors a simpler interpretation: the carbon was created by stars within infant galaxies but was then puffed out into intergalactic space.

If only they could spot the youngest, newborn galaxies, astronomers could learn a great deal about the evolutionary process that connects the big bang to the modern Milky Way. Here, too,



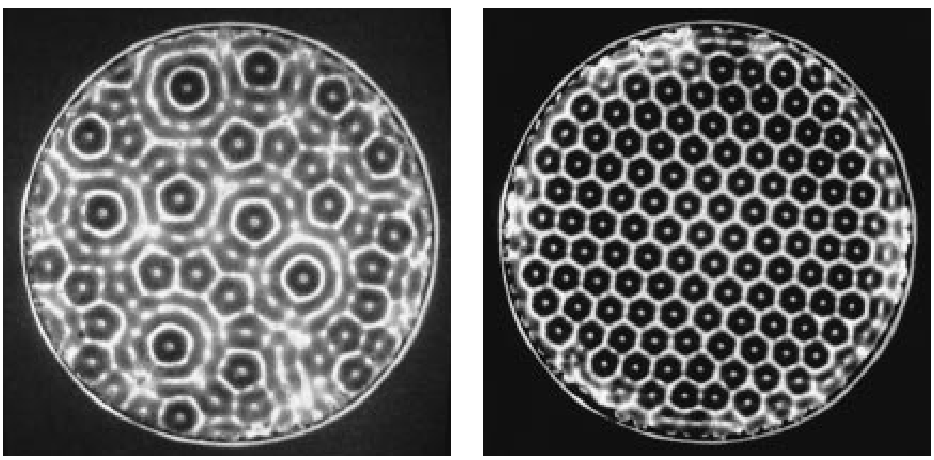
Quasimodal

Quasicrystals, discovered in 1984, shattered the wisdom that shapes having fivefold, sevenfold or other designated symmetries cannot fit together to tile a surface. Now the forbidden quasipatterns can also be seen simply by shaking a shal-

Keck is yielding provocative but puzzling results. S. George Djorgovski of the California Institute of Technology has spent years trying to learn about the birthing process of galaxies. His team's latest observations show many of the faintest galaxies ever seen but still no sign of protogalaxies.

"The universe is very, very strange," Djorgovski says as he reflects on the unseen process of galactic formation. "Nobody knows how this is going on." Perhaps infant galaxies are cloaked in dust that obscures them, or perhaps astronomers need to use a different approach to look for them. Djorgovski is optimistic that Keck will provide some answers. "We're overdue for some nice discovery," he says impatiently.

Keck's start has not been totally free of glitches. Engineering adjustments still eat up a fair amount of time as operators learn the intricacies of the unusual design, and "the weather's been just god-awful for the past year," Djorgovski laments. "But when it all works, it is wonderful." Nobody seems distressed by the telescope's low public profile. Cowie thinks Keck just "operates in the classical Caltech mind-set": researchers are encouraged to work problems through before publishing. That approach seems to suit him and his colleagues just fine. "We've been having a lot of fun working with Keck," he laughs. "It truly is a spectacular beast." *—Corey S. Powell*



W. STUART EDWARDS AND STEPHAN FAUVE

low layer of gooey liquid up and down.

In 1831 Michael Faraday had observed that such vertical vibrations create arrays of standing waves on the surface. W. Stuart Edwards of Haverford College in Pennsylvania and Stephan Fauve of the École Normale Supérieure in Lyons, France, find that vibrating a platter of dilute glycerol—that is 85 times as viscous as water—with two simultaneous frequencies may generate quasipatterns of 12-fold symmetry. When combined with diverse amplitudes and phases, the oscillations give rise to a variety of designs, including double spirals and six-sided honeycombs (*above*). The patterns and their defects bring to light subtle interactions between the fluid's molecules. *—Madhusree Mukerjee*

High Tidings

Ancient, erratic changes in sea level suggest a coming swell

For a geologic nanosecond—a century, in other words—some 120,000 years ago, the earth underwent climatic havoc. New findings show that sea level, records of which are imprinted in limestone of the Bahama Islands, rose 20 feet above that of today and then plunged to at least 30 feet below modern levels. These erratic 100 years came at the close of the last interglacial era, a time when the climate was somewhat similar to ours.

A. CONRAD NEUMANN

BAHAMIAN LIMESTONE records sea level.

That is the reason sea level and climatic change in that period—on the agenda of the June meeting of the American Geophysical Union—are attracting the attention of so many researchers. Although today's climate is cooler, greenhouse warming could bring about greater similarities to the last interglacial. "Maybe there is a threshold for warming that, once exceeded, starts to throw climate into a series of barrel rolls," speculates Paul J. Hearty, a geologist in Nassau. "If we continue to pump carbon dioxide into the atmosphere, are we going to warm the earth and trigger erratic sea-level events like those that happened 120,000 years ago?"

Hearty and his colleague A. Conrad Neumann of the University of North Carolina at Chapel Hill call this bizarre transition from an interglacial greenhouse period to an icehouse one the "madhouse." "What we have discovered in the Bahamas is that there are pulses of catastrophic change that dramatically reshape landscapes," Hearty explains.

Because the region is tectonically stable and made of impressionable calcium carbonate, it provides an ideal chronicle of climate and sea-level changes over the past half a million years. For example, fossil reefs show that coral, which ordinarily stays apace of slow, typical sea-level rise, grew 2.5 meters above modern sea level and then halted. The researchers suggest the coral lagged because water rose and then withdrew too precipitously for it to keep up.

The trick is figuring out what caused so much water to be displaced so violently. The two geologists postulate a glacial surge: sea level was rising slowly as a result of normal interglacial greenhouse warming. Then something pushed the polar ice field beyond a critical point, and ice surged into the ocean—an idea proposed in 1980 by J. T. Hollin of the University of Colorado at Boulder. When the seas receded, presumably due to rapid ice formation at the poles, sand from lagoons in the Bahamas blew over forests, entombing now fossilized palm trees in dunes. Calcium carbonate sands cement quickly when exposed to air; therefore, Hearty and Neumann reason, the water must have withdrawn suddenly, followed by raging storms.

"This is all very intriguing information," comments Thomas J. Crowley of Texas A&M University. "It suggests that the system is sensitive to relatively small fluctuations and that there are things going on during this period we don't understand." Scott J. Lehman of the Woods Hole Oceanographic Institution, however, is not convinced: "I have trouble with the notion that sea level could change so quickly from ice growth. We need to know more about erosion, glaciation and deglaciation rates."

Of course, the implications of the findings for today's climate remain unclear. The effects of modern global warming on sea-level rise are still in the early stages of study. In 1992 the *Topex/Poseidon* satellite began tracking global sea-level change. Yet such collected measurements have their own limitations. Consensus exists that oceans are rising, but satellite and tide data indicate a rise of anywhere between 1.1 and 5.3 millimeters a year. "It's hard to figure out the overall rate," noted Bruce C. Douglas of the National Oceanographic Data Center to a packed room. "The ocean doesn't cooperate very much."

Researchers agreed that the rise has quickened during the past century, concomitant with atmospheric warming, and that coastal erosion and flooding are a reality. With half the planet's population living in coastal areas, ancient and modern data suggest we may be in a madhouse again. —*Christina Stock*

The Mystery of SIDS

A murder conviction revives questions about infant deaths

Rarely has a medical journal published so dramatic an erratum. A recent issue of *Pediatrics* described an unusual murder case in upstate New York. A woman named Waneta E. Hoyt confessed in 1994 that more than 20 years earlier she had suffocated five of her children after she became angered by their crying. Hoyt then retracted her confession, but a jury still found her guilty of murder this past spring. What made the case of interest to readers of the journal is that the deaths had been ascribed to sudden infant death syndrome, in which babies die for no discernible reason. In 1972 pediatrician Alfred Steinschneider reported in *Pediatrics* that two of Hoyt's children had exhibited unusually prolonged apneas, or breathing stoppages, before they died. SIDS, Steinschneider conjectured, might stem from physiological abnormalities causing apnea.

Largely as a result of this paper, the apnea hypothesis became the leading explanation of SIDS, the major cause of death among infants. The report also led to the widespread use of devices that monitor the breathing of infants and sound an alarm when they detect cessation. The Hoyt case has intensified a debate over the apnea hypothesis, the value of monitoring and virtually all other aspects of the syndrome. And the conviction has revived discussion of an excruciatingly sensitive topic: How often is SIDS really murder?

Well before Hoyt's confession, some researchers had questioned Steinschneider's findings. A year after his 1972 piece appeared, *Pediatrics* published a letter that implied, albeit obliquely, that the deaths might have resulted from foul play. Over the years, other research revealed that SIDS rarely befalls children older than one year (one of Hoyt's children was 28 months old). It also occurs infrequently among siblings.

These facts led Linda Norton, a forensic pathologist from Dallas, Tex., to persuade New York prosecutors to reopen the Hoyt file last year. Norton emphasizes that she thinks murder accounts for only a small number of SIDS cases. A recent report cites estimates between 10 and 2 percent, but some investigators favor a smaller figure.

"I am not in favor of going on a witchhunt and viewing every SIDS incident as a potential murder," Norton cautions. But she does think physicians and medical examiners should be more attuned to the possibility that SIDS might stem from abuse or other causes. More rigorous autopsies, Norton suggests, might show that SIDS is less common than is generally thought. According to the latest U.S. government statistics, SIDS occurred 1.3 times for every 1,000 live births in 1991, down from 1.5 per 1,000 in 1980. But in regions where medical examiners look diligently for other causes (including medical problems as well as abuse), frequency can drop to one death for every 5,000 births, Norton says.

As for Steinschneider's apnea hypothesis, it, too, had come under criticism long before the recent murder conviction. Studies done over the past decade have failed to find a correlation between SIDS and apnea, according to Marie Valdes-DaPena, a pathologist and pediatrician at the University of Miami School of Medicine. Research has shown that apnea is actually a relatively common and benign phenomenon, even among healthy infants. The apnea theory is "dead as a duck, completely passé," DaPena declares.

Not surprisingly, studies have failed to show that monitors reduce the risk of SIDS. "It has never been shown that apnea monitors prevented one of these deaths," DaPena asserts. Nevertheless, annual sales of the devices have grown to $25 million since they were introduced in the mid-1970s. Norton, for one, hopes the Hoyt case will spur parents and physicians to reassess the value of the monitors, which she claims can be intrusive and traumatic to families. A study of the instruments, sponsored by the National Institute of Child Health and Development, is under way.


J. GUICHARD *Sygma*

FACE-DOWN sleeping position has been implicated in SIDS by reports from Europe and elsewhere, but research done in the U.S. has failed to support the finding.

Meanwhile researchers continue to probe for other causes and means of preventing SIDS. Investigators have long known that poverty and premature birth are risk factors, but efforts to find factors that can be more readily controlled have for the most part failed. Studies done over the past decade in Europe and Australia have suggested that the risk of SIDS drops by more than 50 percent if children sleep on their backs. J. Bruce Beckwith of the Loma Linda University Medical Center in California calls this finding the most significant he has seen since he coined the term “SIDS” in 1969.

The American Academy of Pediatrics and the U.S. Public Health Service agree. Last year they launched a “Back to Sleep” campaign, recommending the supine sleeping position. But many pediatricians suspect the correlation between SIDS and prone position found outside the U.S. might stem from practices unique to those regions, such as the use of thick, sheepskin blankets as bedding in Australia. Further, a study of 200 SIDS cases in California, reported in the *Journal of the American Medical Association* this past March, found no evidence of an increased risk for prone-sleeping babies. A broader study of sleeping practices, again funded by the National Institute of Child Health and Development, is in progress.

One pediatrician who is withholding judgment on sleeping position is Steinschneider. In fact, he thinks there are not sufficient data to resolve any SIDS-related issue, including his own apnea hypothesis or the value of home monitoring. He says he even believes Waneta Hoyt may be innocent, as she now claims. “Before I make a judgment,” Steinschneider states, “I would need to know more.” SIDS, it seems, remains as baffling as ever. *—John Horga*

Down to Earth

Biosphere 2 tries to get real

Until a year ago, goings-on at the giant greenhouse known as Biosphere 2, which lies just north of Tucson, Ariz., were quasiscientific at best. The project was conceived to explore how humans might colonize space, but its dubious rationale had gradually collapsed in a series of disclosures about some highly unscientific maneuvers. Although the crews of “biospherians” who lived inside for up to two years at a time were supposed to be sealed in, oxygen and supplies were quietly imported, and carbon dioxide was removed from the atmosphere to keep it breathable. An early panel of scientific advisers resigned en masse.

The cultish fantasy shattered completely in April 1994, when the enterprise’s backer, Texas oil heir Edward P. Bass, called in marshals to eject the former managers who had inspired the project and put his $200-million structure in the hands of scientists. Now under the control of a consortium that is led by Columbia University’s Lamont-Doherty Earth Observatory, Biosphere 2 is fitfully searching for a scientific identity.

The possible value of the 3.2-acre edifice, which was built in 1988, resides in the fact that although it consumes prodigious amounts of energy (and money), it loses only about 10 percent of its atmosphere each year. Scientists believe that rate could permit valuable studies of sustainable agriculture and community ecology as well as of how trace elements and gases move between plants and the environment. “The engineering is remarkable by any standards,” states Bruno D. V. Marino, scientific director since last August.

Certainly no other enclosed ecosystem is as large, and none can boast Biosphere 2’s seven different “biomes,” which include a contrived rain forest and a tiny ocean with a chemistry unlike any body of water on the earth. The new management is installing equipment that promises to make the facility perhaps the most intensively monitored patch of vegetation in the world.

That there is some scientific potential seems to be widely agreed. Already one staff researcher has obtained data suggesting a novel and possibly important effect of plants on soil microbes. Yet it is far from clear that Biosphere 2 will be able to perform research of high enough quality to attract outside funding.

Before the 1994 coup, tourists who ogled biospherians going about their daily tasks contributed about a third of the $6-million annual budget. Acting chief executive Stephen K. Bannon, however, sees tourism on that scale as incompatible with research. For the present, Bass is footing the bill, but Bannon says Bass "wants to see that his money is being well spent within two years." To cover all possibilities, Marino is now making pitches to the National Science Foundation.

SPACE BIOSPHERES VENTURES *Sygma*

GLASS BUBBLES were "burst" last year after Biosphere 2 lost all scientific credibility. New management is trying to introduce rigor and realism.

Yet despite the can-do bravado, there are serious obstacles. For all its high-tech, the Biosphere suffers a huge disadvantage: it has no provision for doing multiple duplicate experiments, known as controls. "Replicates are essential for any statistical treatment and for scientific rigor," comments T. Hefin Jones, who studies plant ecology at Imperial College in England. W. Michael Schlesinger of Duke University, who researches the effects of elevated carbon dioxide levels on plant growth—using controls—concurs. "I don't see how they are ever going to get around that," he says.

The preliminary results obtained by staff scientist Guanghui Lin illustrate the problem. Carbon dioxide levels have fallen dramatically as a result of a mammoth ventilation exercise aimed at replenishing the facility's atmosphere. The subsequent slowdown in the growth rates of some plants seems to have prompted a similar reduction in the production of carbon dioxide by soil microorganisms. The implication of this unconfirmed observation is that in a rising carbon dioxide world, planting trees to sequester the gas might not help much—it could stimulate microorganisms to produce more carbon dioxide, thereby offsetting the amount the trees absorb.

But before the result can be published in a scientific journal, it needs to be repeated. Without separate chambers, the only way to do so is to repeat the change of atmosphere in the entire Biosphere, a monumental undertaking that could impede other experiments. And, in any event, the findings are tainted by the fact that the facility is unlike the real world: its glass restricts light from the sun by 50 percent, and there is nothing remotely like a normal insect population. Carbon dioxide levels swing each day by far more than they do in nature.

Jane Lubchenco, a former president of the Ecological Society of America, comments that ecologists have to be willing to study such unique situations. Peter M. Vitousek of Stanford University, a member of the Biosphere consortium, notes that although the project is highly artificial, it is a much easier locale for research than, say, the Amazon basin: by adding isotopes of chemical elements, investigators may examine in detail processes impossible to measure in the field.

Even if supporters are correct, it will be an uphill battle. Biosphere 2 was "in terrible shape" last year, Bannon says. Levels of nitrous oxide were high enough to prompt health concerns, and water contaminated with nitrates was raining on the vegetation. Cockroaches and ants flourished, while more desirable species perished.

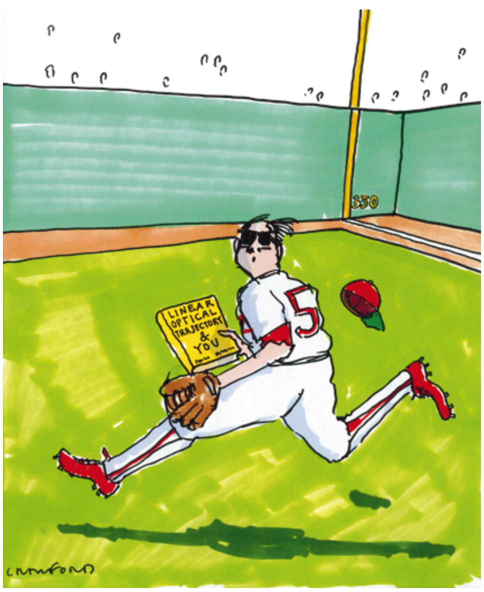
For now, the consortium has decided just to clean house and try to understand the processes going on inside. Giant fans borrowed from a local mining company are forcing warm Arizona desert air through the ersatz Eden, bringing carbon dioxide levels close to normal. Some 200,000 gallons of water have been replaced, as have 12 tons of soil. Attempts are under way to study how the atmosphere has changed over time, a major challenge because some gases were absorbed into the structure's concrete. And the wildly proliferating vegetation is being catalogued.

What will come after the cleanup is still up for grabs. Marino envisages a Biosphere that will be sealed for up to three years while specific experiments are performed. The nature of those tests may depend on the funding agencies. Marino is decided on one point, however. He says he has no plans to seal humans inside again in the foreseeable future. Tourists and survivalists will be disappointed, but the rest of the world might gain insights that could start to justify Bass's millions. *—Tim Beardsley*

How to Catch a Fly Ball

You're Barry Bonds, ace leftfielder for the San Francisco Giants, watching carefully as Lenny Dykstra, leadoff hitter for the Philadelphia Phillies, comes to the plate. The minuscule but muscle-bound Dykstra fouls off two pitches on the plate's outside corner. On his third swing Dykstra whips the bat around again, and you realize, even before you hear the "crack," that the ball is headed your way. What to do?

You know, of course, that since 1968 the leading theory of fly-ball catching has been the optical-acceleration-cancellation hypothesis, which holds that the fielder must run under a ball in such a way that it appears to be moving upward at a constant rate. If the ball appears to be accelerating, it will land behind you; if it is decelerating, it will drop in front of you. This method has stood you in good stead—hey, you've got the Golden Gloves to prove it. But wait! A recent article—in *Science,* no less—has proposed a different and perhaps superior technique.



MICHAEL CRAWFORD

Three psychologists, two from Kent State University and one from the National Aeronautics and Space Administration, argue that most people have a hard time judging acceleration. They say you are better off running in such a way that the ball seems to be moving in a straight line rather than curving downward or upward. If you can accomplish that task, you will easily intercept the ball. What to do? You look up at the ball, and, to your relief, you see that it is accelerating upward *and* curving upward at the same time. Home run. Not your problem. *—John Horgan*

Putting Bombs Away

A controversial exhibit about World War II is canceled

As originally scheduled, the massive Smithsonian Institution exhibit *The Last Act: The Atomic Bomb and the End of World War II* was to open in Washington, D.C., in May, in time for the 50th anniversary of the bombing this month. But after an extended dispute over whether the show was fair and accurate, it was canceled—and the director of the National Air and Space Museum, Martin Harwit, resigned. All that remains of the display are a few videos, the stripped-down fuselage of the *Enola Gay* (the airplane that dropped the bomb on Hiroshima) and questions about how to interpret the history of nuclear warfare.

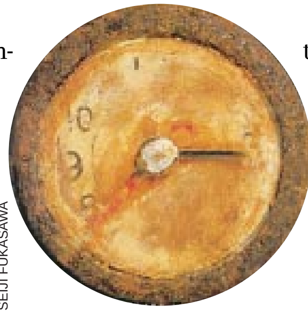
"The bomb is a tremendously powerful symbol," notes Edward T. Linenthal of the University of Wisconsin at Oshkosh, who served on the advisory committee for the exhibit. "From the beginning it meant different things to different people." And it seems impossible to reconcile remorseful and heroic accounts of how World War II ended.

The show's organizers generally viewed the bombing as tragic, as it made manifest the horrors of nuclear fallout and ushered in the cold war. *The Last Act* was intended to describe how and why the U.S. made the decision to bomb as well as the ramifications: the damage to Hiroshima and Nagasaki, the estimated 200,000 people killed between August and November 1945 and the subsequent proliferation of nuclear weapons. "The mission of the *Enola Gay* was one of the pivotal events of the 20th century," Harwit says. "It changed the way we view the history of humanity."

But tragedy was not what various veterans groups wanted to see. They thought an exhibit appearing at an anniversary of the end of World War II should celebrate heroic service. Hugh Dagley of the American Legion points out that thousands of pilots and soldiers "believe their lives were saved" by dropping the bomb. So analysis questioning the wisdom of using the weapon offends some of them.

Surely this period of history is not too difficult to recount somehow? Linenthal sees other emotionally charged displays, such as those in the Holocaust Museum, as examples of how delicate subjects can be depicted successfully. The planners of the Holocaust Museum included survivors, museum curators and historians from the very beginning. By bringing in groups such as the American Legion late in the planning, the Smithsonian lost many veterans' trust that museum officials cared about their complaints, Linenthal explains.

In the case of the Holocaust Museum, however, everyone involved agreed that the murder of millions was a tragedy. The fundamental differences in perspective about bombing Japan made the *Enola Gay* exhibit too complicated, despite the Smithsonian's attempts to satisfy both sides' concerns, Linenthal says. Harwit suggests that in 25 years or so the country might be able to look at the first and, so far, only use of nuclear weaponry against an enemy with more objectivity. Although by then, he points out, all witnesses will be gone.



SEIJI FUKASAWA

TIME frozen in Hiroshima.

Now that the arguing is over, the eight million annual visitors to the Air and Space Museum are left with a wholly inadequate exhibit. On that much, at least, everyone can agree. As Dagley puts it, the new show "tells you nothing about the technology, the mission or the ramifications." Furthermore, Linenthal cautions, if the cancellation of *The Last Act* indicates that only officially sanctioned history can be told, then this episode "sets a chilling and dangerous precedent." Something, no doubt, for the history books. —*Sasha Nemecek*

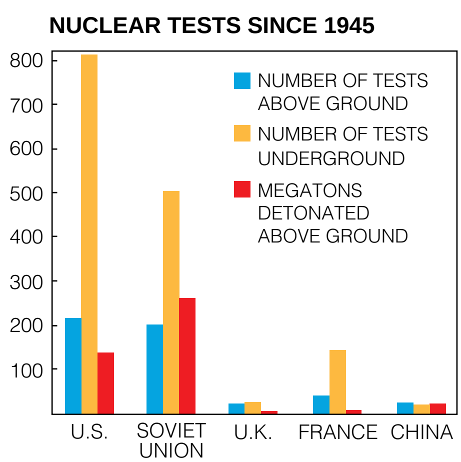
Testing's Toll

In the 50 years since Little Boy and Fat Man destroyed Hiroshima and Nagasaki, 2,034 tests of nuclear bombs have been conducted worldwide, according to Robert S. Norris and William M. Arkin of the Natural Resources Defense Council. China—which exploded four devices between 1993 and April of this year—is still testing, and France has announced plans to restart.

Of the world total, 511 were atmospheric tests. (The most recent of these was conducted by China in 1980.) Together these uncontained explosions were the equivalent of detonating 438 million tons of TNT. When combined with standard risk factors, assessments by the United Nations suggest that fallout from such testing could lead to 1.2 million fatal cancers, notes Arjun Makhijani of the Institute for Energy and Environmental Research. Only about 15 percent of the dose has been delivered; the rest will accrue over coming millennia. The actual number of cancers induced might be much smaller, because very low doses of radiation may be less harmful than risk assessments now assume. But some researchers believe the total could be larger.

The toll will probably never be known, because cancers caused by fallout cannot be distinguished from others. It is clear that some populations are at particular risk. For some 300,000 U.S. military personnel and civilians in high-fallout zones, atmospheric testing resulted in doses around 10 times higher than the global average caused by fallout, according to estimates by the Defense Nuclear Agency and Lynn R. Anspaugh of Lawrence Livermore National Laboratory and Bruce W. Church of the Department of Energy.

Only about 50 U.S. citizens received doses above 0.1 Sievert, which is enough to give a 0.5 percent chance of developing lethal cancer. But 253 Marshall Islanders received higher doses after test shot Bravo was fired at Bikini atoll in the Pacific in 1954: 86 were exposed to more than one Sievert; many suffered burns. Things were even worse in the Altai region of Russia, notes Charles S. Shapiro of San Francisco State University. In one district downwind of the Semipalatinsk test site, 16,000 civilians received more than 0.8 Sievert—much of it from a single test in 1949. —*Tim Beardsley*



Fast Cash

Physicists know that the momentum of a moving object is the product of both its mass and its velocity; similarly, economists can tell you that a working economy is defined both by the amount of money in play and by the speed with which it changes hands. Although much is often made about the amount of money available—during the late 1970s and early 1980s, it was the touchstone for the Federal Reserve's policy—you do not often hear a lot about velocity.

Depending on whom you ask, the reasons for this suspicious silence vary wildly. Is velocity stable enough that it can be ignored, too difficult to measure accurately or somehow irrelevant? At one end of the gamut stand the monetarists, disciples of Milton Friedman of the University of Chicago. Their focus on the volume of money in circulation is based on the implicit assumption that the rate at which dollars change hands varies in relatively predictable ways.


P. AVENTURIER *Gamma-Liaison*

***VOLUME OF CASH** that is available is clearly important to an economy. But the velocity at which it changes hands may prove just as critical.*

At the other sits Benjamin Friedman of Harvard University, who contends that the term "velocity" "should be banned" because it is meaningless and misleading. As Friedman's colleague N. Gregory Mankiw points out, velocity as measured by economists is a mediocre approximation of the underlying notion. No one can determine how long the average dollar stays in someone's wallet or cash register before entering another transaction.

Instead the term denotes simply the ratio between the amount of money in circulation and gross domestic product. For much of the 20th century, explains Robert J. Gordon of Northwestern University, this ratio rose and fell in fairly direct response to interest rates and economic conditions: high interest rates pushed it up because people did not want to hold on to cash; lower rates let it fall as the penalty for stashing cash decreased. Economic expansions also increased velocity, and recessions decreased it as the volume of business to be done rose or fell.

As a true measure of how fast money moves, however, the ratio has two important shortcomings. First, financial marketers have invented banking instruments that behave much like money for their users but do not register in official calculations of the money supply; traders can switch dollars in and out of this "supply" almost instantly without affecting economic conditions.

Second, the way economists count GDP eliminates the vast majority of daily transactions. If you buy a car, the GDP registers the check you write to General Motors, Nissan or Ford—but it omits all the prior transactions in which the manufacturer buys components from suppliers. In an economy that functions increasingly on the basis of vendors, consultants or freelancers rather than on in-house work, Mankiw says, this omission may obscure important shifts in the business climate.

Given all these problems, it is easy to see how Benjamin Friedman might claim that virtually no reputable economist believes the velocity of money is worth thinking about. He even contends that if one could measure the underlying phenomenon—the speed with which a fixed volume of dollars turns over—it would not be worth worrying about. GDP matters, but the mass and speed of the transactions that make it up bring no additional information.

William Poole of Brown University, one of the few who stand against Friedman (Benjamin) and favor Friedman (Milton), argues that evidence from the U.S. and other nations shows that the quantity and the velocity of money do matter. The anti-velocitarians argue that as of the early 1980s, U.S. economic conditions and financial markets differ so substantially from earlier eras that comparisons are impossible; still, Poole suggests their reasoning is solipsistic. "If you're convinced that evidence from the postwar period and from other countries isn't valid," Poole says, "then you can't have a debate."

In a slightly solipsistic turn of his own, Poole has an explanation for the failure of statistical studies to show any useful correlation between the velocity of money and other economic variables: because the Federal Reserve manipulates interest rates—and thus velocity—in its attempts to keep the economy on an even keel, the real relationship among monetary variables is obscured. He points out that the engineering principles underlying optimal control of complex systems predict that there should be no visible correlation between velocity and GDP, just as there would be none between the twitches of a steering wheel and the overall straight path of a car traveling down the highway.

The coming year may offer economists and laypeople some help in sorting out the arguments. The Federal Reserve's tight money policy has stalled monetary growth, and if Poole's beliefs are right, GDP should be faltering as well. If Benjamin Friedman's crew is right, the economy should be largely unaffected by the ups and downs of such inconsequent numbers. Consider it a natural experiment. *—Paul Wallich*

Beyond Binary

New optical technology may challenge CD-ROMs and videotape

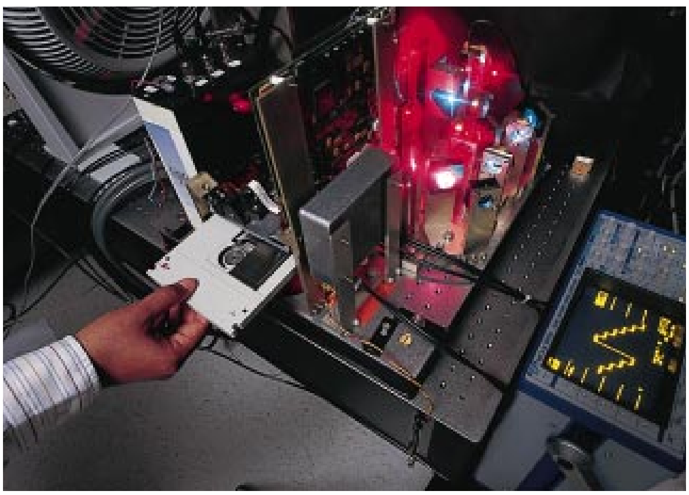
Browse the shelves of your local video store next year, and you may see something new: movies on CD-size digital videodiscs (DVDs) rather than tapes. Two camps of electronics companies are still battling over what form the discs will take, but they do agree on one point. DVDs will offer only prerecorded fare. Folks who want to digitally videotape their favorite cooking show or create their own multimedia masterpiece are out of luck.

A new data storage technology pioneered by Optex Communications in Rockville, Md., could change all that. Optex is wrapping up seven years of work on a drive that will record 5.2 gigabytes of data—eight times the capacity of a CD-ROM and enough for several hours of compressed video—onto an erasable 5.25-inch disc cartridge. The capacity is nothing special: magneto-optical drives will soon equal it. More important is the promise that Optex's drives will be cheap and fast.

"We can make the discs for under $10," asserts Brian L. Williams, a former Bell Atlantic executive now at Optex. A magnetic disk of equivalent capacity goes for about $2,000, in comparison. "The drives will probably cost about $200 more than a standard CD-ROM drive at first," he says. Speed is equally improved. "Conventional optical-recording technologies, because they require heat to make marks, hit limits at about 40 megabits per second," says Donald B. Carlin, the company's chief scientist. "We start at 50"—about as fast as current magnetic hard disks—"and can quickly go to 120. It's a whole new realm."

Such recording rates are possible because Optex's device, awkwardly dubbed an electron trapping optical memory (ETOM) disc, introduces two innovations to optical storage. The first is a material that reacts to light rather than to heat. Optex makes its discs by sputtering a thin film of a metal sulfide doped with two rare-earth elements, such as europium and samarium, onto an etched glass plate at high temperature. This material "can be dirt cheap," says Gerard A. Alphonse, an optics expert at the David Sarnoff Research Center in Princeton, N.J., who gives Optex's technology high marks.

An ETOM drive uses two lasers of different colors. Optex's first prototype sports blue and red gas lasers that can cram up to 10 gigabytes on a disc. Its consumer product, scheduled for testing next year, will replace these with cheaper red and infrared diode lasers.



JOHN McGRAIL

PROTOTYPE OPTICAL DRIVE uses cheap, erasable discs that hold as much as six CD-ROMs and work seven times as fast.

To write data, a cubic micron of the disc is zapped with a very brief pulse of blue light that excites the europium electrons. Energized, they jump to a nearby samarium ion. Some miss and fall back to their ground state, conveniently emitting a reddish-orange flash that confirms the data were received. Most, however, are trapped by the samarium ions. There they will stay for months, probably years—even at temperatures up to 150 degrees Celsius. But zap the spot with a red laser, and the trapped electrons are boosted back to their starting position, yielding a pulse of orange light as they fall. Read the pulse, and you recover the data.

Those data can be more than one bit—a second innovation. CDs and their offspring store information in binary form: a mark is either there (1) or not (0). ETOM introduces shades of gray between these extremes. Write a spot with bright light, and many electrons make the jump, so the disc returns bright flashes when read. Faintly written spots yield proportionately faint responses.

Herein lies ETOM's key advantage. With four distinct levels, one can write twice as much digital information on a disc and read it out twice as quickly; with eight levels, three times the data in one third the time. Optex's scientists have demonstrated 13-level recording in their materials. Their initial discs will employ six levels.

Last year Optex discovered a new variety of ETOM material that responds to the same infrared lasers used in CD-ROM and the coming DVD drives. That bit of luck will help it clear one of the highest hurdles facing any new medium: compatibility with older technologies. The company has already demonstrated a prototype that could use both ETOM and magneto-optical disks. Its consumer drives, Carlin promises, will record on ETOM discs but will also play back CD-ROMs and DVDs.

One hurdle often leads to another, however. The ability to make perfect copies of prerecorded discs has provoked Hollywood before to strangle novel technologies in the crib: witness digital audiotape. So it is no coincidence that Optex hired Raleigh Coffin—former president of CBS/Fox Video, the world's largest distributor of home videos—as its CEO. And it is no surprise that Coffin's eyes light up when he describes a quirk of ETOMs that will add a bit of cost and complexity to his drives.

Because reading a spot on an ETOM disc releases electrons from their traps, it also completely erases the data they encode. As each bit is read by one laser, it must thus be passed to the other laser to be rewritten a microsecond later. In that split-second handoff, Coffin spies an opportunity. "We could design the drive to refresh some data only a certain number of times," he points out, so that a copy-protected movie would be automatically obliterated after, say, the second viewing.

Coffin thinks that although such protection will be important to pacify the DVD producers, it will be critical when people start renting digital movies and multimedia software from services on the network rather than from stores on the street. "If everyone wants to watch *Terminator 2* on Friday night, providers will have two options," Williams describes. They could feed the video slowly over millions of two-hour telephone calls. Or they could download the entire movie in less than 90 seconds to a disc as large and fast as an ETOM—if they can trust that it will evaporate well before pirates could make many illegal copies.

Future possibilities are intriguing, but Optex is now focusing on more mundane matters, such as finding drive manufacturers willing to license its technology. If it is successful, the DVD battlefield may have to make room for yet another player. —*W. Wayt Gibbs*

Sweet Success

Sugary drugs may stick it to disease

Cells, like pills, are sugar-coated. This covering makes them sweet, in a manner of speaking, to microbes, which often fasten themselves to a cell's outer layer. In the past few years researchers have come to realize that this feature plays a crucial role in other important processes as well—including inflammation and organ rejection. Now a small but growing number of pharmaceutical companies are designing medicines to target surficial, sugar-binding proteins.

Sugars—which are often linked in small clusters to form oligosaccharides—have so far lagged proteins in medical research because they were hard to analyze. Two sugar molecules, for instance, can be connected in 22 different ways. Automated equipment, however, is making analysis easier, and new methods of synthesis suggest a boom for the field. Even Ole Hindsgaul of the University of Alberta, a leading carbohydrate chemist who criticizes exaggerated claims for biotechnology, says the area has "extraordinary promise."

One sugary reaction underlying inflammation has already proved a commercial goal. White cells in the blood are captured when damaged tissues produce proteins called selectins, which stick to the characteristic four-sugar oligosaccharides on the leukocytes' surface. Interfere with this sticking, the theory goes, and a damaging overaccumulation of such cells—and the resulting inflammation—might be avoided.

Cytel in San Diego is furthest along in developing a drug that would do exactly that. The company has produced a modified sugar molecule that mimics the oligosaccharide selectins bind to, creating a decoy; selectins should connect harmlessly to the drug instead of to white blood cells. Cytel's compound is being tested in patients to see if it can prevent the inflammatory heart damage, known as reperfusion injury, that often occurs after blood flow has been restored in a heart-attack victim.

Glycomed in Alameda, Calif., which was bought earlier this year by Ligand Pharmaceutical, also has what Hindsgaul terms "an excellent class" of selectin inhibitors. Researchers there are also working on carbohydrates that interfere with growth of blood vessels, as well as some that disrupt chemicals tumor cells need in order to spread.

Mindful of the importance of cell-surface sugars to bacteria, a few manufacturers are examining carbohydrates for potential anti-infective powers. Neose Pharmaceuticals in Horsham, Pa., is testing an oligosaccharide that may suppress infections of helicobacteria in the stomach, which can lead to ulcers. The bacteria will, according to Neose, bind to its drug rather than to the sugars. The company says it is also experimenting with a sugar that may give infant formula some of the infection-fighting properties of breast milk; a more ambitious effort aims to block the sugar-based immune reaction that makes it impossible to transplant organs from baboons and other primates into people.

Some compounds may even work to enhance the capabilities of microbe-fighting cells. Alpha-Beta in Worcester, Mass., for instance, has a multisugar molecule that appears to prevent postoperative infections.

Whereas most researchers in this growing field rely on natural or engineered enzymes to make their sugary molecules, at least one company is pursuing a different tack. Daniel Kahne of Transcell in Princeton, N.J., says he has developed a rapid technique to synthesize oligosaccharides chemically. This process could produce compounds unlike any seen in nature. Because many antibiotics and antitumor agents contain sugars as part of their structure, new variants might improve the effectiveness of such medications.

By attaching carbohydrates to biological molecules in novel ways, Transcell has made so-called permeation enhancers, which ferry drugs across cell membranes, making even large molecules suitable for administration by mouth. "We have sound animal data showing that proteins and peptides can be made orally bioavailable in dogs," states Elizabeth E. Tallett, chief executive of Transcell. Clinical trials with one permeation-enhanced antibiotic may start within a year. High-tech approaches such as gene therapy and antisense compounds might also benefit.

Despite all the advances, a potential drawback to sugar-based medicines might be that many of them are too easily digested to be given as pills. So Oxford GlycoSystems in England is searching for more robust molecules that mimic oligosaccharides. The company already has one promising candidate, a chemical that might attract anticancer drugs to the liver by binding to the organ's cells. Several other large pharmaceutical manufacturers are also working on mimetic compounds. It appears that biotechnology, which has long labored with protein-based drugs, might yet discover that sugars can provide the all-important icing. —*Tim Beardsley*

CHRIS BROWN *SABA*

HEART ATTACK patients may receive a new drug, based on a sugar, that could prevent dangerous inflammation when blood flow restarts.

I.T., Phone Home

Cheap calls on the Internet shake everyone up

The Internet Phone is a bargain. A small New Jersey–based company called VocalTec has developed a way of compressing voice into digital data that can travel across the Internet. The result is an inexpensive way to make long-distance calls. Telephone companies are starting to get worried, and Internet service providers should be, too. Whatever else it may be, the Internet Phone is a harbinger of fundamental economic challenges to the Internet and the telephone companies.

Both interests have drastically different ways of pricing communications bandwidth. The Internet is built on flat-rate charges. Internet providers buy and sell bulk bandwidth for a flat fee, which remains the same no matter what capacity is used. Telephone companies, in contrast, charge for usage. They make money on chatterers.

For most of the 25 years or so of the Internet's existence, these differences have been mostly academic. The Internet and the telephone companies served different markets—one data, the other voice. But technology is blurring the boundaries between these realms. As everything becomes digital—and, U.S. Congress permitting, as telecommunications prices and services become increasingly deregulated and competitive—the differences between approaches to pricing bandwidth become more interesting and potentially profitable.

The Internet Phone is a case in point. It works on a personal computer with a sound card and microphone. The microphone converts voice into digital form. Software compresses the digitized voice and transmits it over the Internet to another computer, which decodes it, decompresses the voice and plays it on its speaker. The sound quality is not great. There is a troublesome delay of about one second. And there is no ringing bell to enable you to reach somebody who is not at the computer awaiting your call—unless of course you telephone them, which seems to defeat the point. But the price is hard to beat.

Depending on where exactly you call and just how long you talk, dialing through the computer can cost a tenth, or even a hundredth, of a long-distance call. VocalTec's software costs $69. Compared with the hundreds of millions of telephone yakkers around the world, a few thousand nerds with talking computers aren't going to worry telephone companies too much. Or are they?

The cost of communications bandwidth and computing falls about 30 percent a year. But as Jeffrey K. MacKie-Mason and Hal R. Varian of the University of Michigan point out, the cost of computers has been falling slightly faster. In 1960 the computers needed to transport an arbitrary amount of data over the Internet cost about 10 times as much as the lines over which it was sent. In 1970 the two costs were about equal. By 1990 the cost of the computers was one tenth the cost of the lines.

The Internet is using cheap computers to take over from the telephone companies the job of switching and routing the messages it receives. VocalTec relies on the cheap power of desktop computers to compress voice to squeeze through most modems. Other companies are already scheming about how to use growing computing power and the Internet to lower the cost and raise the convenience of faxes, voice messages, sound broadcasts, picture transmission and all sorts of other goodies.

These possibilities put telephone companies in a bind. By making the Internet more capable and flat-rate services more attractive, they undercut the usage-based services on which they make their money. In theory the companies can respond by adjusting their prices to sell more flat-rate services themselves. After all, it is telephone companies that provide the bulk bandwidth on which the Internet runs. But telephone companies are understandably worried about promoting price-cutting competition to their own most profitable services.

Even the Internet itself may be at risk. With its growing popularity comes the danger that the Net will sell some of itself too cheap and so become unusually congested. As more Internet services compete, the more misleading becomes the one-price-fits-all policy. Some items cost more to provide than others. Telephone conversations can be particularly expensive because not only do they require far more data be transmitted than in an E-mail message, but they require that every mote of data be sent immediately. All or part of an E-mail, in contrast, can be delayed if a burst of congestion should clog the line.

Creating prices for new telecommunications capabilities will require a balance to be struck between economic theory and market reality. Economists argue that the heart of this equilibrium lies in approaching the business from a radically revised perspective. Instead of an array of competing services, they reckon markets should be treated as a collection of resources—each of which may be more or less in demand at any given moment and should charge according to that demand. When lines are congested, for example, the price of a voice call should be much higher than when lines are free—but that of a delayable E-mail only a bit higher.

Given the power of computers, there is no technical reason why the economists' dream should not be realized. Telecommunications markets could charge prices that vary by the second. But even with computers, telephones and faxes that can automatically seek out the cheapest service, it is not clear that people want to do business this way. Long-distance callers may well prefer predictably priced calls to ones that are sometimes cheap and sometimes expensive. E-mailers have grown used to typing for a flat rate.

Somewhere between the flat-rate pricing structure of the Internet and the usage-based charges of voice telephony is a new approach. Forthcoming Internet protocols and other schemes will allow users to specify the priority of each packet of information traveling over the network. That may clear a path to some middle ground. *—John Browning*

Going Down

Japan invests in an alternative source of energy

OCEAN DRILLING PROGRAM

IT'S A GAS that engineers are seeking on the seafloor.

Gas hydrates—icy deposits of crystallized natural gas and water that form under the crushing pressures and cold temperatures of the deep ocean and Arctic permafrost—have tantalized geologists for the past decade. Gigantic hydrate fields around the world are estimated to contain twice as much energy as all other forms of fossil fuel combined. But these troves have remained largely untapped because retrieving the trapped methane is considered prohibitively expensive while more traditional reserves of energy remain cheap and abundant.

Until now. Japan, the second largest consumer of energy in the 32-nation Organization for Economic Cooperation and Development, has been eyeing such reserves with intent to mine. The Japan National Oil Corporation is planning an $87-million project, which may well culminate in gathering hydrates from the Sea of Japan by 1999. "In terms of developing a natural resource, the Japanese are in a unique position," notes Charles K. Paull of the University of North Carolina at Chapel Hill. "Cost is not part of their consideration. Japan has no energy independence."

According to a recent U.S. Department of Energy report, Japan will be a major importer of natural gas—the fastest-growing source of energy—by 2010. Currently two thirds of the natural gas supply is exported from the political tinderboxes of the former Soviet Union and the Middle East, which places Japan in an economically delicate situation.

Metal Detectors

"It's very different from the normal interaction between art and science," muses Mel Chin, an artist at the University of Georgia, as he tries to explain *Revival Field*—is it an idea, an experiment, a living installation? "I see this as a sculptural project; the raw material just happens to be polluted earth instead of marble." Rufus L. Chaney of the U.S. Department of Agriculture, the other half of the collaboration, uses the term "phytoremediation" to define the concept. Their language may differ, but both men are pursuing the same goal: a simple, green technology for removing heavy metals from contaminated lands. It is a conceptually and economically appealing alternative to carting away the dirt—at a cost of at least $1 million per acre—and depositing it in a landfill.

About 15 years ago Chaney recognized that certain rare "hyperaccumulator" plant species incorporate such high concentrations of heavy metals that they could serve as natural soil cleansers. In the case of valuable metals, such as nickel, saturated plants could be dried and sold as ore. The notion attracted attention from the Environmental Protection Agency, "but then Reagan came into office, and we stopped that work," Chaney recalls.

MEL CHIN

Nevertheless, word of phytoremediation reached Chin, who was intrigued by the "poetic cycle" of using plants to undo the ill

"Japan imports 99 percent of all the oil they use and 96 percent of all natural gas," notes William P. Dillon of the U.S. Geological Survey. "They are very serious about gas hydrates."

If this intent translates into success, Japan will be the first country to develop the technology to tap hydrates. Although U.S. scientists undertook much of the pioneering work on these substances, many had to abandon their efforts when Congress recently slashed the U.S.G.S. budget. Ironically, the early work on hydrates centered on trying to avoid them. Geologists hired by oil and gas companies were asked to keep the substances from clogging pipelines and destabilizing drilling platforms.

Paull and his colleague Ryo Matsumoto of the University of Tokyo will begin the basic research needed to harvest hydrates when they lead the first deep-sea drilling expedition to examine the compounds this November. Leg 164 of the Ocean Drilling Program—a 31-year-old, internationally funded project—will sail to Blake Outer Ridge off the coast of North Carolina. There a hydrate field the size of Vermont is estimated to contain 350 times the amount of energy Americans consumed in 1989. The two-month venture will attempt to quantify the hydrates and learn whether the methane can be removed without destabilizing the seafloor. *—Brenda DeKoker*

effects of the industry that had replaced them. In 1991, with Chaney's guidance, the artist designed a small plot of hyperaccumulator plants at a Superfund site outside St. Paul, Minn. (*left*). The project completed its test run in 1993; the *Revival Field* in Palmerton, Pa., is still gathering data.

Clearly, *Revival Field* is not about landscape aesthetics. Chin considers phytoremediation itself as his artwork; "It is art as process and science as process," he says. Artists such as Robert Smithson create pieces in which they reshape the land, he elaborates. "*Revival Field* is a continuation of their ideas—it shows that the molecular transformation of the land is just as important." The deeply conceptual nature of the project has baffled some of his colleagues—and alienated certain patrons. In 1990 John E. Frohnmayer, then head of the National Endowment for the Arts, denied him an already approved $10,000 grant. Chin appealed and won.

Chaney recognizes a lot of effort yet to come: collecting hyperaccumulator species, cultivating test plots and establishing the viability of harvesting plants as ore. Although Chaney receives scant government funding, news about *Revival Field* has spread interest in phytoremediation. *—Corey S. Powell*

PROFILE: STEPHEN JAY GOULD

Escaping in a Cloud of Ink

Stephen Jay Gould hasn't even appeared yet, and already he has me guessing. Although the world-famous author and evolutionary biologist has taught at Harvard University since 1967, he asked me to meet him here in New York City, where he was born and raised and still keeps a home. Minutes earlier a woman in a French maid's uniform admitted me into a museumlike townhouse on Manhattan's Upper East Side. She leaves me to wait for Gould in a jewel box of a library with an original Warhol above the fireplace. The room is lined with old, leather-bound books devoted to such topics as the history of the Dutch Republic.

Even an intellectual as voracious as Gould, I feel certain, would never have cracked these books. He must have placed them here to provide a veneer of intellectuality. Could Gould, scourge of social Darwinism and all forms of genetic determinism, champion of those with low IQ, self-proclaimed baseball lover, be a status-symbol monger? What I find hardest to believe is not that Gould is a hypocrite but that he is a *flagrant* hypocrite.

Of course, he isn't. Gould makes his entrance in khaki pants and Oxford shirt, the rumpled professor studiously unconcerned with material appearances. When I remark on the beauty of his home, he informs me that it belongs not to him but to his fiancée, or, rather, to her ex-husband. It will soon be sold. Gould and his wife-to-be are moving downtown to a neighborhood and an apartment more to Gould's liking. "It is incredible, isn't it," Gould agrees, his eyes sweeping across the room. His nose wrinkles, as if invaded by an unpleasant odor. "But it isn't me."

So who is he, then? Gould has prohibited personal inquiries, but I am more curious about his intellectual psyche anyway. Most scientists take comfort in showing that our world is somehow inevitable, necessary. But throughout his career, Gould, now 53, has insisted that virtually *nothing* is inevitable. He revels in randomness, or, to use his preferred term, contingency.

Gould began staking out his turf in the 1960s by attacking the venerable doctrine of uniformitarianism, which held that the geophysical forces shaping the earth and life have been more or less constant. In 1972 he and Niles Eldredge of the American Museum of Natural History introduced punctuated equilibrium (also called "punk eek" and, by critics of Gould and Eldredge, "evolution by jerks"). The fossil record, they argued, does not support Darwin's view of evolution as a gradual, continuous unfolding; instead the evidence shows long periods of stasis "punctuated" by relatively rapid bursts of speciation. In subsequent papers Gould and Eldredge contended that speciation must stem not only from natural selection operating at the level of individuals, as conventional Darwinian theory would have it, but also from more complex, contingent factors.

Gould's great bugbear is lack of originality. Darwin himself, critics of punctuated equilibrium like to point out, recognized that evolution might have a variable pace. Something about Gould's authorial style also provokes his detractors—and he has legions—to speculate about hidden agendas. Does his antipathy to genetic determinism stem from Marxist leanings? Is he a closet relativist, who believes science is merely a projection of its culture? Is he engaged in some Oedipal tussle with Darwin? One of Gould's longtime sparring partners, Edward O. Wilson, who also works at Harvard's magnificent Museum of Comparative Zoology, has warned me that pinning Gould down is difficult. "Steve uses the squid tactic," Wilson explains. "When attacked, he escapes in a cloud of ink."

Gould is as squidlike in person as on paper. He talks in a rapid-fire murmur, laying out even the most complex argument with an ease that hints at vast knowledge held in reserve. He decorates his discourse, like his writings, with quotations, which he prefaces with, "Of course, you know the famous remark of—" He often appears distracted, as if he is not paying attention to his own words. I have the impression that mere speech is not enough to engage him fully; higher-level programs of his mind roam ahead, conducting reconnaissance, trying to anticipate possible objections to his discourse, searching for new lines of argument, analogies, quotations.

When I ask about early influences, Gould acknowledges having been inspired by Thomas S. Kuhn's notorious *Structure of Scientific Revolutions.* According to Kuhn, the history of science consists of periods of calm, "normal" research, during which workers are in thrall to a single paradigm, sporadically interrupted by revolutions; then scientists who are usually young and unindoctrinated force their colleagues to yield to a new paradigm for reasons that are often arational. *Structure* led Gould to hope that he, a young man from a lower-middle-class family in Queens whose parents were not college graduates, could make an important contribution to science. The book also helped him to reject the "inductivist, ameliorative, progressive, add-a-fact-at-a-time-don't-theorize-till-you're-old model of doing science."

When I ask Gould if he believes, as Kuhn does, that science does not advance toward truth, Gould denies that Kuhn holds such a position. "I know him, obviously," Gould says of Kuhn, a professor emeritus at the Massachusetts Institute of Technology. Although Kuhn is the "intellectual father" of the relativists, he nonetheless realizes that "there's an objective world out there," Gould asserts, and that "we have a better sense of what it is now than we did centuries ago."

Gould seems to be neither a relativist nor a Marxist, as some detractors have suggested. But is he a Darwinian?

Science is much too boring, Gould continues, for any scientist to be a true cultural relativist. "You've got to clean the mouse cages and titrate your solutions, and you've got to clean your petri dishes." No one could endure such tedium unless he or she thought it would lead to "greater empirical adequacy."

Gould glides past queries on Marx just as easily. He admits he finds some of Marx's ideas compatible with his own. Marx viewed social change as occurring in the "punctuational mode, in which you accumulate small insults to the system until the system itself breaks." I hardly have to ask the next question: Is Gould, or was he ever, a Marxist?

"You just remember what Marx said," Gould replies before my mouth has closed. Marx himself, Gould "reminds" me, once argued he was not a Marxist, because Marxism had become too many things to too many people. No intellectual, Gould explains, wants to identify himself too closely with any "ism," especially one that has become so capacious. Moreover, Marx "really got caught up in notions of predestiny and determinism, particularly in theories of history, which I think ought to be completely contingent. I *really* think he's dead wrong on that."

So Gould is neither a relativist nor a Marxist. Is he a Darwinian? Trying to ease into the topic, I recall that in their original 1972 paper Gould and Eldredge referred to punctuated equilibrium as an "alternative" to Darwin's gradualism. In a 1993 retrospective they call it merely a "complement." Does this word change represent some sort of concession to Darwin's supremacy? "I didn't write that!" Gould exclaims. John Maddox, the editor of *Nature,* stuck "complement" in the paper's headline without checking with the authors. "I'm mad at him about that," Gould fumes.

He then proceeds to argue that alternative and complement do not have such different meanings. "If you claim something is an alternative, that doesn't mean it operates exclusively," he says. "I think punctuated equilibrium has an overwhelmingly dominant frequency in the fossil record, which means gradualism exists, but it's not really important in the overall pattern of things."

Darwin "had the answer right about the basic interrelationships of organisms," Gould concedes, but "that's only a beginning"; evolutionary biologists had other crucial issues to explore. Such as? "Oh, there are so many I don't know where to start," Gould responds. Theorists still had to determine the "full panoply of causes" underlying the history of life, from molecules on up to large populations of organisms. Then there are "all these contingencies," such as the asteroid impacts that are thought to cause mass extinctions. "So I would say causes, strengths of causes, levels of causes and contingency." He muses a moment. "That's not a bad formulation," he says, whereupon he removes a little notebook from his shirt pocket and scribbles in it.

Further, Darwinism might be superseded by some greater theory, just as Newtonian mechanics was by quantum mechanics. "The evolution of life on this planet may turn out to be a very small part of the phenomenon of life," he says. So Gould believes that life exists elsewhere in the universe? "Don't you?" he counters. I tell him I think the question is entirely a matter of opinion. To my delight, Gould winces; for once, he has been caught off guard.

Yes, *of course,* the existence of life

elsewhere is a matter of opinion, he snaps, but one can still engage in informed speculation. Life seems to have emerged rather readily here on the earth, since the oldest rocks that could show evidence of life do show such evidence. "The immensity of the universe, and the improbability of absolute uniqueness of any part of it, leads to the immense probability that there is some kind of life all over."

But like a rebellious son who rails at his own father yet bristles when others do so, Gould can also be fiercely protective of Darwin. He recalls with great satisfaction how in the 1970s he exposed the "lies" of creationists who had seized on punctuated equilibrium as an indication that the theory of evolution was not universally accepted. Gould has also dealt harshly with some scientific challenges to mainstream Darwinism—such as Gaia, the notion that all species somehow cooperate to perpetuate their mutual survival. "Gaia is just a metaphor," he says. "I don't see anything *causal* in Gaia."

Gould is similarly suspicious of the nascent field of artificial life. While intrigued by the potential of computers for exploring alternative evolutionary scenarios, he worries that some artificial lifers are too prone to see evolution in mathematical terms. "Oh, you know Bertrand Russell's famous comment," Gould says. Russell, he enlightens me, once remarked that he wanted to understand " 'the Pythagorean power with which number holds sway above the flux.' Isn't that a great line?" Gould repeats it, with even more relish. "It's a very deep philosophical position, but I also think it's very deeply wrong," Gould chuckles.

ARNOLD NEWMAN

HISTORIAN AT HEART is how Gould, shown here in his office at Harvard, describes himself.

My allotted time with Gould is almost up, and I am still unsure who he is. As far as I can tell, his view of life can be summed up in the old bumper-sticker aphorism: Shit Happens. Gould, of course, puts it more elegantly. Many scientists, he notes, distinguish between science, which involves the unveiling of universal laws, and history, which deals with particulars and contingency. "I think that's a false taxonomy. History is a different type of science." Gould admits that he finds the fuzziness of history, its resistance to straightforward analysis, exhilarating. "I love it! That's because I'm a historian at heart."

Perhaps this is the key to understanding Gould. If the history of life is a bottomless quarry of factoids, he and other scientists can keep mining it forever without worrying that their efforts have become trivial or redundant. That is certainly Gould's hope. For more than a decade, he has been working on a massive treatise called *The Structure of Evolutionary Theory.* He hopes to finish the book, which is already more than 1,000 pages long, by next spring. Will Gould, having released this vast cloud of ink, then turn to other intellectual pursuits? "Oh, evolutionary theory is so expansive," he says with a serene smile, "there's enough there to keep anyone going for a lifetime." —*John Horgan*

Recollections of a Nuclear War

Two nuclear bombs were dropped on Japan 50 years ago this month. The author, a member of the Manhattan Project, reflects on how the nuclear age began and what the post–cold war future might hold

by Philip Morrison

Rarely do anniversaries mark the very beginning of an event. The roots of my own recollections of the Manhattan Project and the first nuclear bomb go back well before August 1945. One thick taproot extends down to 1938, when I was a graduate student in physics and a serious campus activist at the University of California at Berkeley. One night that spring, my friends and I stayed up into the chilly small hours just to catch the gravelly voice of the Führer speaking at his mass rally under the midday sun in Nuremberg. His tone was boastful, his helmeted armies on the march across national borders. His harangue, though delivered across the ocean and nine hours to the east, sounded all too nearby. It was clear that a terrible war against the Third Reich and its Axis was not far off. The concessions to Hitler made at Munich that autumn confirmed our deepest anxieties. World war was close.

"The Trinity Test, the first test of a nuclear bomb, went off as planned, on July 16, 1945, leaving lifelong indelible memories. None is as vivid for me as that brief flash of heat on my face, sharp as noonday for a watcher 10 miles away in the cold desert predawn, while our own false sun rose on the earth and set again."

A fateful coincidence in nuclear physics soon linked university laboratories to the course of war and peace. By early 1939 it became certain that an unprecedented release of energy accompanies the absorption of slow neutrons by the element uranium. I can recall the January day when I first watched in awe the green spikes on the oscilloscope screen that displayed the huge amplified pulses of electrons set free by one of the two fast-moving fragments of each divided uranium nucleus.

The first evidence for this phenomenon had been published only weeks earlier. It was indirect, even enigmatic. The radiochemists in Otto Hahn's laboratory at the Kaiser Wilhelm Institute of Chemistry in Berlin—there were none better—had found strong residual radioactivity in barium, which formed as a reaction product when uranium absorbed neutrons. Notably, a barium atom is only a little more than half the weight of an atom of uranium, the heaviest element then known. No such profound fragmentation after neutron capture had ever been seen. The identification was compelling, but its implications were obscure.

Almost at once two refugee physicists from Nazi Germany, Otto R. Frisch and Lise Meitner (Frisch's celebrated aunt), meeting in Sweden, grasped that the nucleus of uranium must have been split into two roughly equal parts, releasing along the way more energy than any nuclear reaction seen before. Soon this news was out, first carried to the U.S. by the Danish physicist Niels Bohr.

Furthermore, the division process, known as fission, seemed intrinsically likely to set free at least two neutrons each time. Two neutrons would follow the first fission, and if conditions were right, they would induce two more fission events that would in turn release four additional neutrons. Fission resulting from these four neutrons would produce eight neutrons, and so on. A geometrically growing chain of reactions (an idea Leo Szilard, a refugee from Europe newly come to New York City, alone had presciently held for some years) was now expected. The long-doubted, large-scale release of nuclear energy was finally at hand. We all knew that the energy released by the fission of uranium would be a million-fold greater pound for pound than that from any possible chemical fuel or explosive.

The World at War

Relevance to the looming war was inevitable. After hearing the news from Europe, my graduate student friends and I, somewhat naive about neutron physics but with a crudely correct vision, worked out a sketch—perhaps it would be better dubbed a cartoon—on the chalkboards of our shared office, showing an arrangement we imagined efficacious for a bomb. Although our understanding was incomplete, we knew that this device, if it could be made, would be terrible. I have no documentation of our casual drawings, but there are telling letters sent by our theorist mentor J. Robert Oppenheimer, whose own office adjoined ours. On February 2, 1939,

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he wrote his old friend in Ann Arbor, physicist George E. Uhlenbeck. Oppenheimer summarized the few but startling facts and closed: "So I think it really not too improbable that a ten centimeter cube of uranium deuteride... might very well blow itself to hell."

In time, just that would happen, although the process was more complicated than anyone first imagined. I am quite confident that similar gropings took place during those first weeks of 1939 throughout the small world of nuclear physics and surely in Germany, where fission was first found. By the autumn of 1939 Bohr and John A. Wheeler had published from Princeton the first full analysis of fission physics. Gallant Madrid had fallen, and the great war itself had opened. It is a matter of record that by the spring of 1940 several groups of experts had been charged to study the topic in no fewer than six countries: Germany, France (as a nation, soon to become a prisoner of war), Britain, the Soviet Union, the U.S. and Japan. It was certainly not statesmen or military leaders who first promoted the wartime potential of the fission process, but physicists in all these countries. In the U.S., for example, Albert Einstein signed the famous letter to President Franklin D. Roosevelt, just as the war began, encouraging him to pursue the development of nuclear weapons.

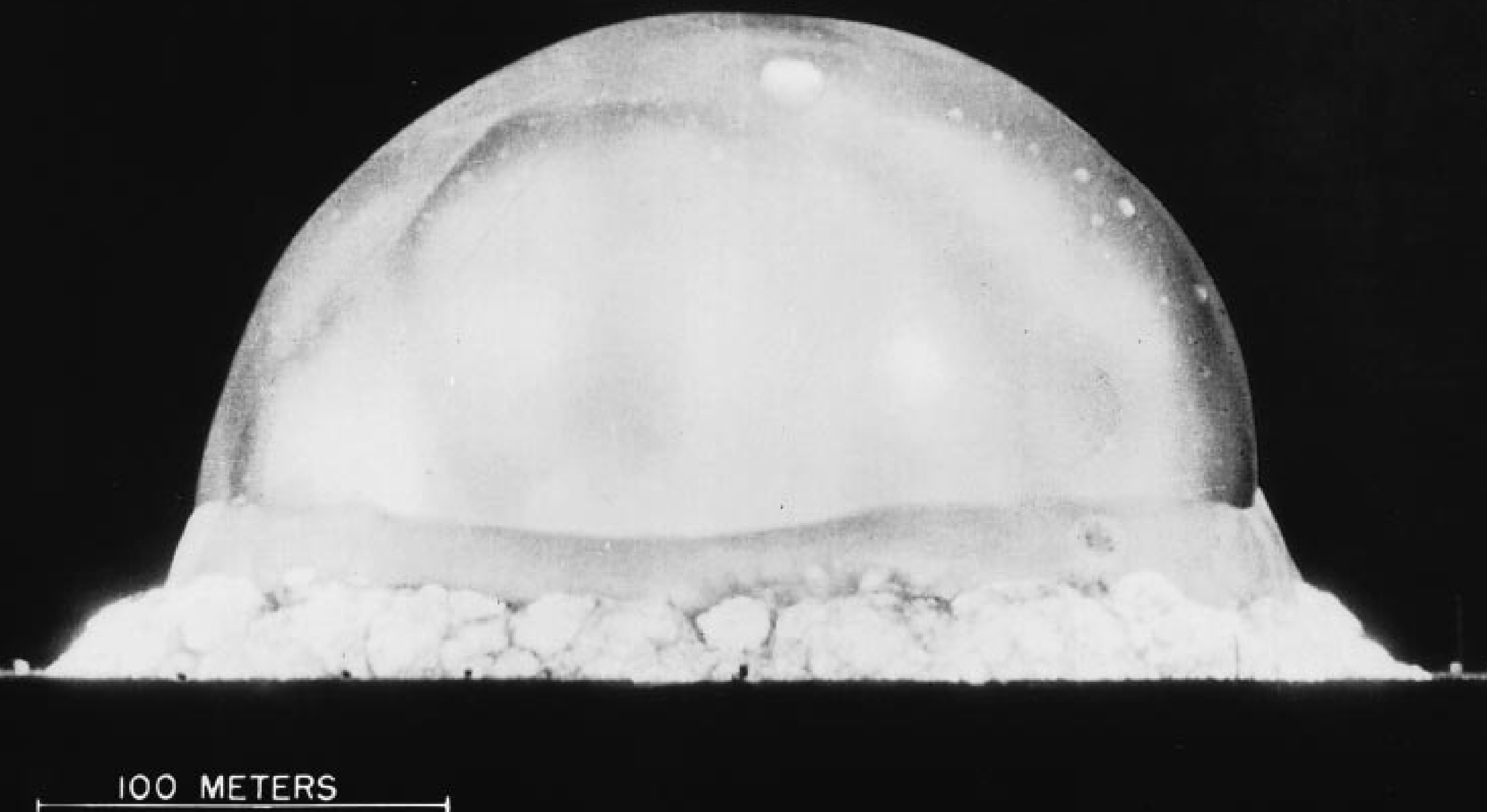
By the end of 1941 all those powers, and Italy, too, were immersed in war, as China and Japan long had been. Physics, of course, was fully caught up in the sudden, sweeping American mobilization. By then I was a physics instructor at the University of Illinois at Urbana-Champaign, where I had moved in 1941 to fill an opening left by two of my Berkeley physicist friends, as first one and then his replacement had come and gone again, both bound for some undisclosed war work. In 1942 most male students marched singing to their classes in military formations, students at the pleasure of the draft authorities. The college year was extended to a full 12 months; we faculty members taught full tilt and embarked as well on war-directed investigations with generous federal support.

Another fateful voice now informs my memories. Every Thanksgiving the physicists of the Midwest met in Chicago. I went to their sessions in 1942. A fellow graduate of our small Berkeley group charged me by telephone to come without fail to visit him at the University of Chicago lab where he worked at the time. I entered that Gothic physics building, my appointment verified by unforeseen and incongruous armed guards, to find my friend Bob Christy sitting quietly at his desk. "Do you know what we're doing here?" he asked. I admitted that it was easy to guess: this must be the hidden uranium project to which so many others had gone. "Yes," he said, in his familiar style of calm speech, "we are making bombs."

I was startled, even hushed, by the ambitious plan with so final and fearful a goal. Christy and I talked, and a question arose: How else could our side lose the war *unless* it was the Germans who first made nuclear weapons? The task was indeed vital; every physicist with relevant competence—they were few enough—had to take part. I was persuaded; my wife concurred. Within weeks I was in the very same Chicago lab, learning how to assist Enrico Fermi, who was in the office next door. I had enlisted, so to speak, for the duration, like many a young soldier before me.

During the bitter war year of 1943, I became an adept neutron engineer, testing again and again detailed mock-ups of the huge reactors to be built in Hanford, Wash., along the Columbia Riv-

BOMB BLAST from the Trinity Test is shown 0.025 second after detonation in the New Mexico desert. At the time of this exposure, the explosion was more than 300 meters across.



er. I recall other lines of thought, too, within the busy circle of theorists and engineers around Eugene P. Wigner. I recognized almost as a revelation that even the small concentration of uranium found in abundantly available granite could provide enough fission fuel to power its own extraction from the massive rock and yield a large energy surplus besides. In principle only—practice does not even today support this dream—an energy source that could use as fuel the mountains themselves would far outlast all fossil fuels. I was also to propose (not alone) a detailed plan to ferret out what the Germans were in fact up to, and soon I became a technical adviser to General Leslie R. Groves's new intelligence organization in Europe—a dramatic and, in the end, worrisome sideline for a young physicist.

Building the Bomb

Here in the States, two giant industrial sites were being swiftly built to produce sufficiently large quantities of two distinct nuclear explosives, uranium and a newly discovered element, plutonium. And we all knew that somewhere—at a hidden "Site Y"—work was under way to develop a bomb mechanism that could detonate these nuclear explosives. But in mid-1944, even as the reactors along the Columbia that would produce plutonium were being completed by 40,000 construction workers, Site Y encountered an unforeseen technical crisis. The favored bomb design had been simple and gunlike: a subcritical enriched uranium bullet was fired into a matching hole in a subcritical enriched uranium target, detonating them both. Yet measurements on early samples proved that this design could not be used with plutonium, and the bulk of the bomb material the U.S. was prepared to make during the next years would be plutonium. A complex and uncertain means of assembly, known as the implosion design, examined earlier but set aside as extremely difficult, now seemed the only way open: you had to squeeze solid plutonium metal to a momentary high density with a well-focused implosion of plenty of ordinary high explosive.

By summer's end of 1944, I was living and working in Site Y amid the beautiful high mesas and deep canyons of Los Alamos, N.M., along with many other scientists and engineers. We had been urgently gathered from the whole of the wide Manhattan Project to multiply and strengthen the original Los Alamos staff, star-studded but too few to realize the novel engineering of the implosion design.

"'Do you know what we're doing here?' [Christy] asked. I admitted that it was easy to guess: this must be the hidden uranium project to which so many others had gone. 'Yes,' he said, in his familiar style of calm speech, 'we are making bombs.'"

Information from German labs convinced us by the close of 1944 that the Nazis would not beat us to the bomb. In January 1945, I was working in Frisch's group, which had become skilled in assembling subcritical masses of nuclear material that could be brought together to form the supercritical mass needed for energy release. Indeed, we had the temerity to "tickle the dragon's tail" by forming a supercritical mass of uranium. We made a much subdued and diluted little uranium bomb that we allowed to go barely supercritical for a few milliseconds. Its neutron bursts were fierce, the first direct evidence for an explosive chain reaction.

By spring the lab had fixed on a design for a real plutonium implosion bomb, one worked out by Christy, and scheduled its full-scale test. Two of us from the Frisch group (I was one, physicist Marshall G. Holloway the other) had been appointed as G-engineers, the "G" short for gadget—the code name for the implosion bomb. We were fully responsible for the first two cores of plutonium metal produced. We had to specify their design in great detail; once enough plutonium compound arrived, we were charged to procure the cores from Los Alamos resources, prepare their handling and by July be ready to assemble the first test core amid the other systems of the complex weapon. By June, though, the battle with Germany was over, but the war with Japan burned more terribly than ever. We kept on toward the still uncertain bomb, in loyal duty to our country and the leaders we trusted—perhaps too much?

The Trinity Test, the first test of a nuclear bomb, went off as planned, on July 16, 1945, leaving lifelong indelible memories. None is as vivid for me as that brief flash of heat on my face, sharp as noonday for a watcher 10 miles

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PREPARING THE BOMB TOWER just two days before the Trinity Test, a group from Los Alamos Laboratory hoists the bomb assembly up to the platform.

ATOMIC SCIENTISTS gather at a base in the Marianas Islands, where the nuclear bombs dropped on Japan in August 1945 were assembled. The author is seated third from the right.

PHILIP MORRISON at Los Alamos Laboratory in 1945.

UPI/BETTMANN   LOS ALAMOS NATIONAL LABORATORY (INSET)

away in the cold desert predawn, while our own false sun rose on the earth and set again. For most of the 2,000 technical people at Los Alamos—civilians, military and student-soldiers—that test was the climax of our actions. The terrifying deployment less than a month later appeared as anticlimax, out of our hands, far away. The explicit warning I had hoped for never came; the nuclear transformation of warfare was kept secret from the world until disclosed by the fires of Hiroshima.

Nuclear War in Embryo

All three bombs of 1945—the test bomb and the two bombs dropped on Japan—were more nearly improvised pieces of complex laboratory equipment than they were reliable weaponry. Very soon after the July test, some 60 of us flew from Los Alamos to the North Pacific to assist in the assembly of these complex bombs, adding our unique skills to those of scores of thousands of airmen on Tinian, where unending shiploads of gasoline and firebombs were entering the harbor.

The Hiroshima bomb, first to be readied, was first to be used, on August 6, 1945. That city was turned to rust-red ruin by the uranium bomb nicknamed Little Boy. The design had never been tested before it was dropped, as the gun design was so simple, though much costlier in nuclear fuel. Then the second version of the just tested plutonium implosion bomb Fat Man brought disaster to Nagasaki. The war soon ended.

With the sense that I was completing my long witness to the entire tragedy, I accepted the assignment to join the preliminary American party hurriedly sent from our Pacific base to enter Japan on the first day of U.S. occupation. Joined by two other young Americans in uniform, I traveled by train for a couple of weeks across Japan, the rails crowded with demobilizing troops. The Japanese were disastrously impoverished and hungry, yet still orderly. Along the tracks, we saw cities large and small, ruined by 100 wildfires set with jelly gasoline by raids of up to 1,000 B-29 bombers, devastation that was the very mark of the old war. The damage in these other cities resembled the destruction visited on Hiroshima by one single nuclear explosion and its aftermath of fire.

We had loosed our new kind of war, nuclear war in embryo, with only two bombs. A single bomber was now able to destroy a good-size city, leaving hundreds of thousands dead. Yet there on the ground, among all those who cruelly suffered and died, there was not all that much difference between old fire and new. Both ways brought unimagined inferno. True, we saw hundreds of people lying along the railway platform at Hiroshima; most of them would die from burns or from the new epidemic of radiation sickness that we had sowed. But many other cities, including firebombed Tokyo, where 100,000 or more had died in the first fire raid, also counted hosts of burned and scarred survivors. Radiation is no minor matter, but the difference between the all-out raids made on the cities of Japan and those two nuclear attacks remains less in the nature or the scale of the human tragedy than in the chilling fact that now it was much easier to destroy the populous cities of humankind. Two nuclear bombs had perhaps doubled the death count brought by air power to Japan.

Fission and then fusion offered havoc wholesale, on the cheap. It was not World War II that the atom's nucleus would most transform but the next great war. The past 50 years have been ruled by one nuclear truth. In 1945 the U.S. deployed about 1,000 long-range B-29s. By the 1960s we had about 2,000 jet bombers, and by the 1980s maybe 1,500 missiles. For more than four decades we kept a striking force comparable with the one General Curtis E. LeMay commanded in 1945, each year becoming faster, more reliable, and so on.

But now *every single payload* was not chemical explosive but nuclear fire, bringing tens or even hundreds of times greater death and destruction. The statesmen on both sides chose to arm and even threaten war with these weapons, a war that would be orders of magnitude more violent than all before it. Yet the statesmen did not follow through on their threats; large-scale nuclear conflict is now recognized for what it is, wholly intolerable.

I returned from Japan at the end of September 1945 to learn that one young man within our small group was gone, killed in the lab by a runaway radiation burst. (He would not be the last, either.) Our temerity about the nuclear dragon had left its legacy in New Mexico as well. America was at peace but clamorous, the new atomic bomb, in all its terror, the center of interest. By the end of the year many scientists, including myself, made clear, concerted, even dramatic public statements about the future of nuclear war.

What we said then was this: Secrecy will not defend us, for atoms and skills are everywhere. No defenses are likely to make up for the enormous energy release; it will never be practical to intercept every bomb, and even a few can bring grave disaster. Passive shelter is little use, for the deeper the costly shelter, the bigger the inexpensive bomb. No likely working margin of technical superiority will defend us either, for even a smaller nuclear force can wreak its intolerable damage.

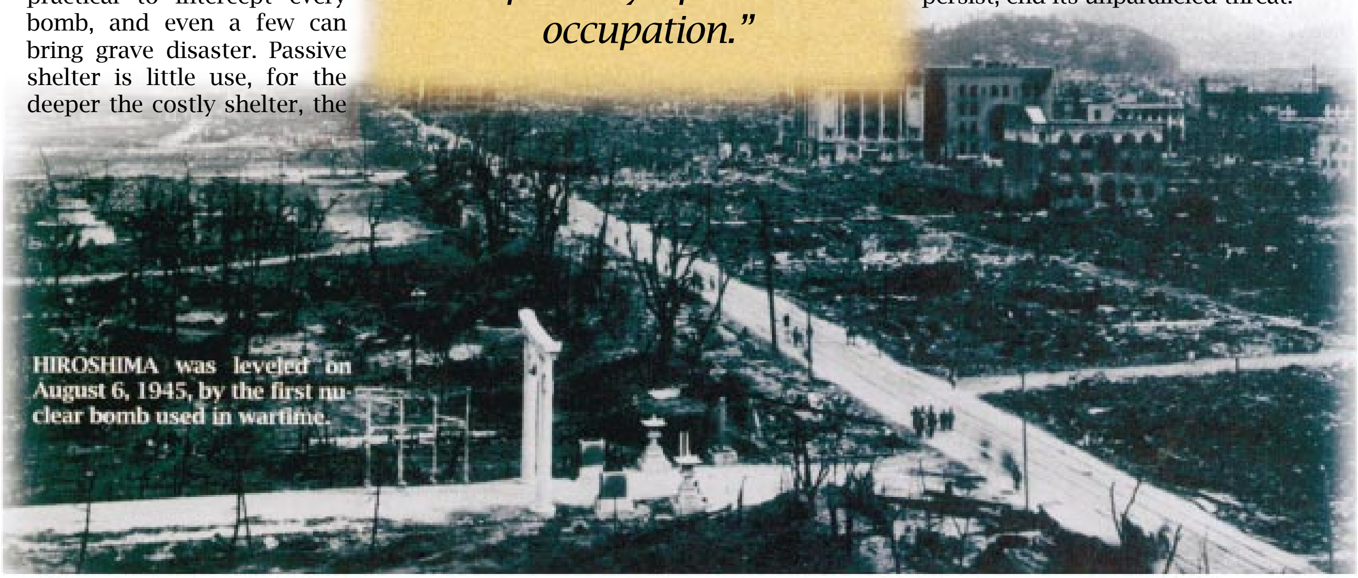
Legacy of the Bomb

I think these views are as right today as they were in 1945. Only one way remains: comprehensive international agreement for putting an end to nuclear war, worked out in rich detail. It is striking that the laboratory leaders of the Manhattan Project said much the same thing as early as August 17, 1945, three days after the peace was made with Japan. But they wrote in secret to the U.S. secretary of war, and their first views remained hidden for many years.

The 1990s have given us an unexpected historical opportunity, as unexpected as was fission itself. The U.S. and the former Soviet Union are right now dismantling some eight or 10 nuclear warheads every day, yet both have a long way to go. We have never had so promising and so concrete an omen of peace, but it is still mainly promise. We need resolute and widespread action. The task is not simple, but was any international goal more important than securing the future against nuclear war? How could we ever have planned war with tens of thousands of nuclear warheads? Did we not know that America would lie in ruin as well? With nuclear weapons, war achieves a final, futile symmetry of mutual destruction.

In 1963 Oppenheimer recalled that when Bohr first came to Los Alamos during the war, the visitor asked his friend and host very seriously: "Is it big enough?" Oppenheimer knew just what Bohr meant: Was this new scale of warfare big enough to challenge the institution of war itself? "I don't know if it was then," Oppenheimer wrote, "but finally it did become big enough." Then it became frighteningly too big, and it is still far too big, but at least no longer is it luxuriantly growing. We can, if we persist, end its unparalleled threat.

"With the sense that I was completing my long witness to the entire tragedy, I accepted the assignment to join the preliminary American party hurriedly sent from our Pacific base to enter Japan on the first day of U.S. occupation."



HIROSHIMA was leveled on August 6, 1945, by the first nuclear bomb used in wartime.

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The Author

PHILIP MORRISON was born in Somerville, N.J., in 1915 and spent the years from late 1942 until mid-1946 working on the Manhattan Project. He taught physics at Cornell University from 1946 to 1965. He then moved to the Massachusetts Institute of Technology, where he is now professor emeritus. Since 1945 Morrison has talked and written, at last rather hopefully, about avoiding a second nuclear war. He has enjoyed reviewing books for this magazine in nearly every issue of the past 350 months.

Further Reading

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A HISTORY OF STRATEGIC BOMBING. Lee B. Kennett. Charles Scribners' Sons, 1982.

THE MAKING OF THE ATOMIC BOMB. Richard Rhodes. Simon & Schuster, 1986.

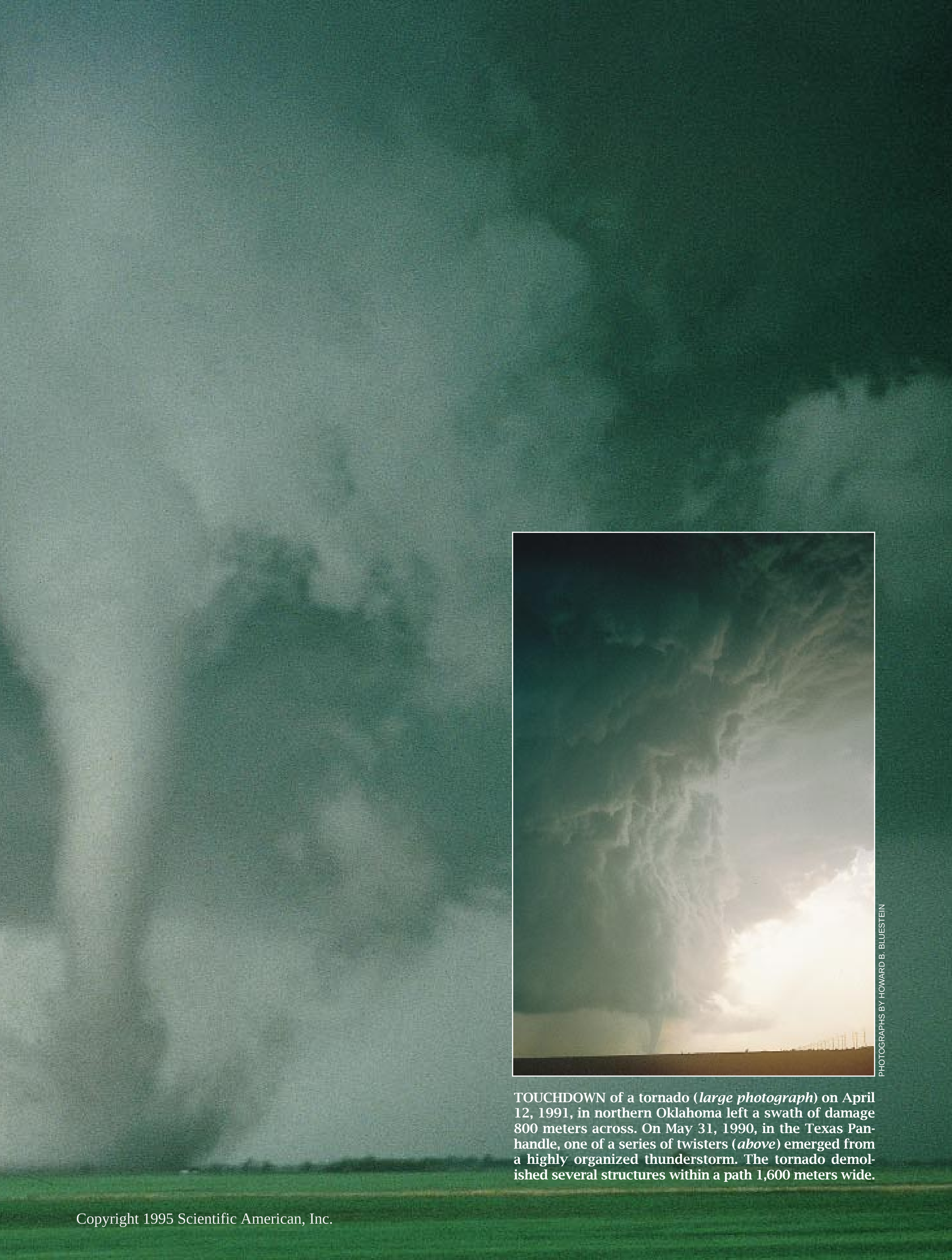
Tornadoes

The storms that spawn twisters are now largely understood, but mysteries still remain about how these violent vortices form

by Robert Davies-Jones

This spring was a frenzied tornado season in the U.S. In May alone, an estimated 484 tornadoes killed some 16 people and ravaged millions of dollars of property. Day after day, forecasts of severe storms sent me and my colleagues rushing from the National Severe Storms Laboratory (NSSL) in Norman, Okla., to Texas or Kansas, returning sometimes at three in the morning. After the day's briefing at 9 A.M., we might set off again, fatigued but hoping once more to collect precious data on the birth of tornadoes.

On Tuesday, May 16, the weather maps revealed the threat of afternoon tornadoes in Kansas. By 5 P.M. a menacing thunderstorm had erupted, fed by warm, moist southerly winds that rose and rotated in an updraft. The storm was a highly organized "supercell," an ideal tornado breeding ground. As William Gargan, a graduate student at the University of Oklahoma, and I approached from the southeast in our instrumented car, called Probe 1, we glimpsed the 10-mile-high top of the monstrous storm, 60 miles away. The thunderstorm was sweeping east-northeast at 30 miles per hour, a quite typical motion in the Great Plains.



PHOTOGRAPHS BY HOWARD B. BLUESTEIN

TOUCHDOWN of a tornado (*large photograph*) on April 12, 1991, in northern Oklahoma left a swath of damage 800 meters across. On May 31, 1990, in the Texas Panhandle, one of a series of twisters (*above*) emerged from a highly organized thunderstorm. The tornado demolished several structures within a path 1,600 meters wide.

As we closed to within 10 miles along Route 50, we saw for the first time the long, dark cloud base. Within a few miles we spotted a twister, shaped like an elephant's trunk, hanging from the rear of the main cloud tower, near Garden City. In trying to maneuver closer on minor paved roads, we lost sight of the twister but spied it again four miles to our northwest. It was thin and trailed horizontally behind its parent cloud before bending abruptly toward the ground at a right angle. Clearly, it was being pushed away from the cloud by the cold air flowing down from the storm, and nearing the end of its life.

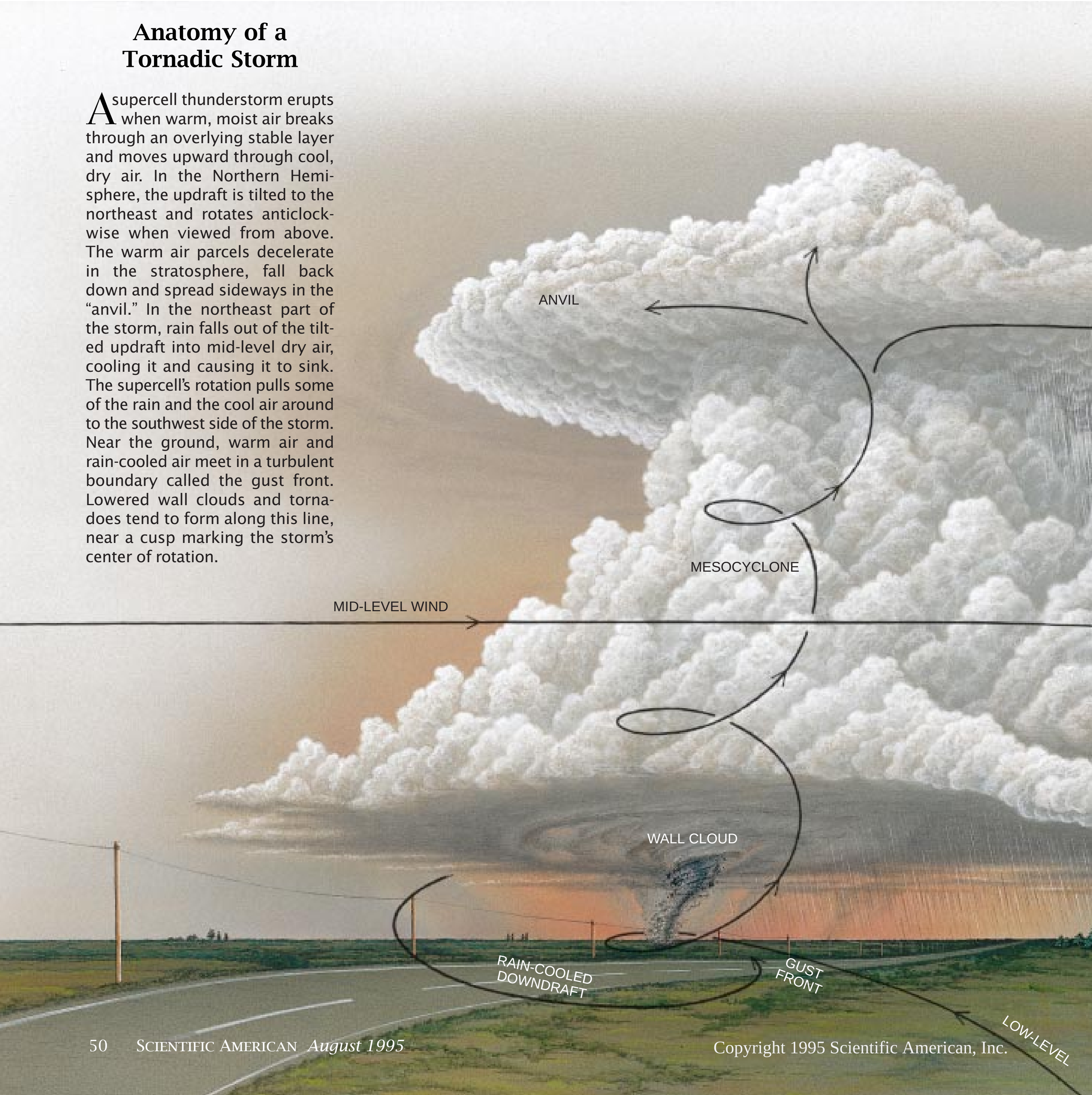
Supercells

Most tornadoes have damage paths 150 feet wide, move at about 30 miles per hour and last only a few minutes. Extremely destructive ones may be over a mile wide, travel at 60 miles per hour and may be on the ground for more than an hour. Tornadoes in the Northern Hemisphere, such as the devastating ones that occur in the U.S., northeastern India and Bangladesh, nearly always rotate counterclockwise when viewed from above. Southern Hemisphere tornadoes, such as those that form in Australia, tend to rotate clockwise. These directions are called cyclonic.

In 1949 Edward M. Brooks of St. Louis University discovered, by examining how air pressure changes at weather stations near tornadoes, that the twisters

Anatomy of a Tornadic Storm

A supercell thunderstorm erupts when warm, moist air breaks through an overlying stable layer and moves upward through cool, dry air. In the Northern Hemisphere, the updraft is tilted to the northeast and rotates anticlockwise when viewed from above. The warm air parcels decelerate in the stratosphere, fall back down and spread sideways in the "anvil." In the northeast part of the storm, rain falls out of the tilted updraft into mid-level dry air, cooling it and causing it to sink. The supercell's rotation pulls some of the rain and the cool air around to the southwest side of the storm. Near the ground, warm air and rain-cooled air meet in a turbulent boundary called the gust front. Lowered wall clouds and tornadoes tend to form along this line, near a cusp marking the storm's center of rotation.



usually form within larger masses of rotating air known as mesocyclones. In 1953 a mesocyclone appeared on a radar screen at Urbana, Ill., as a hook-shaped appendage on the southwest side of a storm's radar echo. Because rain reflects the microwaves emitted by radar, the hook shape indicated that the rain was being drawn into a cyclonically rotating curtain. And in 1957 T. Theodore Fujita of the University of Chicago examined photographs and movies taken by local residents of the base and sides of a North Dakota tornadic storm and found that the entire cloud tower was rotating cyclonically.

In the 1960s Keith A. Browning, a British meteorologist visiting the NSSL's precursor, the National Severe Storms Project, pieced together from radar data a remarkably accurate picture of tornadic storms. He realized that most tornadoes are spawned inside particularly large and vicious storms that he dubbed supercells. These powerful systems develop in very unstable environments in which the winds vary markedly with height and cool, dry air lies atop warm, moist air about a mile deep over the earth's surface. A thin stable layer separates the two air masses, bottling up the instability.

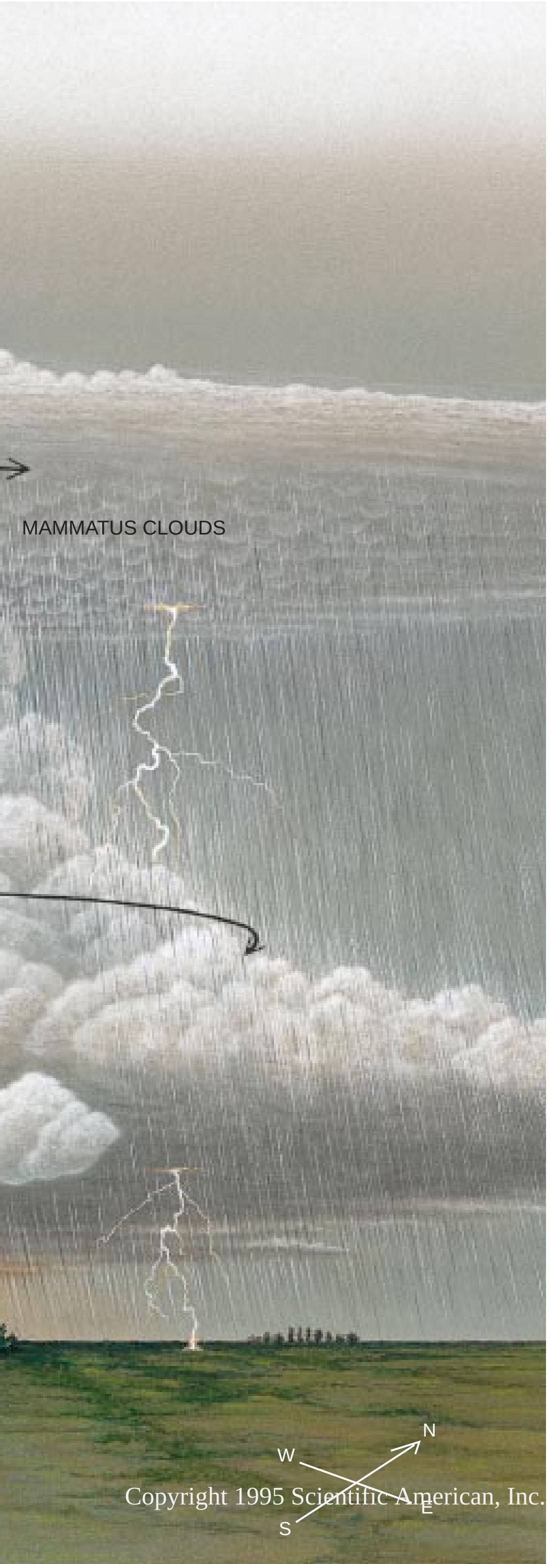
This lid can be pried open if the low-level air is warmed by the sun or if a weather system invades. Fronts, jet streams and upper-level disturbances, common visitors to the Great Plains during tornado season, all may force low-level air upward. Because air pressure falls with height, the rising parcels of air expand and cool. At sufficient height they become cold enough that their water vapor starts to condense into misty droplets, forming a flat cloud base.

In condensing, the vapor releases latent heat, warming the air parcels. They reach a level at which they become warmer than their environment and rise freely to great heights at speeds up to 150 miles per hour, forming a towering thunderhead. Shearing winds tilt the updraft to the northeast.

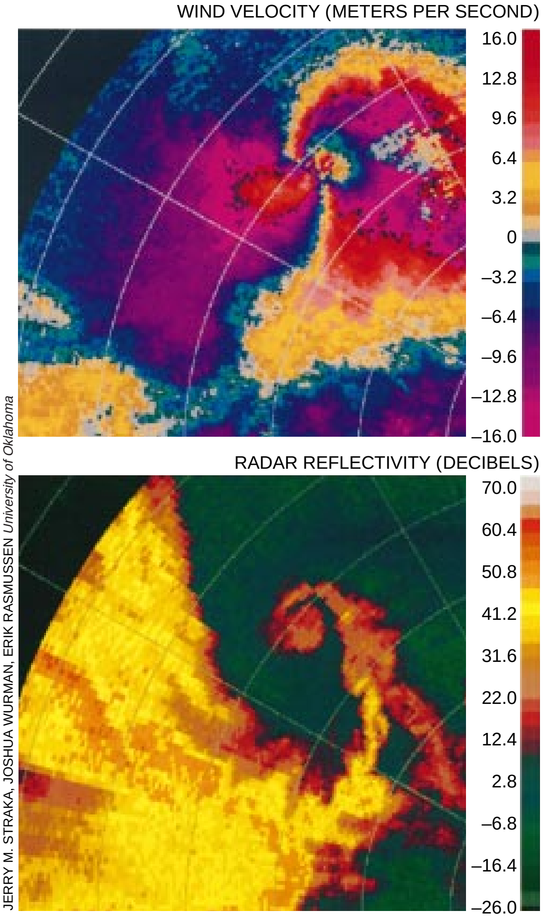
As they ascend, cloud droplets coalesce into raindrops. The buoyancy of the air parcels is partly offset by the weight of their own water and ice. The parcels lose momentum in the stratosphere, sink down to about eight miles and flow out sideways, forming the storm's "anvil." Rain falling out of the tilted updraft evaporates in dry, midlevel air on the northeast side of the supercell, causing this air to cool and sink to the earth. With time the rain and cool downdraft are pulled around the updraft by the storm's rotation. The cool air has higher relative humidity than the warm air and if forced upward becomes cloudy at lesser heights. Thus, when some of this air is sucked into the updraft, a lowered wall cloud forms.

In contrast with most thunderstorms, which contain several updrafts and downdrafts that interfere with one another, supercells contain one or two cells, each with its own coexisting downdraft and broad rotating updraft. The high level of organization allows a supercell to live a long time in an almost steady and intense state that is conducive to tornado formation. A region of updraft one to three miles in radius may begin to rotate with wind speeds of 50 miles per hour or more, forming a mesocyclone. The storm may then develop low-level rotation and even a tornado—usually to the southwest side of the updraft and close to an adjacent downdraft, while the mesocyclone is mature or decaying.

Ultimately, the mesocyclone dies in a

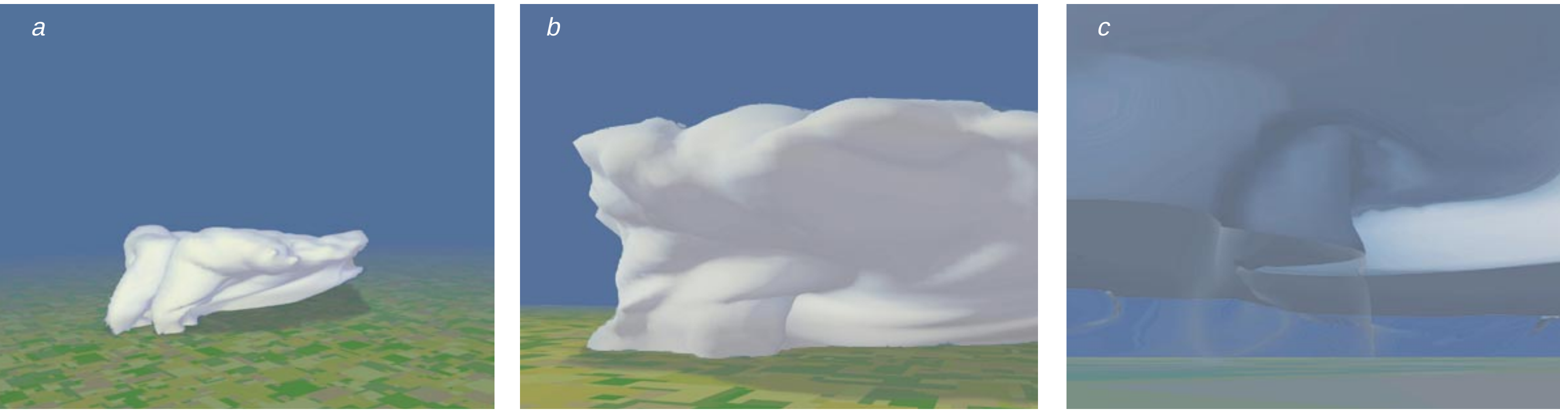


TOMO NARASHIMA



JERRY M. STRAKA, JOSHUA WURMAN, ERIK RASMUSSEN *University of Oklahoma*

SIGNATURE of a tornado may be detected by Doppler radar up to 20 minutes before touchdown. Winds in the clouds changing abruptly across a short distance may signal a potential or actual vortex, as for a tornado (*top*) in Hanston, Kan., observed by the author on May 16. A mesocyclone, in which tornadoes are usually embedded, appears on conventional radar as a hook-shaped appendage to the southwest side of the thunderstorm. The curl in the radar hook (*bottom*) for the storm in Hanston reveals the tornado as well.



COMPUTER SIMULATION of a supercell re-creates a weak, wide tornado by solving hydrodynamical equations for water and air on a grid of points representing space. As the storm begins (*a; 43 minutes after start of simulation*) and evolves (*b; 101 minutes*), the (invisible) grid is augmented by successively finer meshes of points, as close as 0.1 kilometer apart, in regions of intense rotation. The swirling center of the storm is evident in a view from below (*c; 103 minutes*). Rain falling from the dark clouds is not

shroud of rain as its updraft is cut off near the earth's surface by very cold air flowing out of the heart of the downdraft. In persistent supercells, a new mesocyclone may have already formed a few miles southeast of the dying one, along the gust front—the boundary between the warm and cool air. A new tornado may develop rapidly.

Tornado Chasing

To pin down when and where a twister is most likely to appear, the NSSL conducted a Tornado Intercept Project from 1972 to 1986. The intercept teams initially acquired film footage for measuring extreme wind speeds and provided "ground truth" for radar observations. But other benefits ensued. The chasers observed that tornadoes often develop in parts of a storm that are free of rain and lightning, eliminating theories that relied on these stimuli to trigger tornadoes. And in 1975 a rare anticyclonic tornado was recorded. Its rotation, being opposite to that of the earth, was not simply an amplification of the planet's spin.

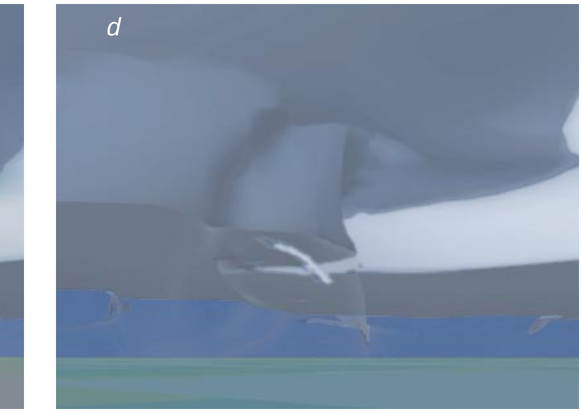
During the past two springs, the NSSL has been hosting another project, the Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX). Measurements are being made in and near supercells by an armada of vehicles. One of these vans is piloted by the field coordinator, Erik N. Rasmussen of the NSSL, who works with meteorologists at headquarters in Norman to choose a target storm and coordinate the entire data collection. Five vans are equipped to obtain upper-air balloon soundings in and near storms, and 12 others have weather stations mounted on their roofs. These instruments are supported 10 feet above the ground, well above the vehicles' slipstream, with the data being stored and displayed on laptop computers inside.

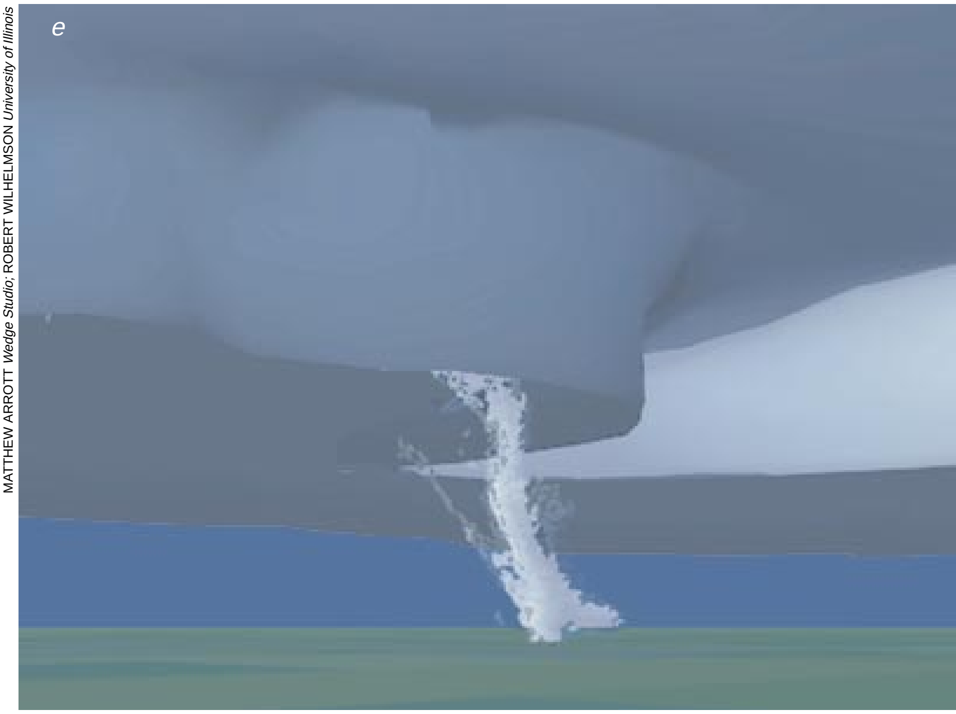
One of these 12 cars aims to obtain film footage of tornadoes for analysis;

Destructive Power

The damage that tornadoes inflict on buildings, such as this residence in Texas, and the distances that they carry heavy objects reveal the extreme wind speeds attained near the ground. In the 1970s the Institute for Disaster Research in Lubbock, Tex., concluded that the worst damage required winds of up to 275 miles per hour. The engineers also noted that windward walls of buildings, generally to the southwest, almost always fall inward—implying that structures are most often damaged by the brute force of a wind, not by the sudden drop in atmospheric pressure. As a result, residents of "Tornado Alley," in the midwestern U.S., were no longer advised to open windows to reduce the pressure inside. The suggestion had caused many people to be cut by flying glass as they rushed to open the windows. Nor were residents told anymore to hide in the southwest corner of the house—where they were in the most danger of having walls fall in on them. Now residents are urged to shelter in a central closet because of the added protection of interior walls.

DAVID SAMS *Sipa Press*





MATTHEW ARROTT *Wedge Studio;* ROBERT WILHELMSON *University of Illinois*

shown for clarity; in addition, a dense wall cloud reaching to the ground has been made transparent. A white vortex begins high in the clouds (*d; 104 minutes*) and rapidly touches down (*e; 107 minutes*).

two others deploy nine Turtles. Named thus because they resemble sea turtles in shape, Turtles are 40-pound instrument packages that are designed to withstand a tornado. They have well-shielded sensors to measure temperature and pressure and are placed on the ground ahead of tornadoes, at 100-yard intervals.

The remaining nine vans are called Probes; their sole mission is to collect weather data in specified regions of the storm. Probe 1's mission is to measure temperature gradients close to and north of the tornado or mesocyclone, a region where large hail frequently falls. Twice this season softball-size hail has smashed Probe 1's windshield.

That Tuesday in Kansas, as the twister died, we raced eastward to stay abreast of the storm and find a new mesocyclone. As we zigzagged in rain along the gravel roads, we encountered two rows of up to eight power poles that were lying in the fields, snapped off two feet above the ground. There must have been a strong tornado hidden in the rain to our northeast. (The next day I read in the newspaper that 150 poles had been downed.)

About 30 miles further east, we spotted a wall cloud, a rotating, pedestal-like lowering, a few miles across, of the main cloud base. A narrow tornado appeared, not out of the dark wall cloud as is usual but from an adjacent higher cloud base. This vortex touched down briefly, raising debris, but lived out its few minutes of existence mainly as a funnel cloud aloft, without visible signs of contact with the ground.

A new wall cloud, which became ominously large and low, developed to the northeast. That, however, failed to produce a tornado. Near Jetmore, a fresh storm developed to the south of the one we were following. We went north to confirm that this older storm was indeed losing its tornado potential, then retraced our path and dropped south to the new one.

Signature of a Vortex

In addition to the aforementioned armada, VORTEX also uses two airplanes flying around a storm, as well as three more vehicles. All of these deploy Doppler radar, instruments that yield vital information about the airflow in tornadic storms. The newest, mobile Doppler radar, built this year by Joshua Wurman and Jerry M. Straka of the University of Oklahoma, has already yielded unprecedented details of tornadoes.

Doppler weather radars measure wind speeds from afar by emitting pulses of microwave radiation and catching their reflections off a group of raindrops or ice particles. If the drops are moving toward the radar, the reflected pulse has a shorter wavelength that betrays this component of the drops' velocity. (State troopers use similar instruments to catch speeding cars.)

The first Doppler measurements in 1971 confirmed that the winds within a "hook" are indeed rotating, at speeds of about 50 miles per hour. This circulation, first apparent at a height of about three miles, is followed by rotation at much lower levels, preceding the development of any intense tornado. In 1973 a small anomaly on the Doppler velocity map of a tornadic storm at Union City, Okla., turned out to coincide in time and space with a violent tornado.

The radar could not "see" or resolve the tornado directly but showed high winds changing direction abruptly across the twister and its precursor in the clouds. This vortex signature typically forms at around 9,000 feet 10 to 20 minutes before touchdown. It may extend upward as well as downward, occasionally reaching seven miles high for large tornadoes.

Although the vortex signature can be used to warn the public to seek shelter in a basement or an interior closet, it can be observed only at quite close range, generally 60 miles or less. At longer ranges of up to 150 miles, tornado warnings can be issued on the basis of Doppler radar detection of the parent mesocyclone. Federal agencies are currently installing a network of sophisticated Doppler radars across the country to improve warning capabilities.

In 1991, using a portable Doppler radar near a tumultuous tornado at Red Rock, Okla., Howard B. Bluestein of Oklahoma University measured wind speeds of up to 280 miles per hour. Although high, these speeds are a far cry from the 500 miles per hour postulated 40 years ago to explain freak happenings such as pieces of straw stuck in trees. (A more likely explanation for this phenomenon is that the wind forces apart the wood grains, which then snap shut, trapping the straw.)

Individual Doppler radar suffices for local warnings, but a second Doppler device that is about 25 to 35 miles away and views a storm from a significantly different angle supplies a far more complete picture for research. Such a dual-Doppler system, used by the NSSL and others since 1974, measures the velocity of the rain in two different directions. Knowing that the mass of air is conserved, and estimating the speed with which rain is falling relative to the moving air, meteorologists can reconstruct the three-dimensional wind field and compute quantities such as vorticity (or local spin in the air). Such data have led them to discover that a tornado is located to one side of its parent updraft, near a downdraft, and to verify that air flowing into a mesocyclone spins about its direction of motion.

Spinning Up

A major breakthrough in understanding the complex rotations in tornadic storms came in 1978, when computer simulations made by Robert Wilhelmson of the University of Illinois and Joseph B. Klemp of the National Center for Atmospheric Research (NCAR) reproduced realistic supercells complete with such features as hook-shaped precipitation patterns. Proceeding in small time steps, the scientists numerically solved the equations governing temperature, wind velocity and conservation of mass for air and water in various forms—vapor, cloud droplets and raindrops—on a three-dimensional array of points emulating space.

In the simulated world at least, scientists were in control. Even without any lateral variations in the initial environment, they were able to create supercells, thereby debunking the popular explanation that tornadoes are caused by colliding air masses. And by "turning off" the earth's rotation, they established that it had little effect during the first few hours of a storm's life. Rather wind direction that at low levels veered with height was crucial to the development of rotation.

In a typical supercell environment the wind near the ground is from the southeast, the wind half a mile above the ground is from the south, and the wind one mile high is from the southwest. Wind that changes speed or direction with height also contains spin. Envision how the wind would make an initially vertical stick rotate: if a south wind blows slowly near the ground and faster higher up, the stick will spin about an east-west axis.

But what if the wind, instead of changing speed, changes direction from southeast to southwest? Imagine the stick moving north, along with the mid-level wind, half a mile up. Then its top is pushed eastward and its bottom westward, so that it will turn about a north-south axis. Therefore, this air has "streamwise" vorticity—it spins about its direction of motion, much like a spiraling American football.

Air parcels with streamwise vorticity have their spin axes tilted upward as they enter an updraft. Thus, the updraft as a whole rotates cyclonically. First proposed by Browning in 1963 and proved analytically in the 1980s by Douglas K. Lilly of the University of Oklahoma and me, this theory explains how the updraft rotates at mid-levels. But it does not explain how rotation develops very close to the ground. As simulations by Klemp and Richard Rotunno of NCAR showed in 1985, low-level rotation depends on the supercell's evaporatively cooled downdraft: it does not occur when the evaporation of rain is "switched off."

The simulations revealed, surprisingly, that the low-level rotation originates north of the mesocyclone, in moderately rain-cooled, subsiding air. As the mid-level rotation draws the downdraft cyclonically around the updraft, some of the downdraft's cool air travels southward with warm air on its left and much colder air on its right. Warm air, being buoyant, pulls the left sides of the air parcels upward; the cold air pulls their right sides downward. Then the cool air starts to rotate about its horizontal direction of motion. But as it descends, its spin axis is tilted downward, giving rise to anticyclonic spin.

Harold E. Brooks, also at the NSSL, and I showed in 1993 that, by a rather complex mechanism, the spin in the subsiding cool air reverses direction before the air completes its descent. Eventually, this cyclonically rotating air is present at very low levels. This moderately cool air flows along the surface and is sucked up into the southwest side of the updraft. Because the flow to the updraft is convergent, the air rotates faster, like an ice skater who spins more rapidly by drawing in her arms.

Despite understanding well how large-scale rotation develops at middle and low levels of a mesocyclone, we have yet to pin down why tornadoes are formed. The simplest explanation is that they are the result of surface friction. This observation seems paradoxical because friction generally reduces wind speeds. But the net effect of friction is

Tabletop Tornado

Laboratory experiments have helped explain why tornadoes can take different forms. In the apparatus built in the 1960s by Neil B. Ward of the National Severe Storms Laboratory in Norman, Okla., and refined by John T. Snow and others at Purdue University, air is spun up by a rotating screen as it enters a lower compartment. It then flows up into the main chamber through a wide central hole, being pulled by exhaust fans at the top. The device has replicated many features of real tornadoes, such as the pattern of air pressures near the lower surface.

Reinterpreting Ward's results, I found in 1973 that the crucial parameter for tornado formation is the swirl ratio *S*, first used by W. Stephen Lewellen of West Virginia University. *S* is the ratio of the tangential velocity at the edge of the updraft hole (controlled by the screen's rotation) to the average upward velocity through the hole (determined by the fan). For *S* less than 0.1, there is no vortex. As *S* is increased, a vortex appears, having an intense upward jet at low levels (*right*). At *S* higher than 0.45, the vortex becomes fully turbulent with a central downdraft surrounded by a strong updraft. And at a critical swirl ratio of roughly 1.0, a pair of vortices form on opposite sides of the parent vortex. For still higher swirl ratios, up to six subsidiary vortices have been observed.

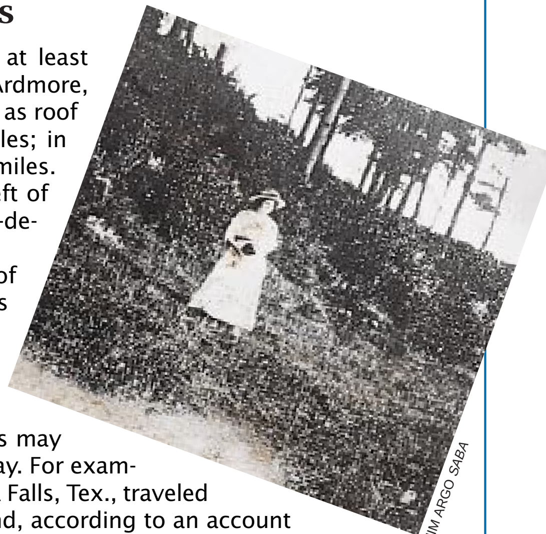
CHRISTOPHER R. CHURCH *Photographed at Purdue University, Tornado Vortex Chamber* much like that in a stirred cup of tea.

Drag does reduce speeds and therefore centrifugal forces in a thin layer near the bottom. It causes the fluid to move inward along the cup's base, as made apparent by tea leaves bunching up at the center. But fluid near the top of this inflow spins faster as it falls in toward the axis because of the ice-skater effect. The result is a vortex along the axis of the cup. W. Stephen Lewellen of West Virginia University concludes that the highest wind speeds in a tornado are located in the lowest 300 feet.

Friction also explains the persistence of twisters. A tornado has a partial vacuum in its core; centrifugal forces prevent the air from spiraling inward through the sides of the tornado. In 1969 Bruce R. Morton of Monash University in Australia explained how the vacuum survives. Strong buoyancy forces prevent air from entering the core through the top. Close to the ground, friction reduces tangential velocity and hence centrifugal forces, allowing a strong but shallow inflow into the core. But friction also acts to limit the inflow winds, not allowing enough air in to fill up the core. Tornadoes intensify and become more stable after they make strong contact with the ground because their inflows become restricted to a thin boundary layer.

The friction theory does not explain, however, why a tornadic vortex signature up in the clouds sometimes foreshadows the touchdown of a tornado by 10 to 20 minutes.

Far-Flung Debris


JIM ARGO SABA

This photograph was carried at least 100 miles by a tornado in Ardmore, Okla., in 1995. Heavy items such as roof fragments can travel tens of miles; in 1985 an airplane wing flew 10 miles. Most of the debris falls to the left of the tornado's path, often in well-defined bands according to weight.

Researchers at the University of Oklahoma are collecting accounts of fallout from tornadoes as a way of gauging airflow within the storms. Twisters appear to lift some objects several miles high, into the main storm. Light debris may return to the earth 200 miles away. For example, canceled checks from Wichita Falls, Tex., traveled to Tulsa, Okla., in April 1979. And, according to an account from 1953 collected by the researchers: "Emily McNutt of South Weymouth, Mass., found a wedding gown in her backyard. It was dirty, as would have been expected, but was intact and in surprisingly good condition. A label sewn into the gown read 'McDonald, Worcester,' indicating that the gown had been blown some fifty miles to its final landing place." (Excerpt from *Tornado!* by John M. O'Toole.)

Reports of tornado fallout can be sent by electronic mail to the Tornado Debris Project at debris@metgem.uoknor.edu

Touchdown

Many of the classic features of tornadoes were unexpectedly demonstrated to us on that May day in Kansas. By the time we had moved to the southern storm in the small town of Hanston, it was getting dark, and operations were ending. But then the field coordinator advised the teams of a rapidly rotating wall cloud in our vicinity. As the warning sirens started wailing, we watched a skinny, serpentine tornado touch down three miles to our southeast.

We took off to the north to place ourselves ahead of the tornado, unaware in the excitement of a deep drainage ditch in the street. It damaged our wheel and tilted our weather station, but we kept going. We turned on to a dirt road to take us east on the north side of the tornado, which had now become a wide column of dust with a bowl-shaped lowering of the cloud base above it. As we got ahead of the tornado, it transformed itself into several smaller vortices, all circling furiously around the tornado's central axis. (In 1967 Fujita observed that some tornadoes left behind beheaded cornstalks in several overlapping swaths. Neil B. Ward of the NSSL later attributed these curious patterns to such subsidiary twisters. Like a point on the rim of a bicycle wheel that circles the center as the wheel moves forward, these frenetic subvortices trace out cycloidal paths.)

Low on gas, we raced ahead of the twister, apprehensive because we did not know if and where the road ended. The tornado was perhaps a mile away and not moving perceptibly across our field of view, indicating that it was heading directly for us at 30 miles per hour. The field coordinator came to our rescue by informing us of a road north, toward Burdett, which we gratefully took. We stopped after a mile to watch the tornado, which had been on the ground for at least 14 miles and now had a classic stovepipe appearance, pass by to our south and recede into the darkness to our east.

We limped home, our car damaged, our data uncertain and our pulses racing, buoyed by the news that great radar data had been obtained from the air and from the new portable ground radar. Looking back, we should have just kept pace with the tornado instead of passing it and turning ourselves, the hunters, into the hunted.

The Author

ROBERT DAVIES-JONES studies the dynamics and genesis of tornadoes at the National Severe Storms Laboratory (NSSL) in Norman, Okla. He is also an adjunct professor of meteorology at the University of Oklahoma. After earning a B.Sc. in physics from the University of Birmingham in England, he studied the sun's convection at the University of Colorado, obtaining a Ph.D. in astrogeophysics in 1969. A year later he joined the NSSL, this time applying his knowledge of fluid dynamics to the weather. He serves as co-chief editor of the *Journal of the Atmospheric Sciences.*

Further Reading

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How HIV Defeats the Immune System

A plausible hypothesis suggests the immune devastation that underlies AIDS stems from continuous—and dangerous—evolution of the human immunodeficiency virus in the body

by Martin A. Nowak and Andrew J. McMichael

The interplay between the human immunodeficiency virus (HIV) and the immune system turns out to be significantly more dynamic than most scientists would have suspected. Recent research indicates that HIV replicates prodigiously and destroys many cells of the immune system each day. But this growth is met, usually for many years, by a vigorous defensive response that blocks the virus from multiplying out of control. Commonly, however, the balance of power eventually shifts so that HIV gains the upper hand and causes the severe immune impairment that defines full-blown AIDS.

We have put forward an evolutionary hypothesis that can explain the ultimate escape of the virus from immune control, the typically long delay between infection and the onset of AIDS, and the fact that the extent of this delay can vary considerably from patient to patient. Most infected individuals advance to AIDS over the course of 10 years or so, but some patients are diagnosed within two years of infection, and others avoid AIDS for 15 years or more.

We argue that the powerful immune response enabling many patients to remain healthy for years is finally undermined by continuous mutation of the virus. As will be seen, within any given individual, new viral variants may emerge that are able to evade the protective forces somewhat. In our view, the accumulation of many such variants can muddle the immune system to the point that it can no longer fight the virus effectively.

To understand how we came to this hypothesis, which is gaining clinical support, it helps to know a bit about how the immune system eradicates viruses in general and how it responds to HIV in particular. When any virus enters the body and colonizes cells, defensive forces launch a multipronged but highly targeted attack. Macrophages and related cells engulf some of the free particles and break them up. Then the cells fit certain protein fragments, or peptides, into grooves on proteins known as human leukocyte antigens (HLAs). The cells subsequently display the resulting complexes on their surface for perusal by the white blood cells called helper *T* lymphocytes.

The Body Fights Back

Each helper cell bears receptors able to recognize a single displayed peptide, or epitope. If it encounters the right epitope on a macrophage or similar cell, it binds to the peptide, divides and secretes small proteins. The proteins help to activate and promote replication of still other components of the immune system—notably cytotoxic, or killer, *T* lymphocytes and *B* lymphocytes.

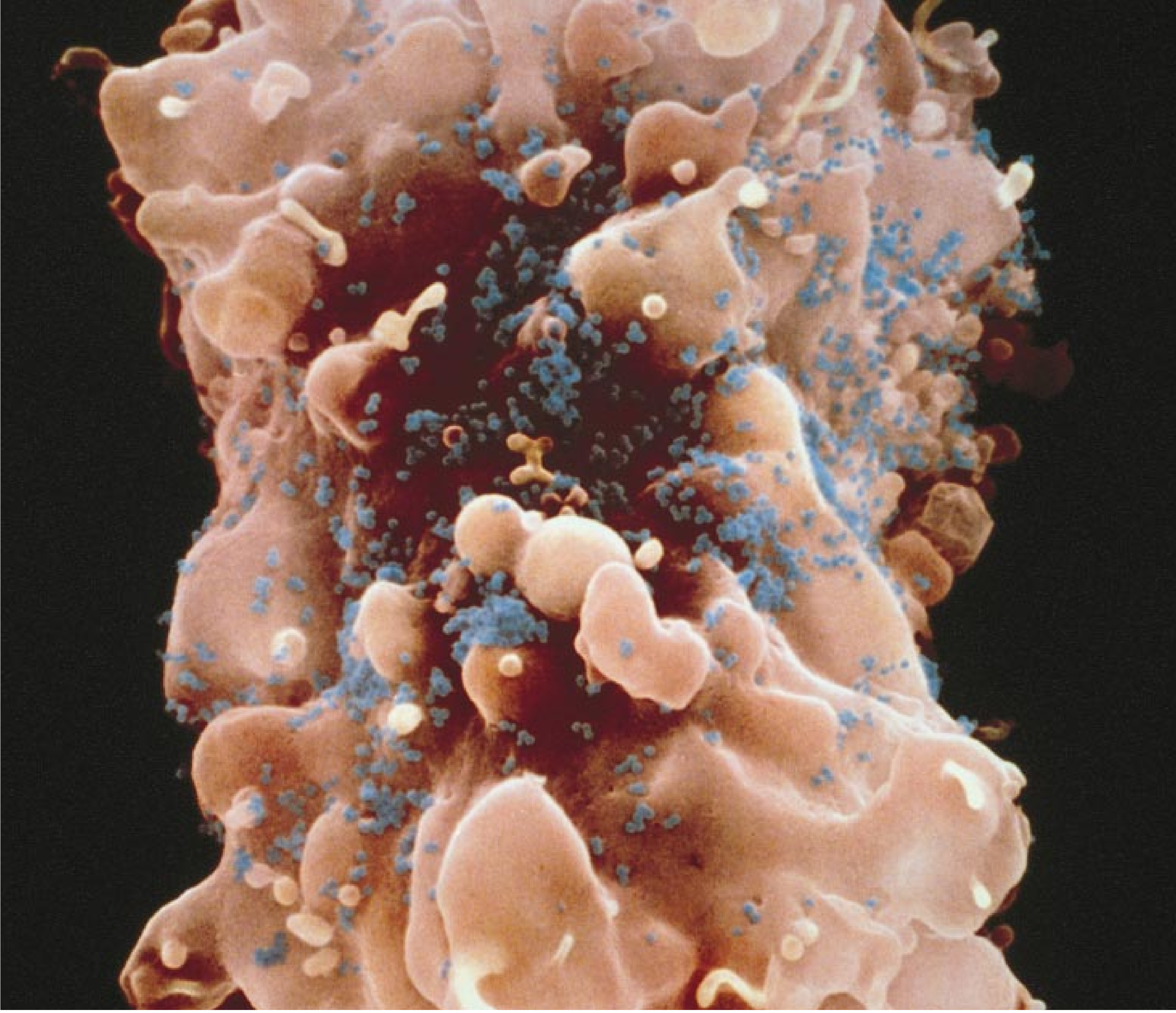
Under the right circumstances, the killer *T* cells directly attack infected cells. Like macrophages, infected cells break up some viral particles, combine certain of the fragments with HLA molecules and exhibit the complexes on the cell surface. If a cytotoxic *T* lymphocyte, through its receptors, recognizes one of the epitopes on a diseased cell, it will bind to the epitope and destroy the cell before more viral particles can be generated. Activated *B* lymphocytes secrete antibodies that recognize specific peptides on the viral surface. The antibodies mark free viral particles, those not yet sequestered in cells, for destruction.

All these responses are believed to participate in the defense against HIV. In the initial stage of HIV infection, the virus colonizes helper *T* cells and macrophages. It also replicates unchecked for a while. As the amount of virus soars, the number of helper cells falls; macrophages die as well, but the effects on them have been less studied. The infected *T* cells perish as thousands of new viral particles erupt from the cell membrane. Soon, though, cytotoxic *T* and *B* lymphocytes mount a strong defense and kill many virus-infected cells and viral particles. These effects limit viral growth and give the body an opportunity to restore temporarily its supply of helper cells to almost normal concentrations. Nevertheless, the virus persists. In the early phase, which may last for a few weeks, about 30 percent of infected patients display some symptoms, often a fever that may be accompanied by a rash and swollen lymph glands. Even those individuals, though, usually go on to enter a prolonged symptom-free stage.

Throughout this second phase the immune system continues to function well, and the net concentration of measurable virus remains relatively low. Nevertheless, the viral level rises gradually, in parallel with a decline in the helper population. Accumulating evidence indicates that helper cells are lost because the virus and cytotoxic *T* cells destroy them, not because the body's ability to produce new helper cells becomes impaired. It is a sad irony that the killer cells required to control HIV infection also damage the helper *T* cells they need to function efficiently.

Patients are generally said to cross the line to AIDS when the helper cell count, which in healthy individuals measures 1,000 cells per microliter of blood, falls below 200. During this stage, the viral level climbs sharply, and measures of immune activity drop toward zero. It is the loss of immune competence that enables normally benign microorganisms (particularly protozoa and fungi) to cause life-threatening diseases in AIDS patients. Once AIDS develops, people rarely survive for more than two years.

LENNART NILSSON *Boehringer Ingelheim International*



PARTICLES OF HIV (*blue spheres*), the virus that causes AIDS, bud from an infected white blood cell before moving on to infect other cells. The immune system controls such spread at first but is eventually outmaneuvered by the virus.

Persistence of a good immune response in the face of constant attack by HIV raises the issue of why the immune system is unable to eradicate HIV completely in most, if not all, cases. Several years ago various features of HIV led one of us (Nowak) and his colleagues in the zoology department of the University of Oxford to suspect the answers lay with an ability of the virus to evolve in the human body.

Evolutionary Theory Predicts Trouble

Evolutionary theory holds that chance mutation in the genetic material of an individual organism sometimes yields a trait that gives the organism a survival advantage. That is, the affected individual is better able than its peers to overcome obstacles to survival and is also better able to reproduce prolifically. As time goes by, offspring that share the same trait become most abundant in the population, outcompeting other members—at least until another individual acquires a more adaptive trait or until environmental conditions change in a way that favors different characteristics. The pressures exerted by the environment, then, determine which traits are selected for spread in a population.

When Nowak and his co-workers considered HIV's life cycle, it seemed evident that the microbe was particularly well suited to evolve away from any pressures it confronted (namely, those exerted by the host's immune system). For example, its genetic makeup changes constantly; a high mutation rate increases the probability that some genetic change will give rise to an advantageous trait. This great genetic variability stems from a property of the viral enzyme reverse transcriptase. In a cell, HIV uses reverse transcriptase to copy its RNA genome into double-strand DNA. This DNA is inserted into a chromosome of the host, where it directs the production of more viral RNA and viral proteins. These elements, in turn, assemble themselves into viral particles that can escape from the cell. The virus mutates readily during this process because reverse transcriptase is rather error prone. It has been estimated that each time the enzyme copies RNA into DNA, the new DNA on average differs from that of the previous generation in one site. This pattern makes HIV the most variable virus known.

HIV's high replication rate further increases the odds that a mutation useful to the virus will arise. To appreciate the extent of HIV multiplication, consider findings released early this year from teams headed by George M. Shaw of the University of Alabama at Birmingham and by David D. Ho of the Aaron Diamond AIDS Research Center in New York City. The groups reported that at least a billion new viral particles are produced in an infected patient each day. They found that in the absence of immune activity, the viral population would on average double every two days. Such numbers imply that viral particles present in the body 10 years after infection are several thousand generations removed from the original virus. In 10 years, then, the virus can undergo as much genetic change as humans might experience in the course of millions of years.

A Scenario of Disease Progression

With knowledge of HIV's great evolutionary potential in mind, Nowak and his colleagues conceived a scenario they thought could explain how the virus resists complete eradication and thus causes AIDS, usually after a long time span. Their proposal assumed that constant mutation in viral genes would lead to continuous production of viral variants able to evade to some extent the immune defenses operating at any given time. Those variants would emerge when genetic mutations led to changes in the structure of viral peptides—that is, epitopes—recognized by the immune system. Frequently such changes exert no effect on immune activities, but sometimes they can cause a peptide to become invisible to the body's defenses. The affected viral particles, bearing fewer recognizable epitopes, would then become more difficult for the immune system to detect.

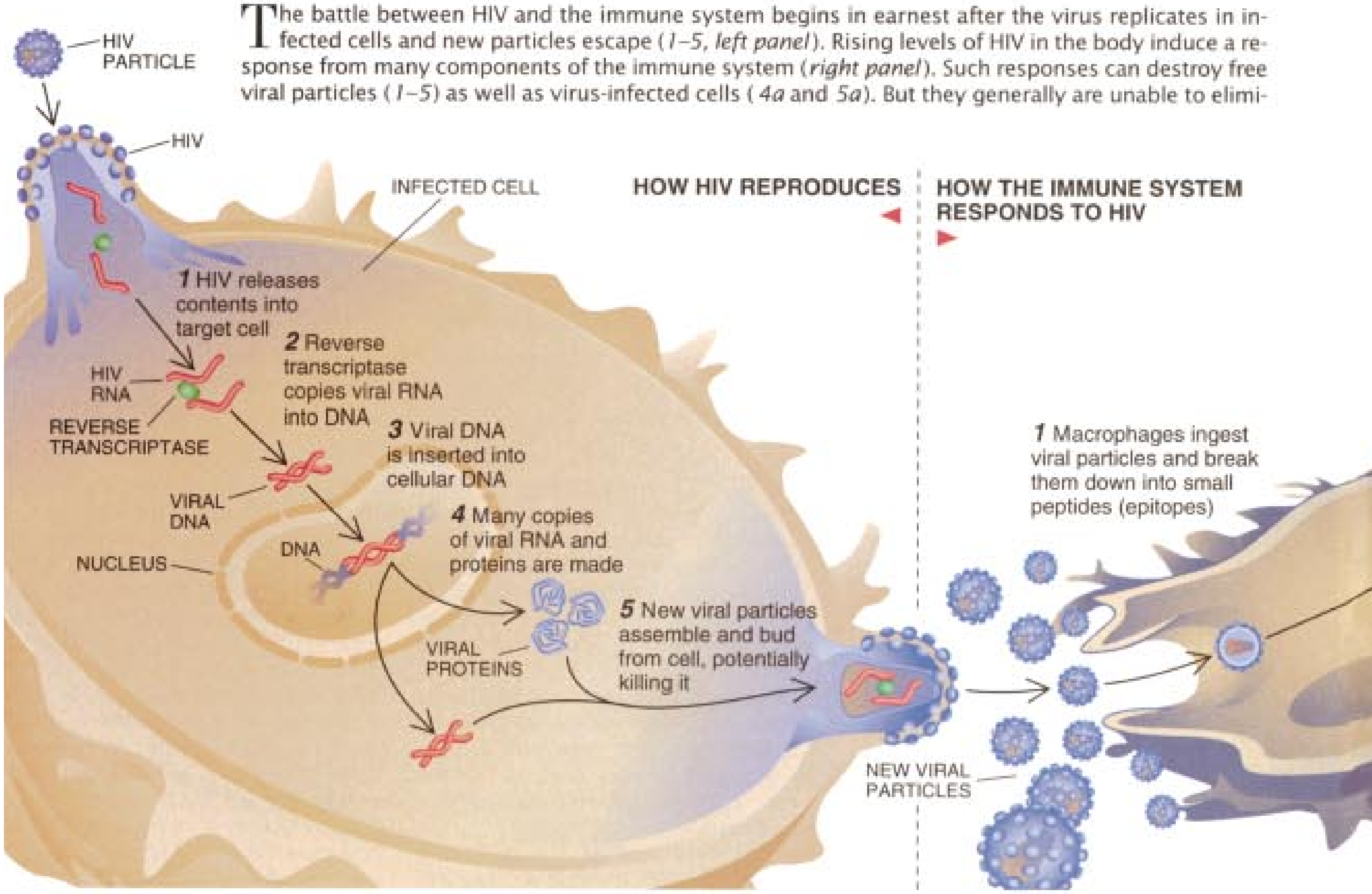
The hypothesis proposed that a mutation able to reduce recognition of an epitope would give a viral variant a survival advantage, at least until the immune system discovered and reacted to the altered peptide. This response would reduce the viral load for a time, but meanwhile other "escape mutants" would begin to break out, and the cycle would continue, preventing full elimination of the infection.

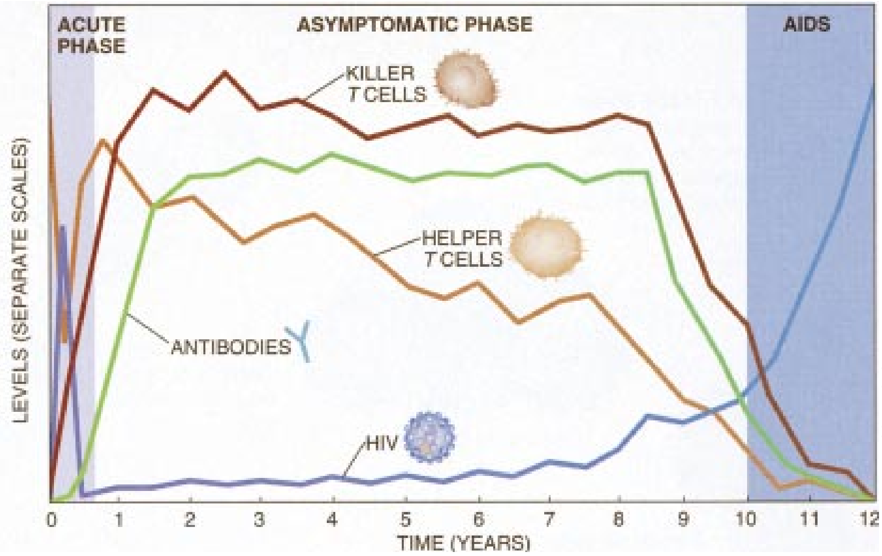
Such a scheme is extremely hard to verify with clinical tests alone, largely because the nonlinear interactions between the virus and the immune system are impossible to monitor in detail. Consequently, Nowak turned to a computer simulation in which an initially homogeneous viral population evolved in response to immunologic pressure. He reasoned that if the mathematical model produced the known patterns of HIV progression, he could conclude the evolutionary scenario had some merit.

The equations that formed the heart of the model reflected features that Nowak and his colleagues thought were

HIV versus the Immune System

The battle between HIV and the immune system begins in earnest after the virus replicates in infected cells and new particles escape (*1–5, left panel*). Rising levels of HIV in the body induce a response from many components of the immune system (*right panel*). Such responses can destroy free viral particles (*1–5*) as well as virus-infected cells (*4a* and *5a*). But they generally are unable to elimi-

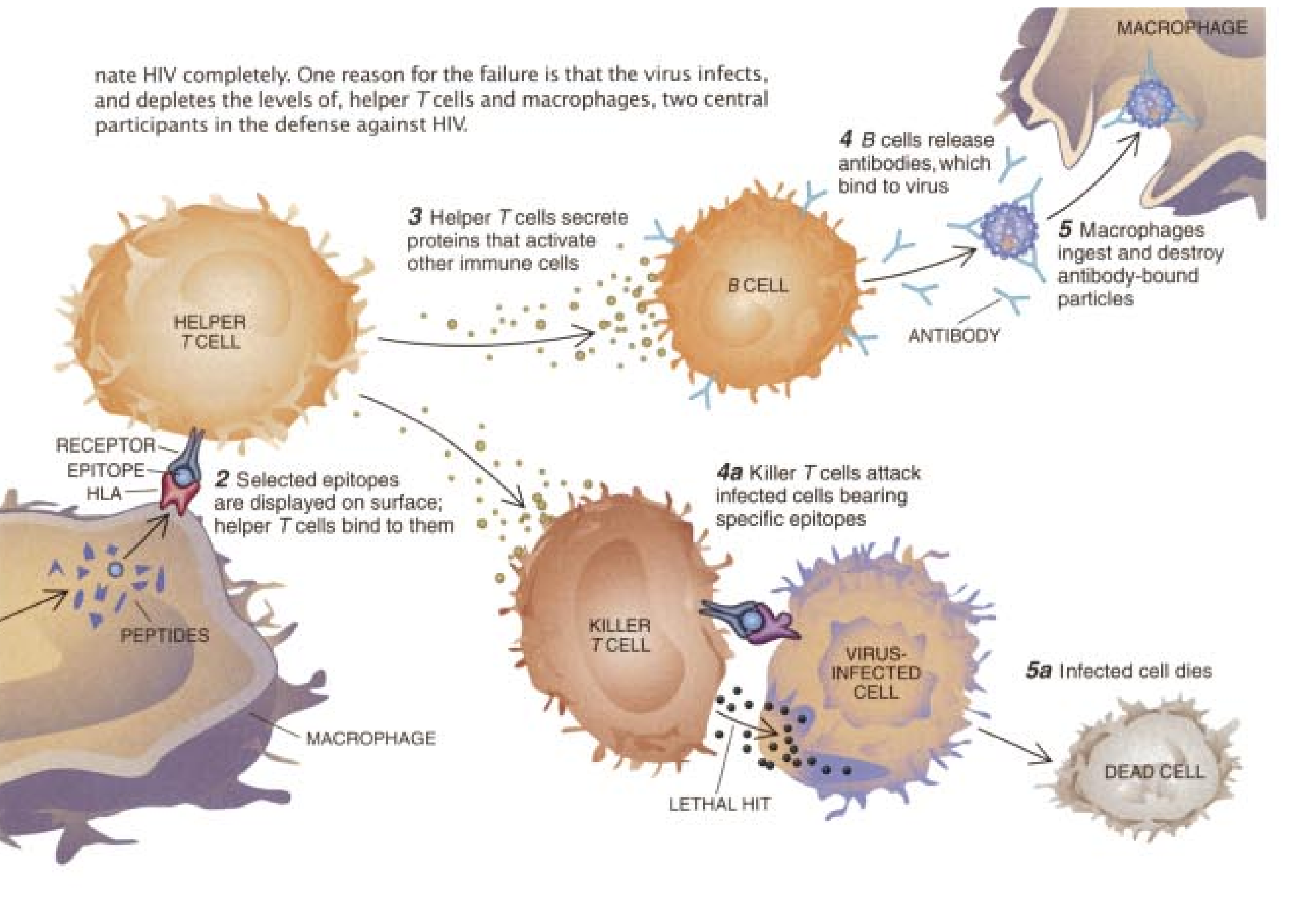




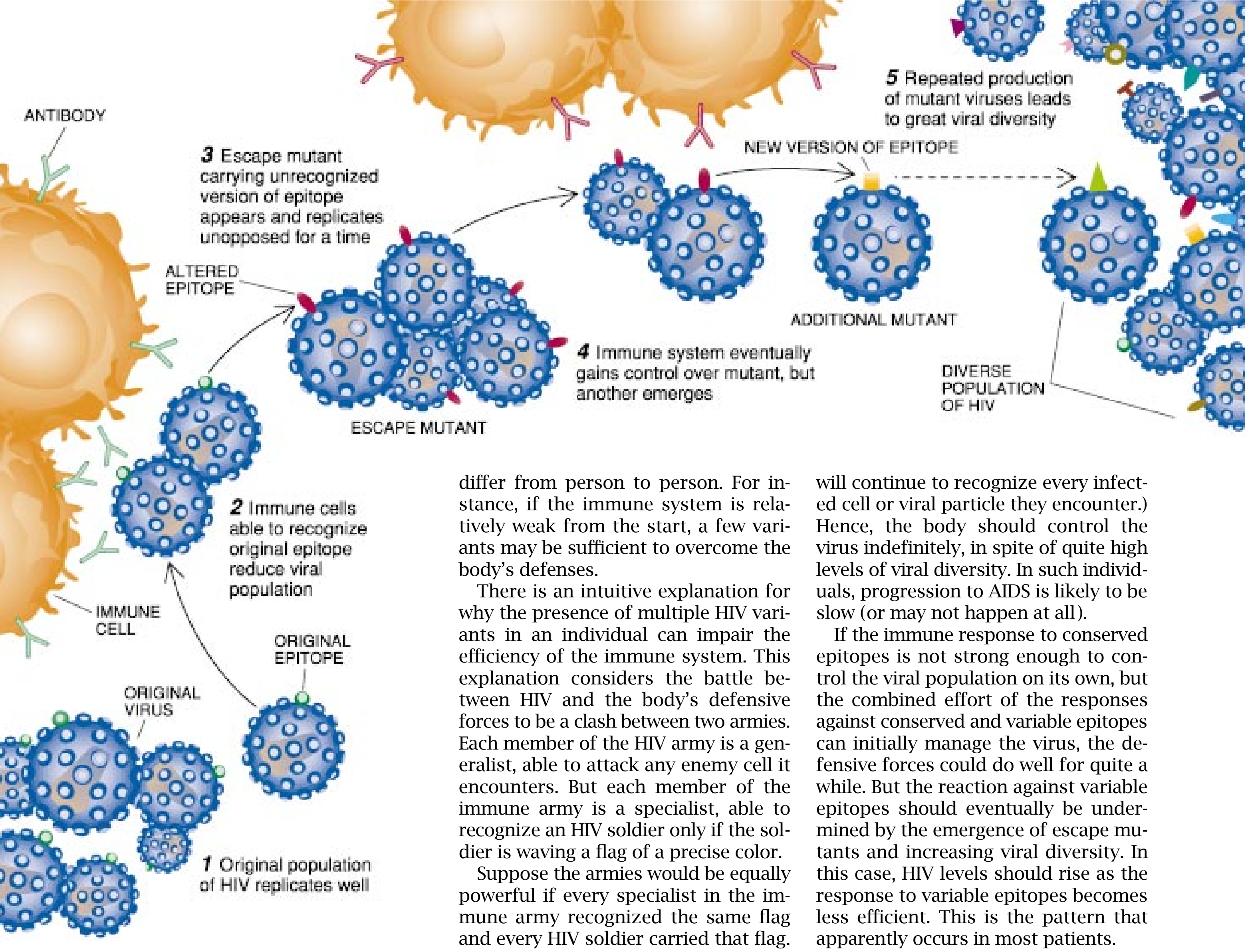
COURSE OF HIV INFECTION typically runs many years, during most of which the patient has no symptoms. Strikingly, the body's defenses—as indicated by levels of antibodies, killer *T* cells and helper *T* cells in the blood—remain strong throughout much of the asymptomatic period, eradicating almost as much virus as is produced. At some point, however, the immune defenses lose control of the virus, which replicates wildly and leads to collapse of the immune system.

important in the progression of HIV infection: the virus impairs immune function mainly by causing the death of helper *T* cells, and higher levels of virus result in more *T* cell death. Also, the virus continuously produces escape mutants that avoid to some degree the current immunologic attack, and these mutants spread in the viral population. After a while, the immune system finds the mutants efficiently, causing their populations to shrink. The model additionally distinguished between two kinds of immune responses: those recognizing epitopes that undergo mutation readily and those recognizing conserved epitopes (ones that appear in an unchanging form on every viral particle in the body, because the virus cannot tolerate their loss or alteration).

The simulation managed to reproduce the typically long delay between infection by HIV and the eventual sharp rise in viral levels in the body. It also provided an explanation for why the cycle of escape and repression does not go on indefinitely but culminates in uncontrolled viral replication, the almost



nate HIV completely. One reason for the failure is that the virus infects, and depletes the levels of, helper *T* cells and macrophages, two central participants in the defense against HIV.



HIV EVADES IMMUNE CONTROL by evolving. In particular, it gives rise to "escape mutants"—variants able to elude immune recognition to some extent. In a simplified example, a viral population bearing just one recognizable epitope (*green in 1 and 2*) undergoes repeated mutations in that epitope (*3–5*). The immune system—represented here by antibody-producing *B* lymphocytes—can keep pace with such maneuvers for a while, but emergence of too many new viral variants apparently undermines the body's ability to cope with the virus.

complete loss of the helper *T* cell population and the onset of AIDS.

In particular, the model indicated that the immune system can often mount a strong defense against several viral variants simultaneously. Yet there comes a point, usually after many years, when there are too many HIV variants. When that threshold is crossed, the immune system becomes incapable of controlling the virus. This "diversity threshold," as we call the breaking point, can differ from person to person. For instance, if the immune system is relatively weak from the start, a few variants may be sufficient to overcome the body's defenses.

There is an intuitive explanation for why the presence of multiple HIV variants in an individual can impair the efficiency of the immune system. This explanation considers the battle between HIV and the body's defensive forces to be a clash between two armies. Each member of the HIV army is a generalist, able to attack any enemy cell it encounters. But each member of the immune army is a specialist, able to recognize an HIV soldier only if the soldier is waving a flag of a precise color.

Suppose the armies would be equally powerful if every specialist in the immune army recognized the same flag and every HIV soldier carried that flag. Now suppose that the HIV army consisted of three groups, each carrying a different flag and that, in response, the immune specialists also divided into three groups, each recognizing a separate flag. Under these conditions, the immune army would be at a significant disadvantage. Any given immune specialist would recognize and attack only one out of every three enemy soldiers it encountered—the one carrying the right flag. The HIV soldiers, meanwhile, would continue to pick off every specialist they met and would ultimately win the war.

Predicting the Course of Disease

Beyond giving us the concept of a diversity threshold, the model offered a possible explanation for why some patients progress to AIDS more quickly than do others. If the initial immune response to conserved epitopes is strong, the efficiency of the defensive attack on HIV will not be undermined very much by mutation in other epitopes. (Many active members of the immune system will continue to recognize every infected cell or viral particle they encounter.) Hence, the body should control the virus indefinitely, in spite of quite high levels of viral diversity. In such individuals, progression to AIDS is likely to be slow (or may not happen at all).

If the immune response to conserved epitopes is not strong enough to control the viral population on its own, but the combined effort of the responses against conserved and variable epitopes can initially manage the virus, the defensive forces could do well for quite a while. But the reaction against variable epitopes should eventually be undermined by the emergence of escape mutants and increasing viral diversity. In this case, HIV levels should rise as the response to variable epitopes becomes less efficient. This is the pattern that apparently occurs in most patients.

If the combined immune responses to conserved and variant epitopes are too weak to control HIV replication from the start, AIDS should develop rapidly. In that situation, the original viral particles would proliferate without encountering much resistance, and so the virus would be under little pressure to generate mutants able to escape immune reconnaissance. Such patients might progress to AIDS even in the absence of significant viral diversity.

The simulation also provided insight into probable properties of the viral population during each stage of HIV disease. In the earliest days, before the immune system is greatly activated, the viral variants that replicate fastest will become most abundant. Hence, even if a patient were infected by several variants at once, after a short time most of the virus in the body would probably derive from the fastest-growing version. And so we expect little genetic diversity during the acute phase of disease.

After the immune system becomes more active, survival becomes more complicated for HIV. It is no longer

DIMITRY SCHIDLOVSKY

enough to replicate freely; the virus also has to be able to ward off immune attacks. Now is when we predict that selection pressure will produce increasing diversity in epitopes recognized by immune forces. Once the defensive system has collapsed and is no longer an obstacle to viral survival, the pressure to diversify evaporates. In patients with AIDS, then, we would again anticipate selection for the fastest-growing variants and a decrease in viral diversity.

Long-term studies involving a small number of patients have confirmed some of the modeling predictions. These investigations, done by several researchers—including Andrew J. Leigh Brown of the University of Edinburgh, Jaap Goudsmit of the University of Amsterdam, James I. Mullins of the University of Washington and Steven M. Wolinsky of Northwestern University Medical School—tracked the evolution of the so-called V3 segment of a protein in the outer envelope of HIV for several years. V3 is a major target for antibodies and is highly variable. As the computer simulation predicted, viral samples obtained within a few weeks after patients became infected were alike in the V3 region. But during subsequent years, the region diversified.

Focus on Killer Cells

The original mathematical models treated the immune system as a unit and did not distinguish among the activities of the various cell types. Because killer *T* lymphocytes seem to exert tremendous immunologic pressure against HIV, the two of us and our coworkers have recently designed models that specifically examine the behavior of those cells. These newer models taught us even more about the way HIV's ability to diversify can erode the defensive competence of the immune system.

We began working on these simulations early in 1994, after one of us (McMichael) became perplexed by the results of studies in which he and several collaborators tracked responses of cytotoxic *T* cells to HIV in initially asymptomatic patients. Those studies followed the patients for about five years and were undertaken in part to assess the influence of different HLA molecules on the ability of patients to combat the virus.

HLA molecules play a critical part in the defensive response because they determine which viral peptides will be displayed on cells and how effectively they are showcased. Any two patients are likely to differ in the precise mix of HLA molecules they possess. In consequence, they will also differ in the peptide epitopes their cells exhibit and in the ability of the HLA-peptide units to attract the attention of the immune system. Most patients infected with HIV seem to recognize just a few of the many potential epitopes generated from the virus's proteins, usually between one and 10.

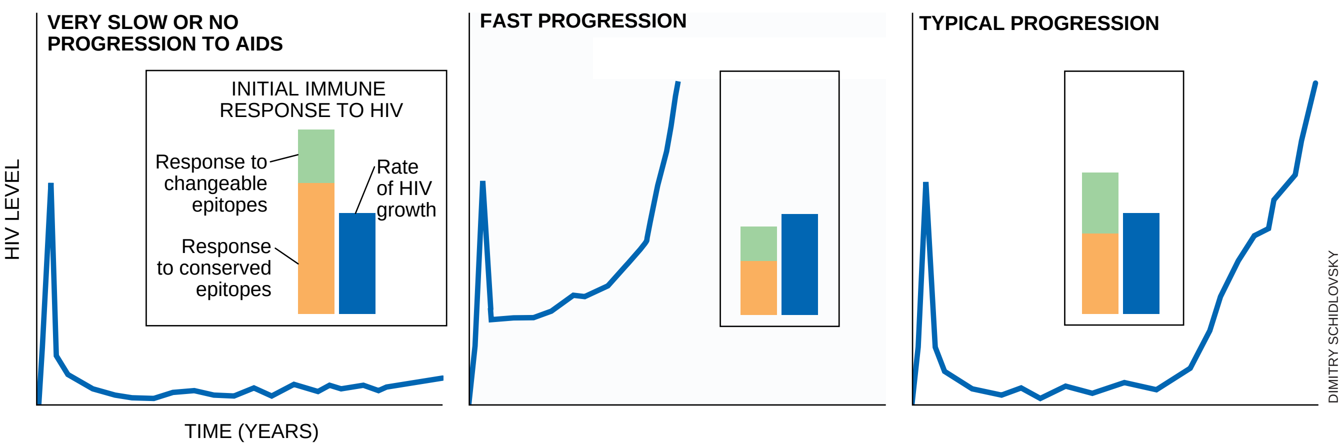
The clinical investigations examined the response of cytotoxic *T* cells to various epitopes in an internal HIV protein called gag. Three of the patients used the HLA variant B27 for such display, and two patients used HLA-B8. In the B27 patients, cytotoxic *T* cell responses were directed at a single fragment of the gag protein, which underwent insignificant variation during the course of the study. In the B8 patients, killer *T* cell activity was directed against a set of three other segments in gag. All three epitopes spawned mutants during the study, and many of the mutant peptides escaped recognition by the host's cytotoxic cells. It also turned out that the relative strength of the responses directed against the three epitopes fluctuated markedly.

These studies were the first to document the existence of mutant viruses able to evade killer *T* cells in the human body. Yet they also raised some puzzling questions, especially this one: Why did the strength of the *T* cell responses to the several epitopes fluctuate so much? In most other viral infections the responses, which are usually directed against one or a few epitopes, are much more stable.

Why Killer Cells Go Astray

It was partly to answer this question that our groups collaborated on making computer models of cytotoxic *T* cell responses to HIV. The programs assumed that breakdown of viral particles in infected cells would result in the display of many epitopes recognized by cytotoxic *T* cells. The models also presumed that most of the epitopes would be capable of mutating and hence of giving rise to viral variants bearing changes in some of their epitopes.

The models introduced random mutations in epitopes and then traced the growth of every new viral variant as well as the abundance of cytotoxic *T* cells directed against each epitope. The abundance of *T* cells recognizing a given epitope—and, hence, the killing power of



SPEED AT WHICH HIV LEVELS RISE (*linear plots*) over the years may depend greatly on the composition of the initial immune response (*insets*). Modeling suggests that if the immune attack directed against conserved epitopes (ones found on every viral particle) can limit viral growth on its own (*left*), the body might keep viral levels low indefinitely—even after the response to readily changeable epitopes inevitably decays. This pattern is uncommon. If the combined responses are weak (*center*), viral levels will rise quickly. If the combined responses are strong but the "conserved" response cannot by itself control the virus (*right*), the typical, fairly slow course of viral multiplication should result. In that situation, levels will begin to soar when the ability to respond efficiently to changeable epitopes is lost.

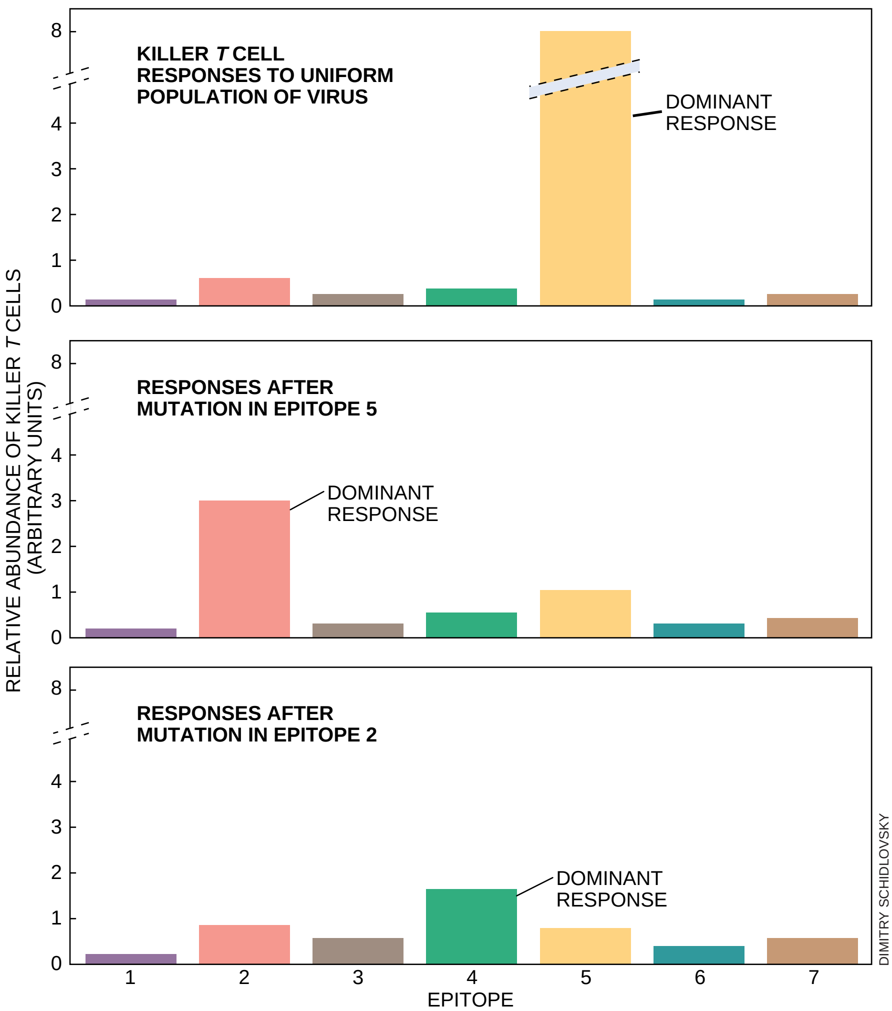
these populations—was made to depend on the number of viral particles bearing that epitope and on the excitatory power of the peptide. (Some epitopes evoke more *T* cell replication than do others.)

The results of the multiple-epitope models were complex, to say the least. In essence, though, the overall efficacy of the immune system declined over time, and the drop resulted from much the same kind of fluctuation in immune reactivity seen in the two patients who produced HLA molecules of the B8 type. The fluctuation seemed to derive from a kind of competition among killer *T* cell populations.

Our calculations suggest that in the body, one clone of killer *T* cells (a population recognizing one epitope) essentially vies with all others for dominance. As the initial killer cell response, which involves many clones, takes effect, the viral population gets smaller, thereby reducing the number of stimulatory signals received by the *T* cells. Ultimately, only the *T* cell clones recognizing the most stimulatory epitopes remain active, and the *T* cell response may even be dominated by a single clone.

Such a process could be beneficial and could potentially eliminate a virus if the microbe did not change. On the other hand, if the epitope fueling the dominant response mutates, the corresponding *T* cell clone may not recognize the mutant. Viral particles bearing this peptide may then multiply virtually unnoticed. Sometimes the immune system will catch up with the renegade group and mount a defense targeted against the new version of the epitope, but other times the defensive system may switch its attention to a different, and originally less stimulating, epitope. This switching can be repeated many times, producing a very intricate pattern in which the relative abundances of *T* cell clones fluctuate continuously. Emergence of an unrecognized form of an epitope can thus cause trouble in at least two ways. In addition to reducing directly the strength of the attack on the altered viral variant, it can induce the immune system to shift its efforts toward less stimulating epitopes.

The global picture taking shape from our recent simulations is one in which diversity of epitopes gives rise to fluctuations of immune responses and diversion to weaker and weaker epitopes. Such diversion results in high levels of HIV, leading to faster killing of helper cells and macrophages and to reduced control of the overall viral population. Put another way, viral diversity seems to drive disease progression. These multiple-epitope simulations can be applied to antibody responses as well.



COMPUTER SIMULATION tracked levels of killer *T* cells in a hypothetical patient. Initially (*top*) the *T* cells responded to a homogeneous population of HIV particles, each of which carried seven recognizable epitopes; epitope 5 elicited the strongest response (*yellow*). After a viral mutant carrying an altered, unrecognized version of this epitope emerged (*middle panel*), the dominant response became focused on a less stimulatory epitope—number 2 (*red*). And after epitope 2 mutated (*bottom*), dominance shifted again, to number 4 (*green*), an even weaker epitope. Such shifts could contribute to reduced immunologic control in HIV-infected patients.

Thoughts on Therapy

Someone unfamiliar with such findings might reasonably suspect that patients who respond to many different epitopes will enjoy better control of a viral population, because a microbial particle not noticed by one clone of immune cells would probably be noticed by another clone. Yet our models predict that in the case of HIV, a response to many different epitopes can be a bad sign—an indication that important epitopes may have undergone unrecognized mutations. The simulations imply that patients whose immune defenses stably recognize one or a few epitopes probably control the virus better than those who respond to a large number of epitopes. This view is supported by an interesting finding from the HLA study described earlier. The two patients who displayed fluctuating *T* cell responses progressed toward AIDS more quickly than did patients who had consistent responses to a single epitope. This study involved too few patients to allow for definitive conclusions, however.

If the models reflect the course of HIV disease accurately, the findings have implications for the development of vaccines (for prevention or treatment) and chemical-based therapies. In the case of vaccines, it would probably be counterproductive to stimulate immune activity against a variety of HIV epitopes in an individual. After all, such stimulation would probably elicit an undesirable competition among immune forces. Rather it may be better to boost the response against a single conserved epitope, even if that epitope is not normally recognized most readily. This response could ideally evoke a persistent, controlling response to HIV. The trick, of course, would be to identify conserved epitopes and find the best way to deliver them.

Another striking implication relates to the fact that the virus replicates quickly and continuously in all stages of infection. This realization has made many physicians conclude that chemical agents able to halt viral replication are probably most effective when delivered early, before the virus has a chance to expand too much. Combination therapies may also be more effective than single drugs, because even if the virus generated a mutant population resistant to one of the substances, the other drugs could still continue to be effective. By retarding the rate of replication, such strategies should slow the speed at which mutants are produced and so limit viral diversity. Our models further suggest that reducing viral levels and curtailing diversity in this way would help the natural immune system to contain the virus.


LENNART NILSSON *Boehringer Ingelheim International*

MOVING IN FOR THE KILL, cytotoxic *T* lymphocytes attack a cancer cell in much the way they ambush virus-infected cells. Many lymphocytes attach to a target cell and secrete substances that drill holes into the cell membrane.

A Broad View of HIV Dynamics

The collected clinical and mathematical findings show that in addition to replicating massively in infected patients, HIV mutates repeatedly and thus spawns an enormous diversity of viral populations. These features enable the virus to evolve in response to the threats it encounters during the course of an individual infection. Mutants able to evade immune attack to some degree appear and predominate until the immune system gathers the strength to quell them—but meanwhile new escape mutants begin to multiply. Power thus moves repeatedly from the virus to the immune system and back for a time.

The reversals do not go on endlessly, though, apparently because the evolution of viral diversity gradually tilts the balance toward the virus. Diversity favors the microbe in part because the variability befuddles the patient's immune system, which becomes less efficient and therefore enables the viral population to grow and to kill increasing numbers of helper cells.

Of course, killing of helper cells impairs the functioning of killer *T* cells and *B* cells, which react strongly only when they are stimulated by proteins released from helper cells. As these two cell types become even less effective, a potentially lethal spiral ensues in which viral levels rise further, more helper *T* cells are killed and the overall responsiveness of the immune system declines.

Generation of mutants thus stimulates a continuous reduction in the efficiency of the immune system. At some point, the diversity becomes too extensive for the immune system to handle, and HIV escapes control completely. As the viral load increases, the killing of helper cells accelerates, and the threshold to AIDS is crossed. Finally, the immune system collapses. In short, it seems that an evolutionary scenario can go a long way toward explaining why HIV infection usually progresses slowly but always, or almost always, destroys the immune system in the end.

The Authors

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The Benefits of Background Noise

Stochastic resonance, the phenomenon by which background noise boosts weak signals, is creating a buzz in physics, biology and engineering

by Frank Moss and Kurt Wiesenfeld

Noise often creates confusion. Try having a telephone conversation while standing on a busy street corner or listening to a radio broadcast riddled with static. Engineers have long sought means to minimize such interference. But surprisingly enough, during the past decade researchers have found that background noise is sometimes useful. Indeed, many physical systems, ranging from electronic circuits to nerve cells, actually work better amid random noise.

This phenomenon, known as stochastic resonance, is most easily described by way of analogy. Imagine a ball sitting in one of two wells—say, a marble in an egg carton. A gentle rhythmic force rocks the whole system to and fro. (This force might correspond to some weak, periodic signal.) Under its influence, the ball simply rolls around in the bottom of one well. If the ball's movements are detectable only when it jumps from one well to another, this weak periodic force will remain hidden. Adding noise to this system—by shaking the egg carton up and down, for example—would seem likely only to mask the rocking motion further.

In fact, it has the opposite effect. The weak force coupled with noise can, on occasion, give the ball enough energy to surmount the boundary between the two wells. Over time, the ball appears to jump back and forth at random. The theory behind stochastic resonance, however, rests on the fact that these jumps are not entirely unpredictable: the chance that the ball switches wells at any one moment is far greater if the weak force is at its peak. Hence, the timing of the jumps reveals a good deal about the periodicity of the weak force.

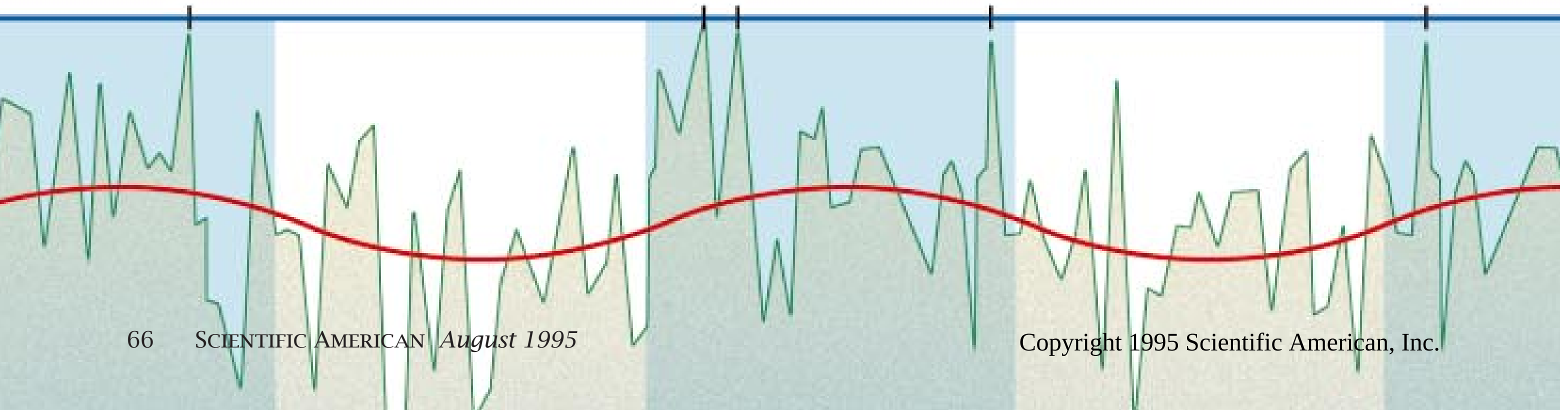
The key feature of this system—and any in which stochastic resonance occurs—is that the relation between its input (here, the weak force) and its output (the ball switching wells) is nonlinear. That is, if the input falls below a certain threshold, there is no output whatsoever. (In contrast, linear systems always produce an output in proportion to their input.) Random noise can benefit faint signals in nonlinear systems by boosting them over the threshold [see "The Amateur Scientist," page 100].

The degree to which a signal benefits depends heavily on adding just the right amount of random noise. The improvement can be measured as a rise in the signal-to-noise ratio (SNR). If too little noise is added, the signal is not significantly boosted. Similarly, adding too much noise overwhelms the enhanced signal. There is an optimal amount of noise that conveys the most information. This finding—that noise is sometimes a bonus rather than a nuisance—has caused a recent burst of interest in stochastic resonance, not only in physics, engineering and biology but in almost every science where noise and thresholds are encountered.

Noisy Light

Three Italian scientists, Roberto Benzi, Alfonso Sutera and Angelo Vulpiani, first developed the notion of stochastic resonance in 1981 to explain a standing paradox in climatology. The problem they addressed was that although the earth's ice ages occur somewhat regularly—every 100,000 years or so—only random events seemed capable of causing them. Geoscientists suspected that a periodically recurring wobble in the earth's orbit about the sun every 100,000 years related to the timing of glaciations, yet this shift alone could not prompt a major freeze. Annual swings in the amount of heat the earth received and retained from the sun—variables dependent on sundry other factors—were known to hold far more influence. The Italian team proposed that these "noisy" large-scale

NONLINEAR SYSTEMS detect only those periodic signals (*red*) that rise above some threshold. Noise (*green*) can boost a weak signal over the threshold and will most likely do so when that signal is close to its peak (*blue region*). Hence, the detector's output (*black ticks*) tells of the weak signal's periodicity.

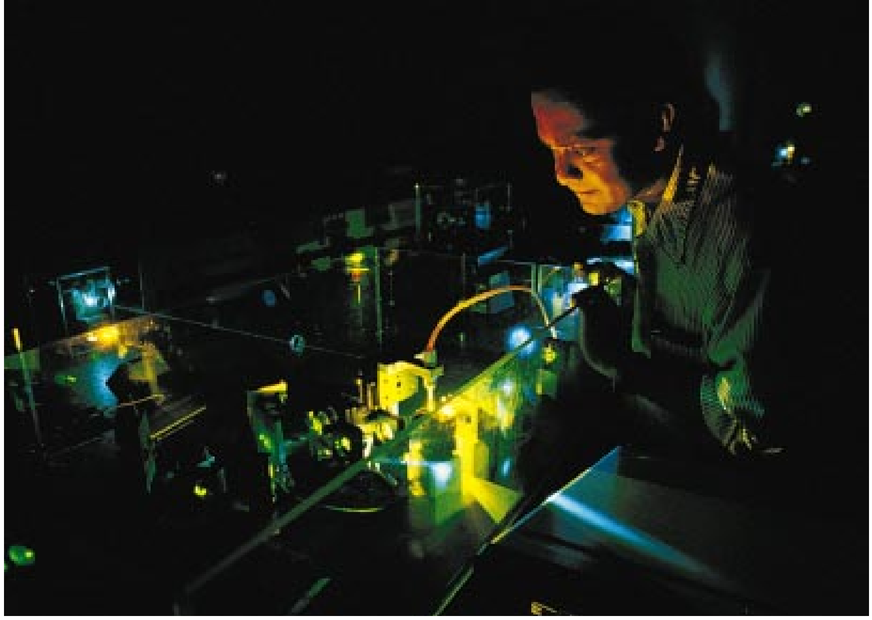


fluctuations might amplify the subtle effects of the orbital eccentricity every 100,000 years. If the strong noise and weak wobble acted together, they argued, it would account for the regularity of ice ages.

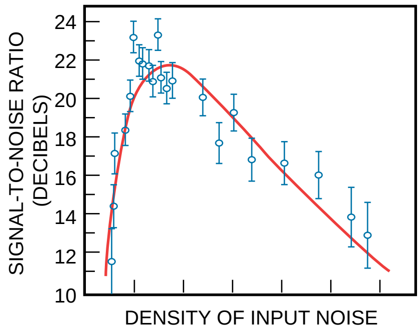
In fact, that puzzle remains unresolved. Nevertheless, stochastic resonance as a concept intrigued many scientists, and only two years later a team of French researchers led by Stephan Fauve confirmed the basic theory using a noisy electrical switch called a Schmitt trigger. The group showed that random electrical noise did amplify weak periodic triggering signals moving through the circuitry. Remarkable as this experiment was, the subject lay dormant for the next five years. Then, in 1988, physicists at the Georgia Institute of Technology, including Rajarshi Roy, Bruce McNamara and one of us (Wiesenfeld), discovered stochastic resonance at work in a ring laser.

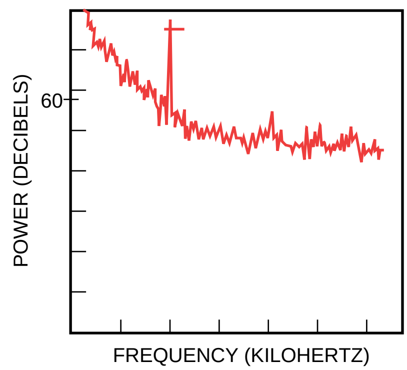
In this device, mirrors reflect laser light so that it travels in a closed loop, either clockwise or counterclockwise. Mathematically, the situation is akin to the double-well model; here the light represents the ball, and each propagation direction corresponds to a well. When the laser is switched on, either direction may have the initial advantage. Once it is running, though, a chance perturbation can cause the light to change directions. In our experiment, we created just such disturbances using a device called an acousto-optic modulator, which generates standing acoustic waves in a crystal. Depending on the frequency of these waves, which we could control electronically, the light travels preferentially in one direction or the other.

To create a signal, we modulated the frequency of the standing waves periodically—an influence that, were it strong enough, would reverse the light's direction at a regular rate. We ensured, however, that it was not that strong. Then we layered "noise" on top of this signal by also modulating the frequency of the standing waves at random. As a result, the light switched direction more or less unpredictably, though to some degree in step with the periodic signal. A detector outside the ring laser recorded when the light traveled counterclockwise, thus producing a time sequence of the switching that included both its regular and random components.



JOE SCHWARTZ *Georgia Institute of Technology*





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RING LASERS exhibit stochastic resonance. Acoustic waves placed in a laser's path can make the light reverse its rotation at a regular rate or at random (*photograph above*). Given a weak periodic influence, some optimal amount of added noise results in the most regular switching (*top graph*). In the power spectrum of the output (*bottom graph*), the weak signal appears as a narrow spike rising above a broad background of noise.

Calculating the so-called power spectrum of this time sequence provided us with a convenient measure of the information content of the switching relative to its own noise. Viewed graphically, the regular component was represented by a narrow peak at the signal's frequency, whereas the random noise appeared as a broad band across all frequencies. The SNR here is simply the height of the narrow peak compared with that of the broad background. We found that the SNR was greatest when the added noise had a particular intensity, demonstrating stochastic resonance. Thus, within a certain range, adding more random noise had actually resulted in more regular switching, not less.

This insight sparked an explosion of research; over the next few years, stochastic resonance was shown to occur in a wide range of physical systems, including other types of electrical circuits and lasers, superconducting quantum interference devices, or SQUIDs [see "SQUIDs," by John Clarke; SCIENTIFIC

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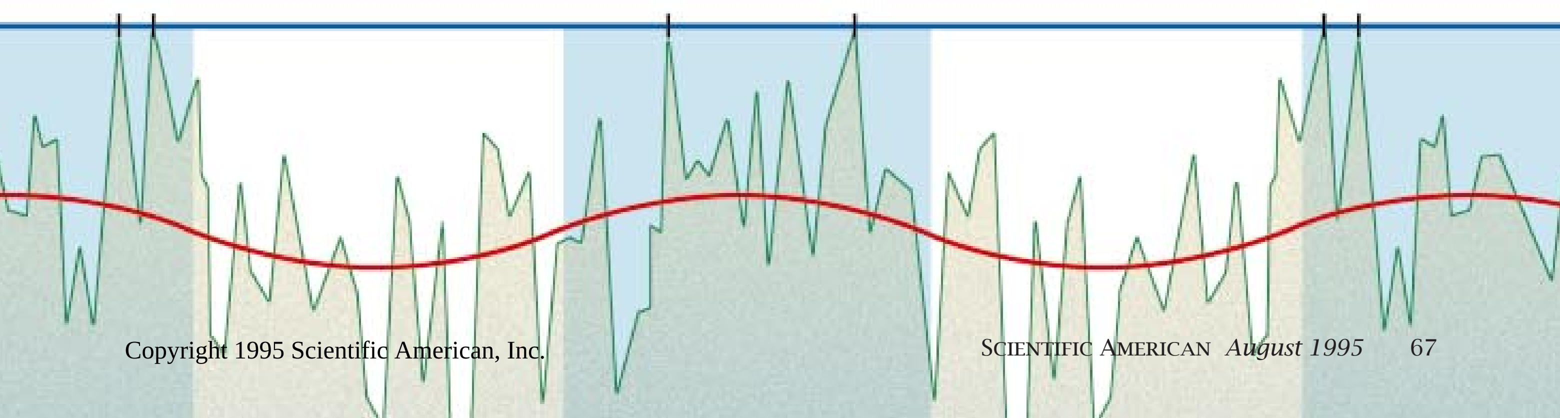

CRAYFISH pursued by a smallmouth bass (*below*) uses hair cells on its tail fan (*top right*) to detect the faint water motions made by nearby predators. Moss found that random noise enhanced the sensitivity of these cells, which act like threshold detectors. The signal-to-noise ratio (*bottom right*) was greatest given a specific amount of added noise, as had been predicted by theory (*green*) and shown in an electrical model (*red*).

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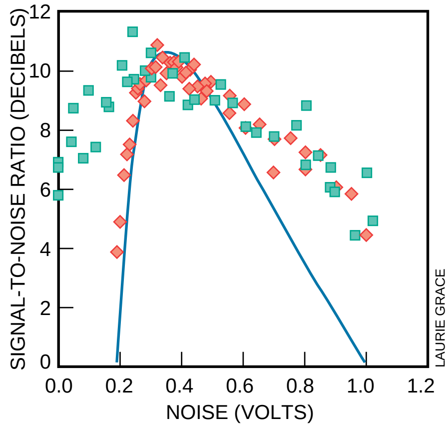
WILLIAM ROSTON



LAURIE GRACE

AMERICAN, August 1994], and many others. Most recently studies of stochastic resonance have begun crossing disciplinary boundaries into sensory biology and perception.

Noise in Neurons

A group at the University of Missouri at St. Louis led by one of us (Moss) decided to investigate whether stochastic resonance or some related phenomenon might play a key role in biological sensing systems. After all, the paramount business of the sense organs is the detection of faint, information-bearing signals traveling through noisy environments. To begin, we chose a very simple system: the mechanoreceptor cells found on the tail fan of the ordinary crayfish, *Procambarus clarkii.*

These cells, which end in fine hairs between 25 and 100 microns long, are specialized to detect weak (and probably periodic) water motions such as those generated by the waving tail of a nearby predatory fish. The hair cells most likely serve as an early-warning system of sorts and are evidently good at that task: not only is the crayfish one of the oldest and most successful animals around, but similar rudimentary water-motion detectors are common to a wide variety of crustaceans, among them shrimps and lobsters.

The hair cell operates in a simple fashion. When moved, the hair generates a nerve impulse, measurable as a narrow spike of about 100 millivolts lasting for about 200 microseconds. That impulse travels along a neuron to a ganglion, or a bundle of nerve cells, located near the top of the tail fan. This terminal ganglion is the last of a series extending toward the animal's brain; it comprises some 200 neurons and connecting interneurons, which aid in information-processing tasks. The terminal ganglion handles all incoming information from the hair cells and makes basic decisions, such as activating the animal's escape reflexes.

We considered this system to be a usefully easy one to study for many reasons. The neuroanatomy suggests that the sensory apparatus does nothing more than transmit nerve impulses generated by hair motions to the terminal ganglion. (Other potentially complicating nerve signals would not be present, therefore.) Further simplifying matters, all the available evidence indicates that the sensory neurons function much like nonlinear threshold detectors. Below a certain level, very weak motions of the hair do not generate nerve impulses.

For our trials, we excised a piece of crayfish tail containing numerous hair cells, the nerve cord and the terminal ganglion. We mounted this entire preparation on a movable post inside a tank filled with saline solution. Next we inserted an electrode into the nerve cord and contacted a single sensory neuron. We carefully tweaked each of the individual hairs to learn which one activated this particular neuron. An electromechanical transducer moved the entire mount through the solution.

When we moved the mount back and forth at a regular rate, we measured a seemingly random pattern of signal spikes in the neuron. These we converted into standard rectangular pulses and computed their power spectra. These spectra were, in fact, very similar to those recorded during the ring laser experiment: they showed a narrow peak representing the periodic signal riding on a broad background of noise. From the power spectra, we obtained the SNR and found that the crayfish hair is surprisingly sensitive. Most of the cells we tested could sense periodic motions of the post as small as about 10 nanometers in amplitude.

In the next stage of our experiment, we reduced the amplitude of the post's motion until it was nearly undetectable.

What motion remained gave rise to a weak periodic signal that we hoped might resemble what a crayfish senses during the approach of a predator. Next we added totally random noise to the signal moving the post—that is, we added an irregular fluctuation to its movements. Our goal was to mimic the noisy environment in which crayfish normally live, under rocks in rapidly flowing streams. We slowly increased the amplitude of this noise and at each level measured and averaged the power spectra of the nerve impulses.

The results of this biological experiment roughly agreed with theoretical predictions and with electronic simulations of a threshold detector, save for a few discrepancies. The theory predicted a more rapid decrease of the SNR at high noise levels. We now know the reason, although we did not at first: real neurons exhibit a refractory period, or "dead time," after each firing event. During this time, they cannot be reactivated. Consequently, as noise levels rise, incidental firings become more frequent, but so, too, do the refractory periods, which blank out some subsequent noisy firings. The net effect keeps the SNR higher than it would otherwise be.

We found another difference as well. The crayfish spectra fell above both the theoretical predictions and the electronic simulation when the noise intensity was small. We attributed this excess to the unavoidable internal noise in sensory neurons caused by biochemical and electrical activity in the cell. Indeed, high levels of such noise drown out the effects of added external noise and prevent stochastic resonance. We tested many sensory neurons obtained from a large number of individual crayfish, and the overwhelming majority showed stochastic resonance. Those that did not, though, were independently shown to be internally noisy. It is an interesting open question as to whether this apparently undesirable yet not uncommon internal noise might itself serve some useful sensory function.

Quantum Noise and Beyond

Although the latest research frontiers in stochastic resonance are in the biological sciences, physicists are not quite done with the subject. In particular, the question has arisen whether stochastic resonance manifests itself on the quantum scale. Recent theoretical work at AT&T Bell Laboratories by Susan N. Coppersmith and Ritva Löfstedt predicts that it does, though under different conditions than in a macroscopic system such as a ring laser.

To understand the situation in quantum systems, picture once again two side-by-side wells. In this case, the wells might represent two stable positions of an impurity in a very small (submicron) metallic wire. From random background vibrations in the atomic lattice, the defect may gain enough energy to surmount the barrier and move from one position to another. So far the problem is analogous to the double-well scenario for macroscopic systems. The new twist is that, in addition, a purely quantum-mechanical effect can take place—the defect can "tunnel" through the barrier without going over it.

To observe quantum tunneling in any system, it must be very cold: the temperature must be close to absolute zero. In fact, when the temperature is low enough, quantum tunneling alone causes random switching. A periodic signal can be laid onto this quantum system by pushing up or down the amount of energy it takes to pass from one well to the other; this pushing can be done by applying an electromagnetic field and altering the potential between the wells. Surprisingly, the theoretical prediction is that to observe quantum stochastic resonance in this case, the underlying potential must be asymmetrical. That is, one well must be deeper than the other, or one position for the imaginary impurity slightly more stable. This situation is the opposite of the classical case, where such a bias in the system diminishes the effect.

These small differences aside, it is remarkable that an extremely simple stochastic process pervades rather diverse areas of science—laser technology, sensory biology and quantum mechanics. In many of these disciplines, technical applications are being found quickly. Some workers are trying to optimize stochastic resonance in SQUIDs so that they might better detect weakly periodic magnetic fields in noisy environments. Along with Vadim S. Anishchenko, Leon O. Chua of the University of California at Berkeley has even demonstrated stochastic resonance in a chaotic electronic circuit (Chua's circuit).

Stochastic resonance holds further potential for the field of medical science, in which numerous physiological functions are marked by thresholds and random variability abounds. Many disorders of the nervous system are characterized by increased sensory thresholds, leading to reduced firing rates in the appropriate sensory neurons. Elderly people, for example, often have difficulty walking and maintaining their balance because of increased firing thresholds in proprioceptors, neurons that sense the angle, velocity and displacement of moving limbs. The addition of random noise to the neural signals lying below these thresholds would amplify the firing rates in the proprioceptors. So perhaps neural noise could improve a patient's locomotion and sense of balance. Answers to several medical questions should be established soon. In the meantime, it seems certain that stochastic resonance will enter a variety of fields both in basic science and in technology.

The Authors

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The Physiology of Decompression Illness

For more than a century, researchers have known that exposure to high pressure can injure or kill. Gradually, they are beginning to understand the underlying mechanisms

by Richard E. Moon, Richard D. Vann and Peter B. Bennett

The helicopter swooped down from a black, early-morning sky. Quickly, one of its occupants was wheeled from the aircraft to our hyperbaric facility at Duke University Medical Center in Durham, N.C. The 42-year-old patient, a lawyer on vacation with his girlfriend, was sleepy and had a rash on his abdomen. From what we had already heard of his case, we suspected he also had gas bubbles in his brain.

Seven hours before, in the late afternoon, he had surfaced off the North Carolina coast feeling fine after his second scuba dive of the day. Forty-five minutes later he developed a headache, became dizzy, had trouble walking and felt a tingling over his abdomen. His vision began to "close in," as he put it, and he became nauseated. Driving back to his hotel, he lost his way, became incoherent and, for a while, did not recognize his girlfriend.

After a neurological examination, the patient and a specially trained nurse were sealed in one of the pressurizable, hyperbaric chambers used to treat his condition. Inside the vessel the pressure was raised to 2.8 times that of the earth's atmosphere and then, over a period of six hours, reduced in stages to one atmosphere while the patient breathed pure oxygen. This treatment is standard for most forms of decompression illness—a catchall term for the various gas-bubble-related maladies suffered from time to time by divers, compressed-air workers and others. The following day a magnetic resonance imaging scan of the man's head was consistent with our suspicion about bubbles: it showed pointlike areas of excessive fluid in the brain, suggesting swelling of tissue initiated by bubbles.

After about a week of what he called "visual disorientation," and other than some inner-ear symptoms that eventually resolved, the diver recovered fully, as do most patients who suffer serious problems of this kind and are recompressed in a chamber.

Ultimately, what made this case important to us was the way it fit an evolving hypothesis we had about the role of the heart in decompression illness. Classic theories rarely implicated the organ, but a posttreatment examination of this diver showed he had a heart condition known as a patent foramen ovale, a kind of conduit through which bubbles could get into the arterial blood. Once in the arteries the bubbles could obstruct blood flow to vital organs, particularly the central nervous system (the brain and spinal cord).

Unique Medical Legacy

The treatment of the vacationer and especially the discovery of his heart anomaly were in a way typical of the history of the disease. In the two centuries that people have breathed compressed air, researchers have compiled—often as a result of unfortunate injuries to these hardy souls—a remarkable record of how the human body responds to stresses for which it was not designed. From the narcotic potency of pressurized nitrogen and the toxicity of pressurized oxygen, to the effects of heat loss and the bizarre symptoms of pressure on the central nervous system, diving has created a rich and unique body of medical knowledge.

Of all these afflictions, the most common and yet imperfectly understood is decompression illness. The underlying cause—bubbles in the blood or tissue—was established as early as 1877, and the disease has been studied intensively ever since. Gas bubbles were first implicated in the disease by the French physiologist Paul Bert. He proved that the bubbles were composed of nitrogen; because oxygen is metabolized by tissue cells, it is not usually a problem during decompression.

What made the illness possible was the invention of the air pump and, subsequently, in 1841, the caisson, a pressurized chamber typically used during the construction of tunnels or bridge foundations under rivers. Laborers would enter a caisson through an air lock and work in an atmosphere of compressed air that prevented flooding. Later, when the workers were decompressed back to one atmosphere, they often developed joint pain and occasionally more serious problems: numbness, paralysis, loss of bladder or bowel control and even death.

It was at the St. Louis Bridge, built in the early 1870s, that decompression sickness received its familiar name, the "bends." Laborers with decompression sickness sometimes walked with a slight stoop, a posture affected at the time by fashionable women and known as the Grecian Bend. In all, about 600 men worked in the caissons of St. Louis. Neurological decompression sickness, the more serious form of the disease, affected 119 of them; 14 died.

Among the injured was Alphonse Jaminet, the workers' physician, who after leaving the caisson one evening became dizzy and unable to speak and suffered limb pain and paralysis of one arm and both legs. He elevated his legs and drank rum, and within a week his symptoms resolved. Surprisingly, many of the most severe cases of decompression illness resolved spontaneously. On the other hand, some did not, leaving the afflicted crippled for life. Besides these serious cases, there were many more incidents of lesser symptoms, usually joint pain.

The Brooklyn Bridge, constructed at about the same time as the St. Louis Bridge, also had casualties. Twenty men died, and many more had lasting neurological problems. Washington Roebling, the chief engineer, became paralyzed and had to supervise the bridge's completion from his bed.

Modern treatments for decompression sickness have their origins in 19th-century observations that when afflicted men reentered the pressurized caisson, their bends symptoms often improved—a consequence of reduced bubble size. At about this time, Bert reported that breathing pure oxygen helped to relieve signs of bends in animals. Nowadays virtually all treatments involve recompression and slow decompression while breathing oxygen. Although recompression several hours or even days after the onset of symptoms can result in improvement, a favorable outcome is most likely when recompression begins quickly.

Who Is at Risk

Today the group of people at risk has swelled to include divers, workers in caissons, pilots who experience drops in pressure when they fly to high altitudes and astronauts who don low-pressure space suits before leaving their vehicles. In the U.S. about 900 cases are reported each year among recreational divers. Although the incidence of decompression illness even among U.S. divers is not known, it has been estimated that recreational divers worldwide are afflicted at about one incident per 5,000 to 10,000 dives. For commercial divers, who often encounter higher pressures for longer periods, the rate is about one incident in 500 to 1,000 dives.

What is perhaps most disconcerting about these cases is that most of them cannot be dismissed as the consequences of reckless diving. To avoid the disease, divers use either tables or waterproof computers that tell them how deep and how long they can stay down without undue risk. These tables evolved from work in the early years of the 20th century by the British physiologist John S. Haldane. Haldane's tables and their successors drastically reduced both the rates of decompression sickness and the numbers of severe cases. Nevertheless, as many as half of all cases of decompression sickness are suffered by divers who claimed to have been diving within the limits specified by a standard table (or by a computer algorithm, all of which are derived

DAVID DOUBILET

DECOMPRESSING DIVERS use a line to hold their position at a specified depth. Ascending slowly and making appropriate stops minimize bubble formation in tissues and the risk of the bends.

from similar mathematics as the tables).

Part of the reason why decompression illness has been so slow in yielding its secrets is that it is not a single malady but rather a collection of loosely related ailments. The term "decompression illness" refers to both decompression sickness and arterial gas embolism. Both are a function of bubbles and differ mainly in the ways in which the gas gets into the body and, to some extent, in their symptoms.

Arterial gas embolism occurs when an obstructed airway prevents gas expanding within the lungs from escaping. Typically this situation occurs when a novice or panicky diver holds his or her breath during a rapid ascent. As the pressure surrounding the diver's body decreases, gas in the lungs expands and can rupture the organ and escape into the blood. The syndrome can also result from a blockage of only part of the bronchial tree, perhaps because of asthma or a respiratory infection. Following blood flow, these bubbles are carried into the arterial circulation and often to the brain. Obstruction of blood flow, which either impairs the functioning of brain tissue or kills it outright, is the most probable explanation for the common symptoms: sudden loss of consciousness, convulsions, and paralysis in the left or right half of the body.

Clinical observations suggest, however, that the underlying mechanisms of the disease go beyond simple obstruction of blood flow. For example, some patients improve after recompression, then inexplicably deteriorate—long after any bubbles could possibly remain. Studies in animals by Desmond F. Gorman and his co-workers at the University of Adelaide in Australia have demonstrated that after air embolism there is a slow but steady reduction in brain blood flow even after bubbles have been totally cleared from the vessels. There is evidence to suggest that this persistence of pathology might be caused by bubble damage to the endothelium (the lining of the blood vessels) and the subsequent accumulation of white blood cells, which might obstruct flow directly or indirectly through the release of chemical mediators.

Decompression sickness, on the other hand, is a consequence of bubbles that form within the tissues. The inert gas that causes the condition (usually nitrogen or helium) enters the body during a dive through the lungs and, at the elevated pressures of ocean depths, dissolves in the blood. Circulation carries this dissolved gas to the capillaries, where it diffuses into the tissues. This diffusion—both into the tissues at depth and out of them on ascent—is quick in the spinal cord and brain because capillaries are close together and these organs are well perfused with blood. These are "fast tissues," within which blood flow is the primary controller of inert-gas exchange. By this criterion, the joints are "slow." They are less perfused, so gas uptake and elimination is less rapid. In skeletal muscle, inert-gas exchange varies quite a bit. Blood flow through the muscles of a cold, resting diver is at a low level, but it can be 10 times greater in a warm diver who is exercising.

Washing out the Nitrogen

The body tissues of an air-breathing diver who has surfaced contain significant amounts of excess nitrogen [*see illustration on page 76*]. Eventually this gas taken up during the dive is washed out by the blood and transported to the lungs, where it is exhaled. When the pressure of all the dissolved gases in the tissues exceeds the ambient pressure surrounding the diver, the tissues are said to be supersaturated. During this time, bubbles can form, just as they do in a container of carbonated beverage when it is opened. Indeed, using ultrasound techniques, researchers have observed bubbles in the bloodstreams of divers and aviators subjected to sudden decompressions of as little as 0.3 atmosphere.

Paradoxically, bubbles do not seem to form within the blood itself. Experiments first performed by Charles Darwin's grandfather, Erasmus, showed that when sealed in its natural container—a blood vessel—and isolated from the circulation, blood does not bubble even when severely decompressed. These observations were confirmed in our laboratory, where we could not detect bubbles in blood in an isolated vein even after we decompressed it from 122 atmospheres. Something in addition to supersaturation seems to be required for bubbles to form.

On the other hand, studies using x-rays have found pockets of gas in the joints of the limbs and in and around the spine, even without decompression. These pockets form as a result of viscous adhesion between moving tissue surfaces. One example is the "cracking" of a joint, the audible formation and collapse of a bubble. Residual gas from these pockets may act as the nuclei from which the bubbles that cause decompression sickness are formed. These nuclei are outside the vascular (blood-carrying) system, but as they expand they might rupture tiny capillaries and in this manner seed bubbles in the circulating blood. A related phenomenon can be seen in a glass of beer, in which bubbles tend to emanate from gas-filled crevices along the side.

The many different symptoms of decompression sickness arise from various combinations of intravascular and extravascular bubbles. Limb pain, for example, probably results from bubbles encroaching on the nerve endings and stretching tissues around the joints. Numbness or paralysis is caused by the presence in the spinal cord of bubbles, which physically disrupt nerve cells and their circulation. Coughing and shortness of breath (cardiorespiratory bends, or the "chokes") are brought on by large numbers of venous gas bubbles impinging on the capillaries in the lungs.

Besides these direct effects, it now appears that there may be secondary ones as well. As foreign bodies, bubbles can activate the coagulation system, exacerbating the blockage of blood flow. Evidence gathered by Charles A. Ward of the University of Toronto has implicated complement, a group of molecules that circulate in the blood and are important in fending off infections.

Shortcut to the Arteries

Although implicated in all forms of decompression illness, bubbles do not by themselves signify trouble. In fact, we and other researchers, such as

RODICA PRATO

GRECIAN BEND was the chic Victorian posture from which decompression sickness derived its more familiar name.

Under Pressure

As soon as the technology of compressed-air diving allowed people to venture below about 40 meters, a dangerous but not altogether unpleasant effect of breathing highly pressurized nitrogen was discovered: narcosis. The condition, more poetically known as "rapture of the deep," is often compared with alcohol-induced intoxication.

In the late 1930s the U.S. Navy began replacing nitrogen in the breathing mixtures for deep dives with helium, which is much less narcotic. The procedure was so successful that it was thought for a time that there would be no further barriers to deep diving. By the 1960s a new obstacle at about 150 meters was discovered by one of the authors (Bennett). He called it high-pressure nervous syndrome (HPNS).

The signs and symptoms of this strange condition affect the pressurized diver at depth and are, in some respects, almost the opposite of those of nitrogen narcosis. The syndrome is characterized by dizziness, vomiting, tremors, fatigue, somnolence, myoclonic jerking, stomach cramps, reduced intellectual performance, poor sleep with vivid dreams and nightmares, and changes in the electrical activity of the brain, such as increased slow waves and microsleep, in which divers remain conscious only as long as their attention is engaged. The deeper the dive and more rapid the compression rate, the more severe the symptoms.

Experiments by Bennett in the late 1960s on the effects of inert gases on cell membranes began to suggest a cause—and a remedy. At high pressures, nitrogen, argon and other physiologically inert gases exert their narcotic effects in essentially the same ways as those of general anesthetics, which are believed to cause the membranes of neural cells to expand. Bennett suspected that many of the same mechanisms underlay HPNS. Subsequent experiments suggested that narcotic gases caused the surface tension in lipid membranes to fall, whereas non-narcotic helium or neon caused it to increase, implying that the gases constricted the membranes.

It was therefore hypothesized that the addition of 5 to 10 percent nitrogen to a mixture of helium and oxygen would result in a mixture that would not change the surface tension of a membrane and therefore not cause either narcosis or HPNS.

In the early 1970s, at Duke University Medical Center, Bennett used such a mixture for the first time. This new "trimix" did indeed ameliorate the tremors and other symptoms of HPNS. During trials in 1981, using new chambers at Duke, divers were compressed to pressures equivalent to depths of 460 to 686 meters. High rates of compression, however, still resulted in some HPNS. Another problem was the great density of the gas at these pressures, making it hard to breathe.

DUKE UNIVERSITY

DEPTH RECORD was set in 1981, when divers were compressed to a pressure equivalent to 686 meters.

Researchers with Comex, a French diving company, began experimenting with a new mixture, in which nitrogen was replaced with hydrogen—half as dense as helium but still at least weakly narcotic. During deep-diving experiments in which the hydrogen pressures exceeded about 25 atmospheres, there were occasional episodes in which divers suffered debilitating effects, such as psychosis or "out of body" experiences. In 1989, however, a mixture of 1 percent oxygen in equal proportions of hydrogen and helium was used successfully in an ocean dive to 500 meters—with excursions to 520 and 534 meters—and in 1993 in a simulated dive (in a chamber) to a world-record depth of 701 meters.

These dives required some seven days of compression and more than 30 days of decompression. Like astronauts, the divers lost body weight and cardiovascular conditioning. Albeit at great cost, invaluable insights into the human body often accrue when the limits of its environment are pushed into outer space or the deep sea. *—R.M., R.V., P.B.*

Richard Dunford of the Virginia Mason Medical Center in Seattle, have used ultrasound devices to examine recreational divers immediately after underwater excursions and have found that bubbles are extremely common in the venous system, the right ventricle of the heart and the pulmonary artery. Such venous bubbles are presumably harmless because they are normally filtered by the pulmonary capillary network and subsequently exhaled.

But if there are enough of these bubbles, the filtering ability of the pulmonary capillaries can be exceeded, allowing the bubbles to enter the arterial system. Alternatively, a heart condition may allow the bubbles to go directly from the right to the left heart (bypassing the circulation to the lungs), with more or less the same result. Bubbles that enter the arterial blood in this manner might reach the brain, disrupting vision, speech, thinking, personality or consciousness.

The most common such heart condition is a patent foramen ovale, a small opening between the right and left atria of the heart (such as we detected in the vacationer we treated in 1988) present in 10 to 20 percent of the population. Using a technique called bubble contrast echocardiography, patent foramen ovale can be detected by observing bubbles passing from the right to the left atrium [*see illustration on page 77*]. Another, rarer condition known as atrial septal defect could have much the same effect.

In 1986 we began looking for patent foramen ovale in all patients admitted for treatment of decompression illness. If the existence of the condition does increase the risk of decompression illness, we reasoned, then it should be more prevalent in divers who have experienced the disease. Indeed, our studies showed that a patent foramen ovale can be detected in about 50 percent of divers who have suffered serious neurological decompression sickness, sug-

Deeper into the Abyss—and Back Again

Peculiar creatures are nothing new in the watery deeps. In recent years, though, there seem to be more than ever before: there is the British film producer, a woman who recently led an expedition to the wreck of the *Lusitania,* in 100 meters of water off the Irish coast; the anesthesiologist from Indianapolis who spends his vacations in pitch-dark caves, diving hundreds of meters through water-filled passages deep in the earth; and the systems analyst who breathes neon and oxygen while visiting 120-meter-deep wrecks off the eastern U.S. coast.

Welcome to the world of technical diving, where no wreck seems too deep, no cave too lengthy, no breathing mixture too esoteric and no piece of equipment too costly.

Technical diving differs from conventional scuba in the way an ascent of Mount Everest is not a stroll in the park, explains Richard D. Vann, director of applied research at the Hyperbaric Center at Duke University Medical Center. The critical difference, he adds, is that "there's a top to the mountain, but there's no real limit to how deep divers go. People just keep going deeper and deeper and deeper. As they do, the certainty that they will be seriously injured or die becomes greater."

Over the past five years the activity has managed to establish itself as a small industry in its own right, with a glossy magazine, an annual trade conference (the last one, in San Francisco, drew 2,000 people) and even tour arrangers catering to its enthusiasts. It has also been linked to a moderate increase in diving-related fatalities and serious injuries, as some try to dive beyond their training or experience, or extremely well prepared veterans fail to complete complicated and sometimes unprecedented dives.

Although once enjoyed mainly by adventurous males not overly concerned with personal safety, recreational scuba diving has become no riskier than skiing. The metamorphosis was achieved through decades of improvements in equipment and training. Recreational divers were limited to breathing ordinary compressed air and to depth-and-time exposures that do not require decompression in stages on the way up. These restrictions in turn led to a limit of 39 meters, a depth at which standard tables recommend that a diver spend no more than 10 minutes unless staged decompression is planned.

For the vast majority of divers the 39-meter limit is not onerous. Technical divers, however, use sophisticated methods and equipment, some adapted from commercial and military diving, to go deeper. "It opens up places you can't see any other way, such as deep shipwrecks and caves," says Michael Menduno, editor of *aquaCorps,* a bimonthly magazine devoted to technical diving. "It's not easy, and there is some danger involved," adds Billy Deans, a veteran technical diver who helped to establish the field. "But it is now possible to go to 250 or 300 feet [about 90 meters] with an acceptable degree of risk."

Acceptable, that is, to extremely experienced divers with some cash to burn. The training alone can cost several thousand dollars. And it is not uncommon for a technical diver to step into the water wearing $9,000 worth of equipment, including diapers (a dive to 80 meters, with its staged decompression, can occupy at least two and a half hours).

For the privilege of spending half an hour on the seafloor at 77 meters, a diver would need at least four separate tanks, each with its own breathing rig, or "regulator." Two big bottles of an oxygen, helium and nitrogen "trimix," worn on the back, would cover the descent, a 30-minute bottom interval and just over half of the ascent. Smaller bottles of "nitrox-2" (36 percent oxygen and 64 percent nitrogen) and

DAN BURTON

***TECHNICAL DIVER** Billy Deans shows what it takes to go below 70 meters.*

pure oxygen, strapped to the sides of the body, would be used during the decompression, above 34 meters. The decompression stops—12 in all—would start at 37 meters and continue at three-meter intervals all the way to the surface.

What sights and sensations could possibly justify this kind of danger and expense? The same ones described in almost any escapist novel of science fiction or adventure written in the past century: the thrill of using advanced technology and esoteric techniques to access forbidden regions, some of them beautiful and unexplored. “The areas beyond 130 feet [39 meters] are truly amazing,” Deans says, without quite being able to elaborate.

The increased risk comes from the enclosed environments (wrecks and caves) that are the usual destination and also from the fact that during a decompression dive, any malfunction or mishap must be dealt with deep under water. An ascent to the surface without adequate decompression would almost certainly cause paralysis or death.

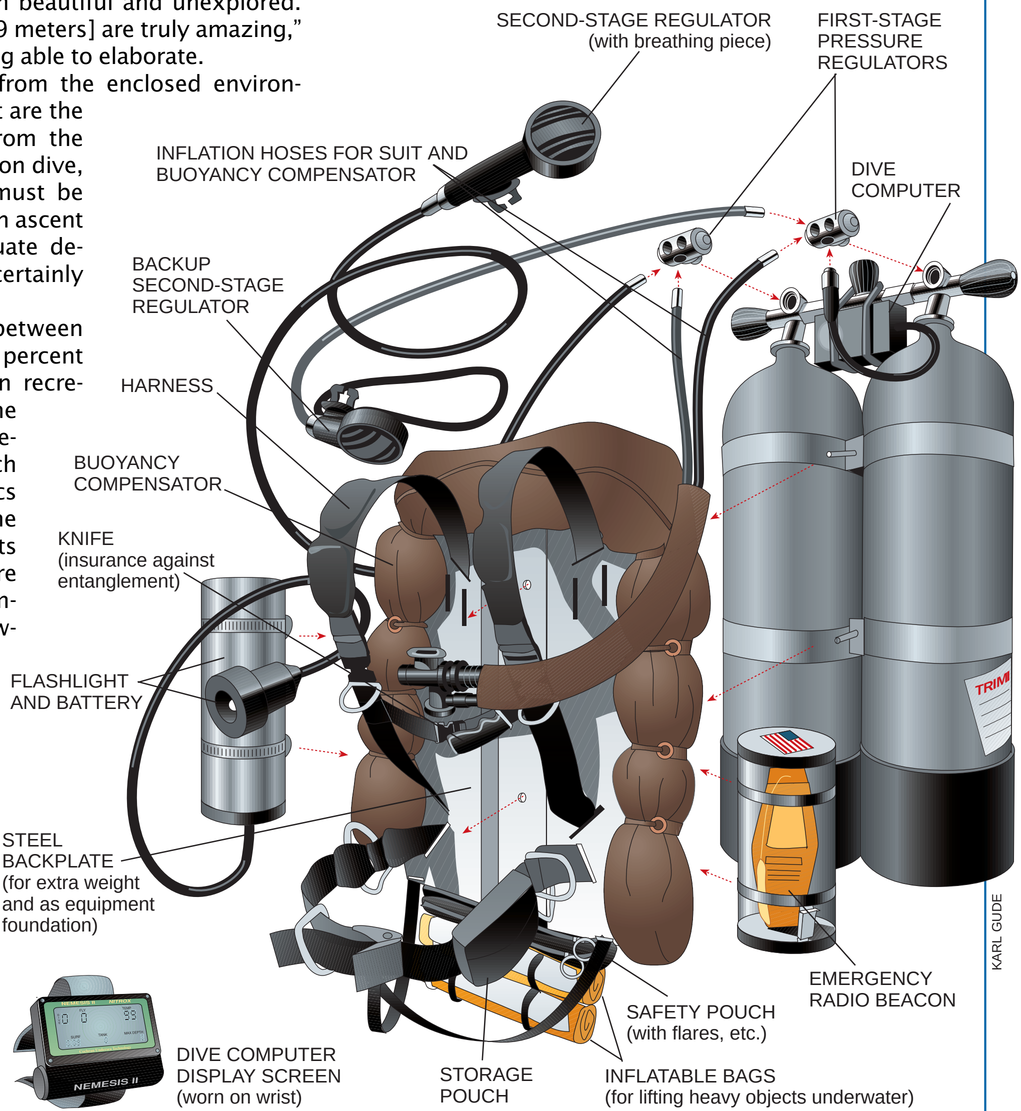
Technical divers make up between one quarter and one half of 1 percent of the estimated three million recreational divers in the U.S. No one seems to doubt that they are seriously injured and die at much higher rates, but the specifics are lacking. And although the technical community is small, its members tend to spend more time in the water, making comparisons difficult. In 1993, however—a particularly bad year—about a tenth of the 92 fatalities of U.S. divers took place during dives that could be considered technical.

Caves are especially hazardous because of the opportunities to get disoriented or trapped. In 1993 seven U.S. explorers fully trained and certified in cave diving died in caves, according to Divers Alert Network, which insures divers and advises physicians on the treatment of diving injuries. In 1994 two died, including Sheck Exley, a pioneering and greatly admired technical diver. This past March two more died in a Mexican cave. In addition, there have been a number of fatalities in recent years on the wreck of the *Andrea Doria* (some 60 divers have died at the wreck—about a dozen more, it has been noted, than the number who drowned when the ship sank in 1956).

Vann, who is also research director of the Divers Alert Network, recalls an avid cave diver who shared his conviction that “the most incredible thing in the world is to swim through this narrow opening into an enormous room that no one’s ever seen before.” This diver died in the narrow opening of a Florida cave not long after.

To its credit, the technical diving community seems to make little or no attempt to downplay the danger. Unlike other diving publications that are for-profit, *aquaCorps* publishes excruciatingly detailed “incident reports” in every edition. “I think it’s important to keep banging away on the safety issue,” says editor Menduno.

Deans, the proprietor of Key West Diver, Inc., one of the oldest facilities for technical diving instruction, has not had a fatality or serious injury in the five years he has been offering this kind of training. Nevertheless, he says he confronts prospective students with their mortality, making them watch a videotape showing the “recovery of the body of an extremely foolish individual who dove [and perished] on the *Andrea Doria*.” When the tape was made, “rigor mortis had set in.... It’s not a pretty sight. He happened to have been my best friend.”



Although improvements in equipment and training will undoubtedly make technical diving less risky, as they did for recreational scuba, danger seems in some ways integral to the activity. For some, it is part of the experience as well. “There’s always a lunatic fringe that gets off on the fact that they might not come back,” Menduno says. “They’re not people I dive with.” —*Glenn Zorpette, staff writer* gesting that individuals with the condition were five times more likely to suffer serious decompression problems. Though not conclusive proof, this statistical correlation has encouraged us to continue studying this mechanism.

Puzzling Neurological Symptoms

Another promising area of research concerns the two major forms of neurological decompression sickness—cerebral and spinal. They have distinct patterns of symptoms, with insults to the spinal cord usually affecting mainly the lower half of the body: leg weakness, loss of sensation and impaired bowel and bladder control. Cerebral bubbles, in contrast, generally manifest themselves as hemiplegia (paralysis of one side of the body), difficulty in speaking, impaired consciousness, personality changes or convulsions. Such cerebral symptoms are relatively uncommon. In fact, a central mystery of neurological decompression sickness is why the spinal cord is so much more frequently affected than the brain.

Cerebral decompression sickness appears to be caused by bubbles that enter the brain via the arterial blood. These bubbles may have several origins, as discussed earlier. Studies by James Francis of the Royal Navy of Great Britain and G. Pezeshkpour, Drew Dutka, John M. Hallenbeck and Ed T. Flynn of the U.S. Naval Medical Research Institute, on the other hand, demonstrated that spinal decompression sickness is most likely caused by bubbles that form within the substance of the cord itself. One hypothesis, which seems to account for differences in both frequency and bubble formation sites, centers on the fact that the spinal cord is subject to continual movement—which, as in the joints, might generate bubble nuclei by viscous adhesion. Moreover, the spinal cord is completely enclosed by a relatively inelastic connective tissue membrane. Noting this fact, Brian A. Hills, then at the University of Texas at Houston, and Philip B. James of the University of Dundee in Scotland presented experimental evidence in 1982 that development of bubbles within the substance of the spinal cord could increase the pressure and cause a secondary reduction in blood flow, compounding the damage initiated by bubbles.

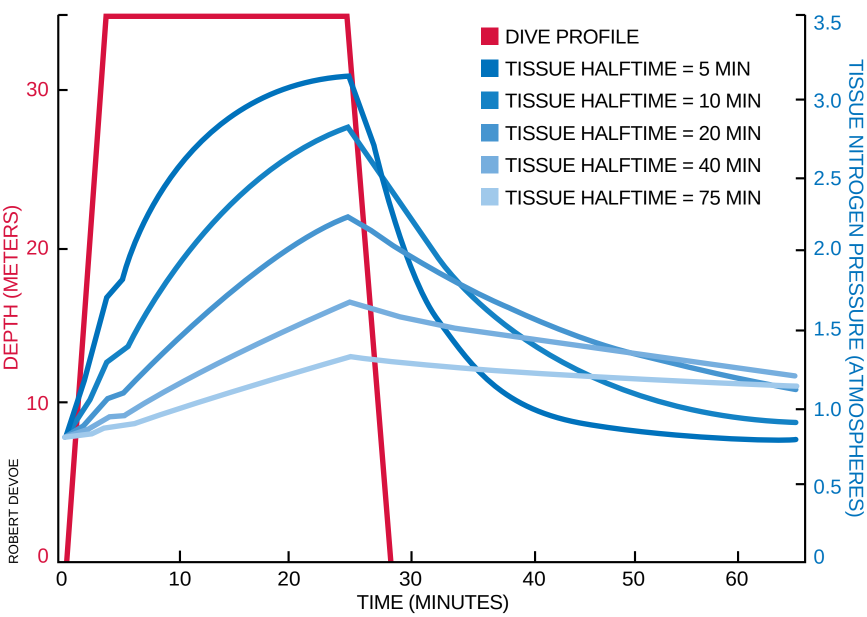
Making Diving Safer

Reducing the risk of getting bubbles in the venous system might seem like a good idea because fewer could enter the arterial system by way of the transpulmonary passage or patent foramen ovale. Toward this end, slower or interrupted ascents may prove useful. Studies using animals have shown fewer bubbles when the pressure was decreased at a rate corresponding to an ascent rate of nine meters per minute rather than 18 meters per minute, the rate traditionally taught to divers.

In practice, it can be extremely difficult for a free-swimming diver, particularly an inexperienced one, to ascend so slowly. Another way of accomplishing much the same result is by interrupting the ascent with a "safety stop" for several minutes at a depth of five or six meters. (Such stops are by definition at the end of dives short enough not to require mandatory decompression stops by standard decompression tables.) Recently Donna Uguccioni, now at the Divers Alert Network, showed that a three-minute safety stop at six meters reduces venous bubbles by 50 percent. Furthermore, slow ascent and safety stops might allow rapidly exchanging neurological tissues, such as the brain and spinal cord, sufficient time to eliminate excess inert gas, thereby reducing the degree of supersaturation and the possibility of bubble growth.

Another method of reducing the dissolved nitrogen tension that induces bubble formation is to breathe higher concentrations of oxygen. When the pressure of nitrogen is higher in the tissues than in the blood, the gas diffuses into the blood, where it can be transported to the lungs and eliminated. The greater the pressure difference, the more rapidly the gas is removed. Breathing pure oxygen helps by increasing this pressure difference. Even if bubbles have formed, oxygen still has value, because their elimination depends on the difference between nitrogen pressure in the bubble and that in the surrounding tissue.

This effect has been known for almost a century and has led to several different applications of oxygen in diving, both in and out of the water. Almost all recreational diving is done with ordinary compressed air, but some specialized or advanced techniques demand breathing mixtures with something other than the usual 21 percent of oxygen. For example, divers on mandated decompression stops sometimes breathe pure oxygen. Scientific, commercial and growing numbers of recreational divers use enriched-air "nitrox" mixtures, with either 32 or 36 percent oxygen. The higher proportion of oxygen enables a diver to stay down somewhat longer at a given depth without needing staged decompression or, alternatively, to use the same profile with a lower risk of decompression sickness.



NITROGEN PRESSURES in tissues increase and decrease at different rates during and shortly after a dive, depending mainly on the affected tissues' blood flow. The pressures are shown here in five tissues, each with a different "halftime"—the time required for the tissue nitrogen to reach half of its possible maximum. While the pressure of the dissolved gas exceeds the ambient pressure, the tissues are said to be supersaturated. Supersaturation is necessary for bubble formation, which can lead to decompression sickness. Such curves only approximate gas behavior in real tissues, which is actually more complex and not fully understood.

Depth limits are important with these high-oxygen mixtures, because oxygen in a breathing mix can produce dangerous toxic effects when its pressure in the mix exceeds 1.5 to 1.7 atmospheres. For a nitrox mixture with 32 percent oxygen, for example, the safer end of this depth limit would be at about 37 meters. In its most serious form, oxygen toxicity manifests as generalized convulsions, which can result in drowning.

Computing Safer Tables

How do we link knowledge of the physiology of decompression sickness with safer and more efficient decompression tables and computer algorithms? Incorporating ideas concerning the physiological mechanisms into mathematical models can guide underwater excursions to minimize the risk of affliction. Typically these models estimate the pressure of inert gas in various types of tissues perfused at different rates. It is assumed that bubbles form when the tissues become supersaturated by some factor, usually around two. This type of model was invented by Haldane almost a century ago.

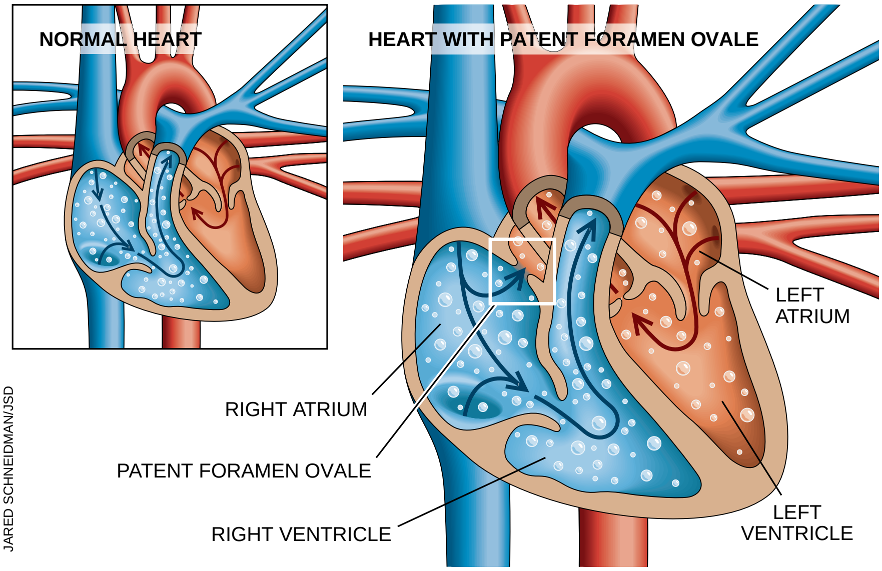
The basic approach has been refined many times over the years, but it is still not totally satisfactory. Recent developments, however, have improved the model or promise to do so. Perhaps the most important advance has been the simple notion that avoidance of decompression sickness is a matter of probability rather than a clear demarcation between safe and unsafe.

This idea, developed in the mid-1980s by Paul K. Weathersby, Louis D. Homer and Flynn of the U.S. Navy, is based on models that estimate the probability of decompression sickness for any given dive. To be done well, the models require large databases with precise details on hundreds of dives that resulted in decompression sickness as well as on thousands that did not. Such databases are ordinarily difficult and expensive to produce; fortunately, the computers that many divers now wear may help. These computers measure and record depth quite accurately and continuously update tissue-nitrogen calculations and can transfer the data to personal computers on the surface.

The significance of the probabilistic method is its more realistic approach to the notion of safety. Like skiing or driving a car, diving has risks that can be reduced but never eliminated. Thus, safety, in this context, can be considered whatever probability of being afflicted with decompression sickness that a diver is willing to accept. Someday diving computers based on probabilistic models should reflect this reality by enabling divers to declare the probability they are comfortable with and then conduct their dives accordingly.

Ideally, these models should be sensitive to individual variations. Current models, no matter how sophisticated, apply only to the "average" diver. For some scuba enthusiasts, such as the tourist we treated in 1988, specific medical conditions or other factors mean that these models may not apply. Even divers without such conditions are subject to fatigue, stress, immunologic variabilities and other factors that might influence susceptibility from one day to the next.

The challenge for the coming decades will be to improve the models while extending them to cover more of the people more of the time. Divers, caisson workers, pilots and astronauts stand to benefit, of course. So, too, does anyone interested in the ways the human body responds to the greatest environmental and physiological stresses its habitat has to offer.



VENOUS BLOOD (*blue*) is separated within the normal heart from arterial blood (*red*) being pumped to the tissues, resulting in almost all the venous bubbles being trapped by the lung capillaries. At least 10 percent of the population, however, has a small opening, known as a patent foramen ovale, between the left and right atria. It can allow bubbles to cross into the arterial system, through which they may cause damage in the brain and other organs.

The Authors

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Frog Communication

In striving to be heard by rivals and mates, these amphibians have evolved a plethora of complex strategies

by Peter M. Narins

When the sun sets behind the peak of El Yunque in Puerto Rico, the hillside comes alive with sound. But not exactly with song. The calls of myriad forest creatures build up to a cacophony as loud as a subway train passing six meters away. One particular bellow is apt to make my uninitiated students jump and clap their hands to their ears, shouting, "What *is* that?" More often than not, it is the *Eleutherodactylus coqui,* or coqui, a 36-millimeter-long amphibian that is the star, amazingly enough, of local lullabies—as well as of my ongoing studies on frog signals.

In 1970, as a young electrical engineer looking for a research project in communications, I chanced on Robert R. Capranica of Cornell University describing an experiment with the North American bullfrog. Electronically synthesizing its mating call, he broadcast it to a captive male, which instantly emitted a similar bellow. But when Capranica presented the croaks of 34 other species of frogs and toads, not once did the bullfrog respond. Capranica also found that both frequency bands present in the call were needed to elicit a reply.

I began to wonder how the subtleties of these sounds related to the environments for which the frogs are adapted. Two decades later I am still studying that problem. For the most part, the calls seem to be solutions to the challenge of signal processing in the presence of noise. Most frogs live in rain forests, which also support numerous other signaling creatures. The small number of sounds a male frog produces has to be easily distinguished from those of other individuals and species in the acoustically complex environment. (Female frogs, on the other hand, rarely call.)

One amphibian strategy, that of spectral separation, is also utilized by radio stations in a large city, which each transmit within a separate segment of the electromagnetic spectrum. In a rain forest, different amphibian "users" of the acoustic space may likewise occupy private channels. Nearly every species of frog in the Caribbean National Forest, where El Yunque is located, seems to call within a band of frequencies not shared by any other group. Such a separation persists even though the frequencies are constrained by other factors. Large frogs have deep voices—that is, they call at low frequencies; small frogs emit high chirps. Because coquis at higher elevations of El Yunque are—for unknown reasons—larger, their voices are deeper. And cold frogs repeat their calls at slower rates, because the muscles controlling the sounds slow down.

The frequencies claimed by a species are used with much efficiency. The coqui has a simple, two-note, *co-qui* call. The *co* note, at about 1,160 hertz (for a male at an altitude of 900 meters), appears to indicate territorial boundaries to other males: on presenting a signaling male with the calls of another, we found that the first dropped its *qui* note and called exclusively *co.* Nor did

MALE COQUI FROGS in the Caribbean National Forest of Puerto Rico vie for the attention of a female (*left*) by treating the animal to sounds as loud as an 18-wheel truck seven meters away.

the first male care if the call was electronically changed to *qui-co.* The *qui* note, on the other hand, entices females. Neurophysiological studies show that a large population of auditory neurons found exclusively in female coquis are maximally sensitive around 2,090 hertz, in the frequency range of the *qui.*

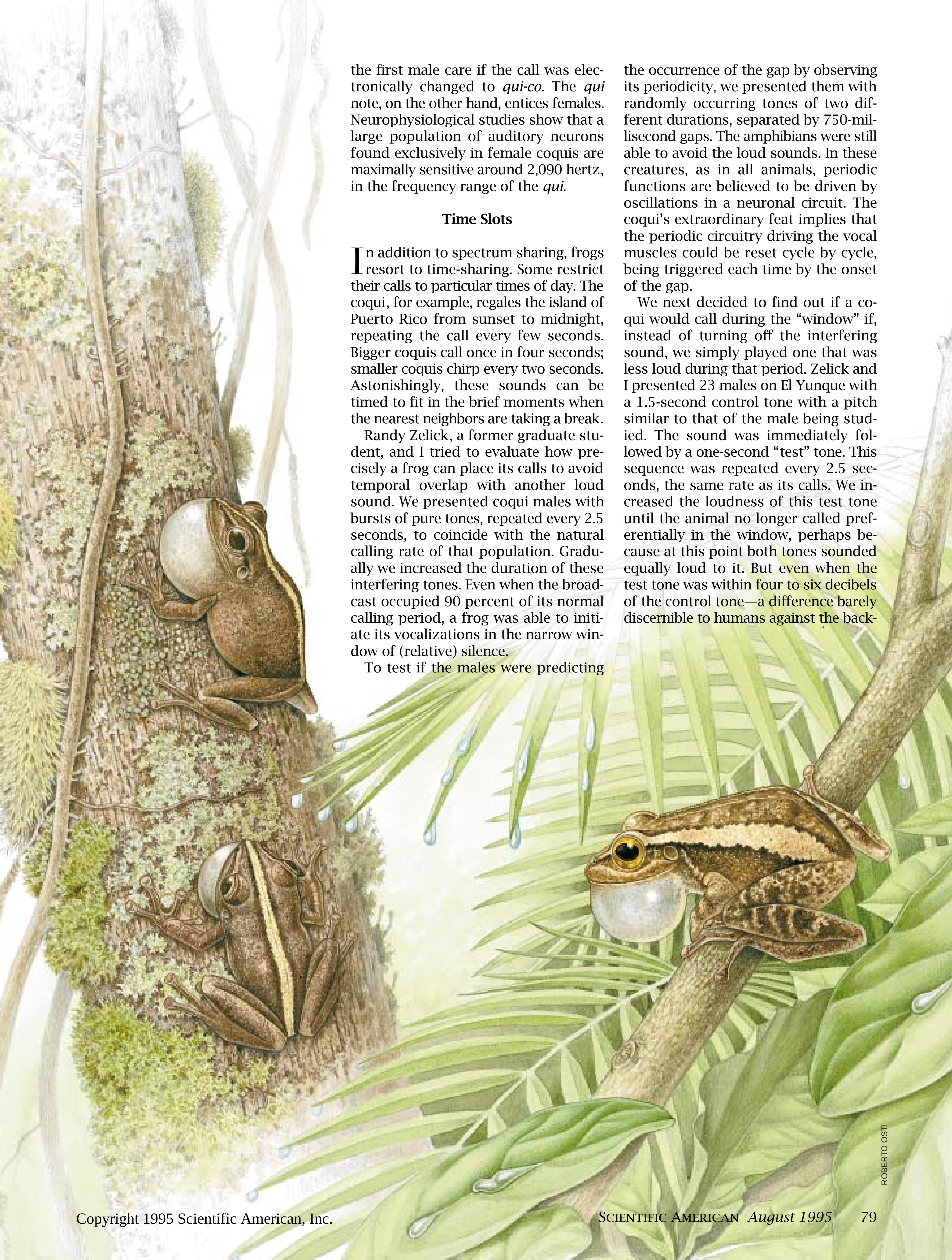
Time Slots

In addition to spectrum sharing, frogs resort to time-sharing. Some restrict their calls to particular times of day. The coqui, for example, regales the island of Puerto Rico from sunset to midnight, repeating the call every few seconds. Bigger coquis call once in four seconds; smaller coquis chirp every two seconds. Astonishingly, these sounds can be timed to fit in the brief moments when the nearest neighbors are taking a break.

Randy Zelick, a former graduate student, and I tried to evaluate how precisely a frog can place its calls to avoid temporal overlap with another loud sound. We presented coqui males with bursts of pure tones, repeated every 2.5 seconds, to coincide with the natural calling rate of that population. Gradually we increased the duration of these interfering tones. Even when the broadcast occupied 90 percent of its normal calling period, a frog was able to initiate its vocalizations in the narrow window of (relative) silence.

To test if the males were predicting the occurrence of the gap by observing its periodicity, we presented them with randomly occurring tones of two different durations, separated by 750-millisecond gaps. The amphibians were still able to avoid the loud sounds. In these creatures, as in all animals, periodic functions are believed to be driven by oscillations in a neuronal circuit. The coqui's extraordinary feat implies that the periodic circuitry driving the vocal muscles could be reset cycle by cycle, being triggered each time by the onset of the gap.

We next decided to find out if a coqui would call during the "window" if, instead of turning off the interfering sound, we simply played one that was less loud during that period. Zelick and I presented 23 males on El Yunque with a 1.5-second control tone with a pitch similar to that of the male being studied. The sound was immediately followed by a one-second "test" tone. This sequence was repeated every 2.5 seconds, the same rate as its calls. We increased the loudness of this test tone until the animal no longer called preferentially in the window, perhaps because at this point both tones sounded equally loud to it. But even when the test tone was within four to six decibels of the control tone—a difference barely discernible to humans against the back-



ROBERTO OSTI

ground noise of the forest—59 percent of the males were able to place their calls in the window. Such a small shift in intensity was apparently sufficient for resetting their neural oscillator.

Ear-Splitting Decibels

Despite such sensitive adaptations, neatly partitioning frequency and time among all local frog species is not always possible. So various other strategies have evolved. Males of many species produce a periodic, stereotyped call that increases redundancy, so that the caller can be identified and located even if some of its croaks are drowned out. Moreover, the eardrum and other parts of the auditory receptors of an amphibian are tuned to the tone and characteristic period of that species' call, allowing for sharp, selective hearing.

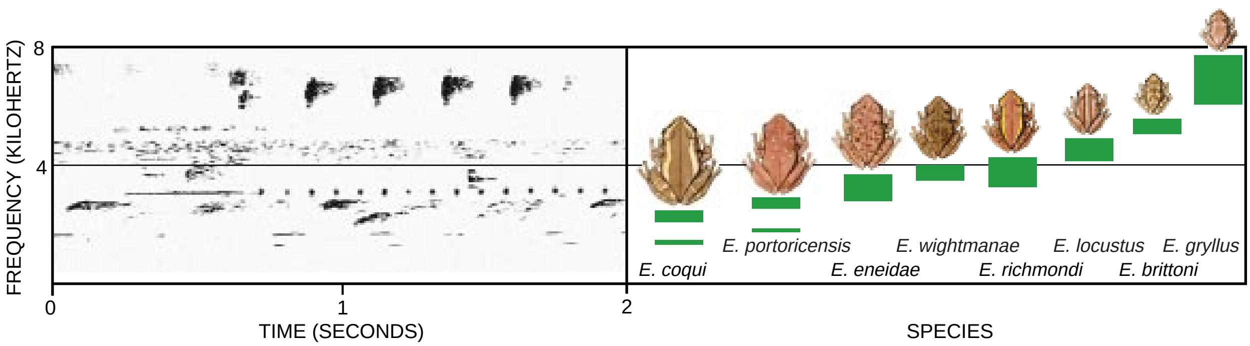
By far the most obvious adaptation is loudness. In forested areas one male coqui occurs in every 10 square meters, so it is subjected to intense pressure to drown out its neighbors for the benefit of a distant female. A coqui sitting half a meter away calls at between 90 and 95 dB SPL, close to the human threshold of pain. (SPL, for sound pressure level, refers to the lowest pressure difference audible to the human ear at 1,000 hertz, $P_0 = 0.0002$ dyne per square centimeter. Sound pressures P are described in decibels with respect to this standard, as $\text{dB} = 20 \log P/P_0$. A jackhammer, for example, produces noise that is 100 dB SPL.) As a result, the male is exposed to potentially damaging levels of sound from its own call for 11 months a year.

Wondering how such a small creature protects itself from its own racket, I decided to measure how loud it sounds at the ear. In the early evening, as a coqui chirped in the vegetation near El Verde, I carefully extended a probe microphone to within 13 to 35 millimeters of its eardrum. Peak levels of its *co* and *qui* notes at such distances were an ear-splitting 114 and 120 dB SPL, respectively.

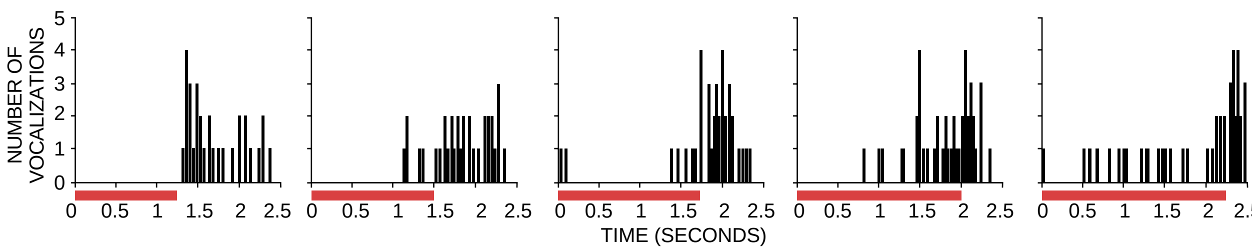
Although these external pressures are very high, the amount by which the eardrum moves—and thereby stimulates or possibly overstimulates the sensitive inner ear—also depends on the pressure inside the eardrum. Male frogs vocalize by squeezing their lungs with their nostrils and mouth shut. Air is forced over the vocal cords and into a

Sharing Spectrum and Time

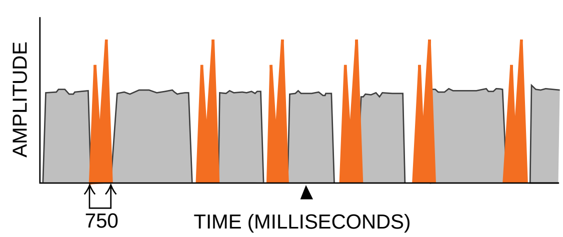
Tone and timing help to distinguish the calls of different forest creatures. A two-second sound spectrogram, taken near El Verde in Puerto Rico, analyzes the frequencies in the sounds made by eleutherodactylid frogs (*below*). In addition to repeating its signals at different rates, each species occupies a well-defined frequency range (*green bands*).



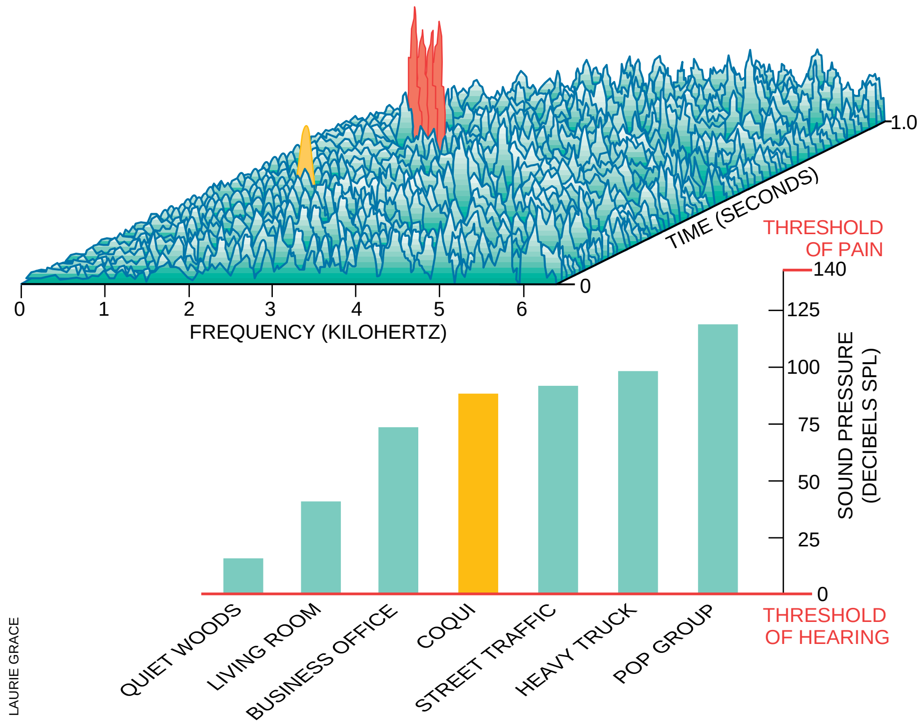
Experiments on a male *E. coqui* demonstrate that the animal can also time its calls so that they do not coincide with those of its neighbors (*below*). A loud tone of different durations (*red bars*) was played to the coqui and was repeated 65 times, every 2.5 seconds, to simulate the rate of the frog's own signals. Even when the tone occupied 2.25 seconds out of its calling period (*far right*), the coqui was still able to place most of its calls in the 0.25-second "window" of silence.



Further, a coqui can call within this gap even if its call does not recur periodically and is thus unpredictable (*right*). Two notes of different duration (*gray*), separated by 750-millisecond gaps, were played in random sequence. The coqui called reliably (*orange peaks*) within the gaps. Had the frog kept signaling at the rate of the first two calls, the animal's third call would have coincided (*arrowhead*) with an interfering tone.



JOHNNY JOHNSON AND ROBERTO OSTI



SOUND LEVEL in the forest, as heard by a coqui, is measured by the peak velocity of vibrations of the frog's eardrum (*top*). The membrane responds vigorously to the coqui's own call: *co-qui* (*co* is yellow; *qui* is red); the higher-frequency peaks are caused by other frogs and insects. The coqui's loudness (*bottom*) places the 36-millimeter-long amphibian in the same class as street traffic.

closed system of chambers that includes the mouth cavity. A thin-walled sac at the base of the mouth then blows up like a balloon, radiating the call from the vocal cords into the environment.

To learn how much the eardrum actually moves as a coqui calls, I collected 10 of the loudest males from the trees around the field station in El Verde and flew with them to the University of Konstanz in Germany. I had arranged to collaborate with neuroethologists Günther Ehret and Jürgen Tautz, using their laser Doppler vibrometer (LDV), which produces a low-powered helium-neon laser beam. When the beam is aimed at a male frog's eardrum, some of the light scattered by the membrane reenters the laser. If the eardrum is stationary, the wavelength of the returned light is the same as that of the outgoing laser beam. But if the wavelengths differ, the LDV calculates the velocity with which the eardrum moves and from that, the amount it moves—to within a billionth of a meter.

We set up 10 individual aquariums for the displaced males, complete with tropical plants, high temperature and humidity to simulate their home. Much to our chagrin, not one of the frogs called at all for the three weeks I was there. We concentrated on measuring their eardrum displacement in response to the playback of a coqui's call, adjusted so that the levels of the *co* and the *qui* notes at the eardrum were 66 and 73 dB SPL, as they would be for a neighbor's call in the wild.

Our experiments serendipitously offered a very interesting observation. The experimental protocol involved a double-blind format in which I aimed the laser at the eardrum and presented the call, 130 times, while Ehret and Tautz monitored the eardrum response. Then we ran a control trial, in which I aimed the laser at a point on the skull while the call was rebroadcast, to ensure that the entire frog was not vibrating in response to the sound. (We had earlier discovered that shining the laser beam on the frog in the darkened laboratory would make it completely immobile.) We subtracted the control spectra from the experimental spectra to get the net motion of the eardrum.

Late one night my hand slipped during a control run, and I inadvertently aimed the laser to one side of the frog. To our astonishment, the LDV revealed that the skin overlying the lungs was clearly vibrating in response to the sound. We immediately proceeded to "map" the frog's body. It turned out that a small region of the lateral body wall responded to sound, and it was only slightly less sensitive than the eardrum [*see top illustration on next page*].

Next we measured the pressure fluctuations inside the mouth cavity as a small speaker pressed to the lateral body wall applied sound. With Barbara Schmitz, also at the University of Konstanz, we showed that these sounds caused the eardrum to vibrate. These studies indicated an unbroken air link from the lung to the eardrum. Such an internal pathway suggests not only how frogs locate the source of a sound but also how they protect themselves from their own calls.

Saving the Ear

Our own ears and those of other mammals and birds are pressure receivers: the eardrum is stimulated by sound coming from the outside, while the inside remains at constant pressure. A receptor of this type cannot distinguish between directions. (At rather high frequencies, however, the waves have lengths that are small enough to be blocked by the head, allowing for some directionality.) The origin of a sound is usually sensed by analyzing both the time of arrival and the intensity differences between the two ears.

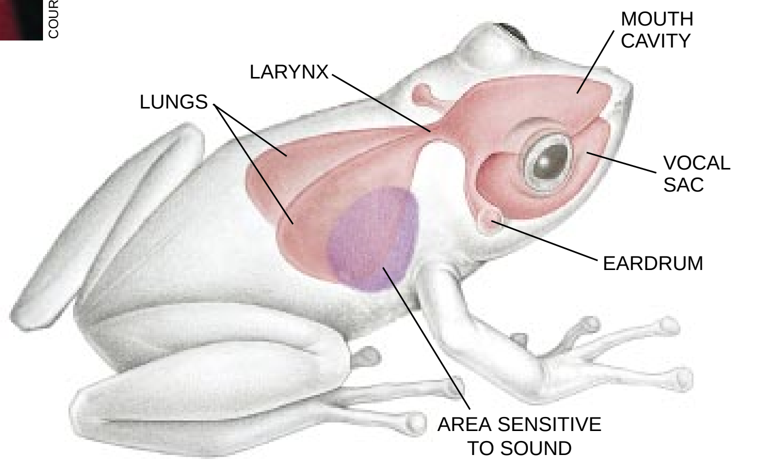
In a pressure-gradient receiver ear, such as that of many insects, the sound reaches both sides of the eardrum, which reacts according to the pressure difference across it. This type of ear is inherently directional, because the pressure (or phase) that sound presents at either side depends on how much farther it has to travel to get to one side than to the other. The path lengths depend, in turn, on the angle at which the sound is incident. Comparison between two ears can enhance directionality [*see bottom illustration on next page*].

Frogs have an intermediate arrangement. Their ears are asymmetrical pressure-gradient receivers: sound impinges on both sides of the eardrum, but with unequal pressures, the difference between which is measured. This receiver is also directional, but more complex than the insect ear. At the internal surface, sound arrives by at least two routes—via the opposite ear and through the acoustic pathway from the lungs.

The air routes suggest a novel way in which frogs might protect themselves from overstimulation. When a male calls, the high air pressure in its mouth cavity is communicated to the eardrum, which bulges out. Because that membrane is pulled tight, the response to sound is dampened. In addition, sounds generated by the vocal cords impinge both on the inner surface of the eardrums and on the outer surface, after being radiated from the vocal sac. If the sounds arrive nearly in phase—so

COURTESY OF PETER M. NARINS

AIR PATHWAYS connecting a coqui's lungs to its ears were discovered inadvertently, by laser measurements made of the frog's body wall (*left*). The helium-neon laser beam revealed that part of the skin vibrates in response to sound, communicating the motion to the lungs and indirectly to the eardrum. Apart from allowing the frog to hear through its sides (*below, purple area*), the internal airways (*pink*) may help protect the ears from being damaged by the loudness of the frog's own calls. The sound, after being radiated by the vocal sac, reaches the eardrum both by internal routes and from the outside, so that its effects on the eardrum largely cancel out.



ROBERTO OSTI

that periods of high pressure coincide on both sides—the eardrum will not move much in response.

To test this theory by observing the eardrum motion of calling frogs, we had to return to El Verde. Pamela Lopez, my graduate student at the time, and I used a portable LDV for the delicate measurements. Because the target has to be extremely stable, we were restricted to studying only those individuals calling from solid objects, such as large tree trunks or houses. More problematic was that the coqui call most vigorously in humidity approaching 100 percent, during or just after rain. The LDV does not operate in rain, because the laser beam must be uninterrupted on its way to and from the target.

That summer was one of the driest on record for Puerto Rico. To induce the frogs to call, we found that spraying water on the test animal for a few minutes worked very well. The other problem we faced was that the laser required a 110-volt power source. Fortunately, local residents were most cooperative when asked if we could plug in our extension cord to make laser measurements on a frog's eardrum.

Our results confirmed that the eardrum does in fact vibrate in response to a male's own call, but with a very small vibration amplitude. We are now investigating the phases at which sound arrives on the inner and outer sides of the eardrum to test the theory further.

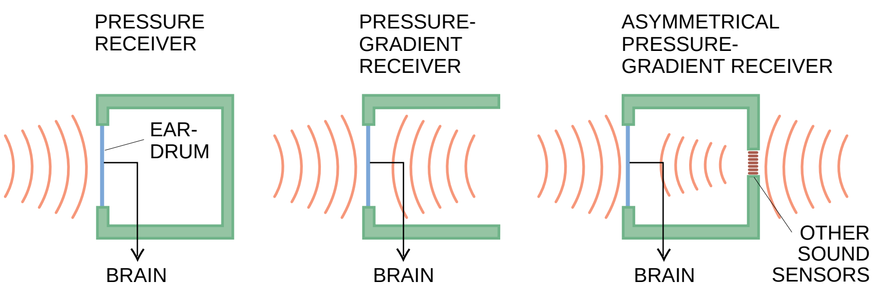
Ground Sound

A few frogs, unable to compete with the coqui and others in loudness, shrillness or persistence, exploit entirely different media. The white-lipped frog *Leptodactylus albilabris,* a ground-dwelling, nocturnal creature found along marshes, ditches and mountain streams throughout much of Puerto Rico, employs this tack. Males call from within clumps of dense grass, under fallen vegetation or from shallow depressions or burrows in the muddy soil. (Females of the species are camouflaged and silent.)

The night I first heard a white-lipped frog, I carefully approached it, but he instantly ceased calling. After several futile attempts, I managed to capture some calling males and bring them back to California. In the laboratory of Edwin R. Lewis at the University of California at Berkeley, we investigated the frog's extraordinary sensitivity to my distant footfalls. Transmitted through the ground, the steps must have made the frog shake. But how did the creature detect such delicate vibrations?

We found a population of nerve fibers originating in the inner ear of this frog that responded vigorously when it was vibrated at frequencies between 20 and 160 hertz. The most sensitive fibers responded to peak accelerations of about 0.000001 g (where $g = 32$ feet per second squared, the acceleration caused by gravity), making them 100 times more sensitive than mammalian inner-ear organs.

Vibration sensitivity of frogs and toads is known to reside in the sacculus of the inner ear [see "The Hair Cells of the Inner Ear," by A. J. Hudspeth; SCIENTIFIC AMERICAN, January 1983]. In the white-lipped frog, this organ consists of a sac filled with a slurry of dense calcium carbonate crystals, resting on 600 sensory hair cells. When the animal shakes, the upper surface of the hair cells and the roots of the hairs move back and forth; the massive sac



JOHNNY JOHNSON

THREE TYPES OF EARS prevail in the animal kingdom. In the pressure receiver (*left*), common to birds and mammals, the eardrum responds to the pressure variations of sound impinging from the outside, while the inside remains at constant pressure. A single ear cannot distinguish direction. In the pressure-gradient receiver (*center*) of many insects, sound reaches both sides of the eardrum, which responds to the pressure difference across it. One ear alone can detect the source of a sound. In the asymmetrical pressure-gradient receiver (*right*) found in frogs, sound impinges on both sides of the eardrum, but with unequal pressures. This ear is also directional.

at the tips of the hairs remains stationary because of inertia. As a result, the hairs bend, modulating the normal discharge rate of the nerve fibers.

But a seismometer as sensitive as that of the white-lipped frog must have some function other than detecting the presence of researchers. To investigate this possibility, Lewis and I used a geophone. This device consists of a coil held by a spring within a strong magnetic field; vertical movements of the earth generate a voltage in the coil. Connecting amplifiers and headphones and placing the geophone near a calling white-lipped frog, we were quite pleased to find that it recorded a heavy thump simultaneously with the call.

After a rain, the male white-lipped frog buries its rear end in muddy soil, leaving its head and forelimbs exposed. When the frog croaks, its vocal pouch expands explosively, striking the ground. The impact generates a Rayleigh wave of vertical vibrations that travels along the ground's surface at roughly 100 meters per second (and with a peak acceleration of 0.002 g at a distance of one meter). The energy in this wave contains frequencies in the same range in which we had found the nerve fibers to be most sensitive.

To test if the thumps were being detected by the neighboring white-lipped frogs, Lewis and his colleagues constructed a "thumper" from the solenoid of an electric typewriter. We triggered the device with a tape recording of a male's call, thus simulating the animal's thump rate and pattern. Even though we insulated the thumper so that the airborne sounds it made could not be heard, males within three meters of our artificial frog consistently entrained their calls to its, producing a chorus.

We do not yet know if the males respond differently to the acoustic and seismic components of a neighbor's call. Although vibrations are usually associated with bulk movements of the body, and sound with airborne pressure changes impinging on the ears, the perception of these stimuli appears to be intimately related. Recent studies of leopard frogs in our laboratory and elsewhere have revealed two significant populations of nerve fibers. One set originates in the amphibian papilla, a low-frequency sound sensor, and the other set in the sacculus, with its vibration-sensitive hair cells. But both bundles of fibers respond to sound as well as to vibrations. The main difference between sound and vibration in this case could well be the route these stimuli take to reach the sensors. Such pathways have not been fully elucidated.

In addition to the white-lipped frog, three other species of vertebrates—the blind mole rat of Israel (*Spalax*), the Cape mole rat of South Africa (*Georychus*) and the bannertail kangaroo rat of the U.S. Southwest (*Dipodomys*)—have now been shown to communicate seismically. Recently Albert S. Feng of the University of Illinois, Jakob Christensen-Dalsgaard of Odense University and I discovered that one species of Malaysian tree frog (*Polypedates leucomystax*) exhibits a particularly unusual behavior. During courtship, females living in dense mats of floating vegetation perch on a reed or blade of grass and tap their rear toes rhythmically. This activity occurs in the dark, persists for several minutes and is only occasionally accompanied by calls. Males on neighboring reeds quickly locate and mate with the tapping female.

The taps seem to serve as vibrational signals that indicate the female's presence. This behavior is remarkable: in most tree frog species, stationary males call, and females localize them. Also, this is the first time a terrestrial vertebrate has been found to transmit seismic signals through a substrate other than earth. Probably, the different environments in which frogs live offer several other media that are likewise being exploited. I expect to spend many more years deciphering these diverse signals.

ALBERT S. FENG *University of Illinois*; © SPRINGER-VERLAG

PETER M. NARINS

DIVERSE MEDIA are exploited by frogs in propagating their calls. The female Malaysian tree frog (*top*) attracts the smaller males at night by tapping its toes on a reed. A male white-lipped frog from Puerto Rico (*bottom*) not only calls but also transmits vibrations through muddy ground. Nearby males entrain their thumps to others', creating a chorus.

The Author

PETER M. NARINS has studied communication in frogs, golden moles, krill, forest birds and Cape mole rats across all seven continents. After earning a master's degree in electrical engineering in 1966 from Cornell University, he went to Chile as a Peace Corps volunteer for three years. Returning to Cornell, he completed a doctorate in neurobiology and behavior in 1976. Two years later he joined the faculty of the University of California, Los Angeles, where he is a professor of physiological science. In his free time he enjoys amateur radio, playing guitar and watching birds.

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JAMES V. SCOTTI

HEIDI B. HAMMEL AND NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Comet Shoemaker-Levy 9 Meets Jupiter

Images of a comet that broke apart and plummeted into Jupiter continue to dazzle astronomers a year afterward

by David H. Levy, Eugene M. Shoemaker and Carolyn S. Shoemaker

We were working underneath the dome of the small Schmidt telescope at Palomar Observatory in California, in a cramped room cluttered with papers, books and a laptop computer. It was May 22, 1993. Carolyn sat hunched over her stereomicroscope, an instrument she has used to examine photographs for asteroids and comets for more than a decade, since she joined her husband, Gene, in his survey of these small wanderers in the sky.

Gene has spent a significant part of his career examining such objects. His studies in the 1950s demonstrated how the large pockmark in the desert east of Flagstaff, Ariz., formed after a small asteroid struck the earth. He later investigated craters on our own moon and on the moons of the outer planets, as well as the remnants of ancient collisions in the Australian outback. More recently Gene, along with Carolyn, has been engaged in a systematic search for asteroids capable of striking the earth.

Peering at his computer that day, David checked his E-mail to see whether any newly detected comets or asteroids needed to be added to the observing schedule. Writer and lecturer by day, amateur astronomer by night, David has accumulated 21 comet-hunting trophies, eight of them for sightings he made using a 16-inch-diameter telescope in his backyard. Since joining forces in 1989, we three together have found 13 comets. Despite this level of combined experience, the revelation of May 1993 took us—and the rest of the scientific community—by complete surprise.

David's E-mail conveyed astonishing news from the International Astronomical Union's Central Bureau for Astronomical Telegrams—a kind of wire service for astronomers. A comet we had discovered two months earlier would strike Jupiter in July 1994. After a professional lifetime examining impact craters and the bodies that make them, Gene might actually get to see a collision.

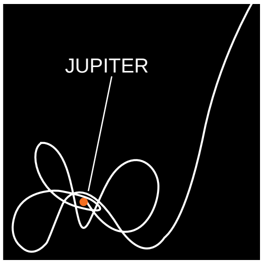
The Impact of Impacts

As anyone who has gazed at the moon through even the smallest telescope knows, the lunar surface is studded with impact craters. The moon itself probably formed from the remains of a collision. During our planet's youth, a body the size of Mars may have

SHOEMAKER-LEVY 9 first appeared in the form of a flattened comet with wings extending from either side. More detailed images revealed that the comet was composed of a train of distinct nuclei. These fragments collided with Jupiter just 16 months after their discovery, each leaving a huge and curiously shaped dark blemish on the planet.

The Comet Chronicles

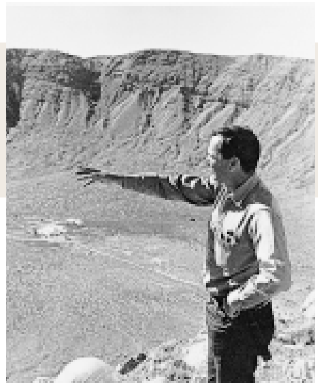
The collision of a large comet with a planet is an exceedingly rare occurrence, and astronomers now appreciate their good fortune that the impact of Shoemaker-Levy 9 with Jupiter came in 1994—and not in any earlier year. A series of celestial and human developments led to the discovery that S-L 9 would strike Jupiter and allowed scientists to witness the comet's final fireworks in magnificent detail using the *Hubble Space Telescope.* Some key events are noted here.



SOURCE: PAUL W. CHODAS

1929: A short-period comet becomes captured into an unstable polar orbit around Jupiter at about this time.

1956: Eugene Shoemaker completes doctoral studies of how a small asteroid carved a huge crater in the Arizona desert 50,000 years ago.



COURTESY OF EUGENE SHOEMAKER

KEITH SCHREIBER

1960: David Levy acquires his first telescope, a 3.5-inch reflector. Curiously presaging his later triumph, his first astronomical sighting is of Jupiter.

struck the earth, melting it and sending into orbit a stream of debris that eventually congealed to form the moon [see "The Scientific Legacy of Apollo," by G. Jeffrey Taylor; SCIENTIFIC AMERICAN, July 1994]. Tectonically static and without air or water, the moon can retain its crater-scarred face indefinitely. Erosion and the deposition of sediments constantly smooth the earth's surface, which consequently shows few craters, although our world has been hit far more often than the moon. For example, comets showered the earth during its formative period between 3.9 and 4.6 billion years ago, bringing carbon, hydrogen, nitrogen and oxygen—critical elements that allowed life to evolve.

Such collisions have also taken life away. Sixty-five million years ago an object somewhat larger than Halley's comet slammed into what is now the coast of Mexico's Yucatán peninsula. The impact gouged a crater 170 kilometers across and launched debris worldwide. As the multitude of tiny ballistic missiles fell back toward the earth, meteors filled the sky, and the atmosphere became red-hot. Fires erupted over the earth's surface, but the global inferno was soon followed by persistent darkness, as dust lifted into the atmosphere blocked the sun's rays. Months of planet-wide cooling then gave way to centuries of greenhouse warming from the carbon dioxide released during the impact from the target rocks. Many species became extinct.

That ancient catastrophe demonstrates that projectiles from space can indeed affect this planet significantly. Our research program at Palomar was one of several designed to assess the rate at which interplanetary intruders of this kind collide with the planets and satellites. We did not, however, expect to witness such a colossal impact in the near future.

A Lucky Discovery

Our discovery of the comet began quietly enough. Little could we imagine then that we were about to make some of the most important observations of our lives. It was a dark and soon-to-be stormy night—March 23, 1993—that found us at our usual tasks, around the smallest of Palomar Observatory's four regularly used telescopes, an instrument with a 26-inch mirror and an 18-inch correcting lens designed to survey broad areas of the sky. We were accompanied on this observing run by Philippe Bendjoya, an astronomer visiting from the University of Nice.

Clouds slowly filled the sky, and although the haze did not completely hide the heavens, we knew it would obscure fainter stars, asteroids and possible comets on our films. So we stopped our normal observing routine. Instead we decided just to expend some film we knew had been partially exposed to light. (The poor weather conditions seemed to merit using this problematic film.) One of our standard fields of view contained the planet Jupiter and was in the clear. We took three exposures—one with Jupiter and two of nearby parts of the sky—before clouds closed the gap. Later that night a short break in the overcast allowed us to take a second view of the Jupiter field.

Two days later Carolyn began scanning the images taken on that cloudy night. Using her stereomicroscope, she was looking for the three-dimensional effect caused by the slight shift in position of an asteroid or comet relative to the background stars. Suddenly she sat up straight in her chair and announced, "I don't know what this is, but it looks like a squashed comet." Carolyn was not exaggerating. The object really did look like a comet that someone had stepped on. A typical comet has a nucleus several kilometers across composed of ices, rocky material and organic compounds. When it nears the sun, the ices turn directly from solid to gas and release dust to form a light-scattering halo called a coma. The pressure of solar radiation then blows this material into an elongate tail. But instead of a single coma and tail, our new comet had a bar-shaped agglomeration of comae, with a composite tail stretching to the north. The strangest observation was that on either end of the bar was a pencil-thin line of light.

Our weird discovery needed confirmation with a better telescope. We contacted our colleague James V. Scotti of the University of Arizona, who was observing that night from the Spacewatch telescope atop Kitt Peak in Arizona. Jim agreed to take high-resolution television images of the comet. He was stunned. "There are at least five discrete comet nuclei side by side," Scotti explained to us over the telephone as he described the view, "but comet material exists between them. I suspect that there are more nuclei that I'll see when the sky clears."

We immediately reported this bizarre comet to Brian G. Marsden, director of the Central Bureau for Astronomical Telegrams at the Harvard-Smithsonian Center for Astrophysics, and Scotti followed with his observations. The next

1982: Carolyn Shoemaker joins her husband in his search for comets and asteroids. They use a specially constructed stereomicroscope to compare two images of the same part of the sky taken at different times.

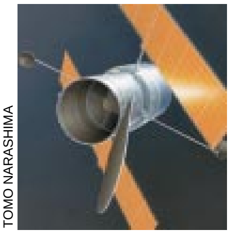
TERENCE DICKINSON

NASA

1986: *Challenger* explodes during liftoff, grounding the fleet of space shuttles and delaying the launch of the *Hubble Space Telescope* and the *Galileo* probe.

1989: David Levy joins Eugene and Carolyn Shoemaker in the hunt for comets and asteroids using a telescope at Palomar Observatory in California.

ALAN LEVENSON



TOMO NARASHIMA

1990: *Hubble* is placed into orbit by the space shuttle *Discovery,* but many technical problems plague the telescope, including a flawed main mirror.

day Marsden's office announced the discovery. The description of the object was so unusual that astronomers around the world began to examine it at once. Jane Luu of Stanford University and David Jewitt of the University of Hawaii obtained a magnificent image using the 88-inch reflector at Jewitt's institution. They later resolved 21 separate nuclei strung out, they wrote, "like pearls on a string."

In accordance with a tradition that has gone on since the time of the French comet hunter Charles Messier more than two centuries ago, this comet was named after its discoverers. Because it was the ninth in a series we had found that traveled around the sun in short-period orbits, it took the formal title "Periodic Comet Shoemaker-Levy 9." We call it S-L 9, for short.

Close Encounters

By the middle of April 1993, Marsden, Syuichi Nakano in Japan and Donald K. Yeomans of the Jet Propulsion Laboratory in Pasadena, Calif., had determined that the comet we had uncovered was actually in an orbit about Jupiter. They also ascertained that the comet had passed very close to the planet about eight months before we located it. Such proximity would explain why there were multiple fragments.

On July 7, 1992, S-L 9 had approached within about 20,000 kilometers of Jupiter's cloud tops. As it made a hairpin turn around the giant planet, it came apart because the pieces nearest Jupiter were deflected more sharply than those farther away. The difference in orbital paths resulted from the decrease in the strength of Jupiter's gravitational attraction between the near and far sides of the comet. The stress on S-L 9 was extremely weak, but it nonetheless broke up the comet easily. This behavior suggests that the original body was merely a pile of fragments held together by their weak gravitational attraction for one another.

Although astronomers had earlier established that comets have orbited Jupiter for brief periods in the past, S-L 9 is the first comet that anyone has seen in orbit about a planet. Jupiter indeed had not one but 21 tiny new moons. Yet these recently acquired satellites were not to last long. After further calculations, Marsden announced that the fractured comet would crash down on Jupiter in July of 1994.

Astronomers and planetary scientists immediately wondered what the impacts would entail. Would they see immense fireworks during the collisions, or would the event be a cosmic fizzle? H. Jay Melosh of the University of Arizona, for instance, suggested that the comets would penetrate so deeply into Jupiter's atmosphere before exploding that the planet would essentially swallow them with scarcely a trace. In contrast, Thomas J. Ahrens and Toshiko Takata of the California Institute of Technology, Kevin Zahnle of the National Aeronautics and Space Administration Ames Research Center and Mordecai-Mark Mac Low of the University of Chicago all proposed that each nucleus would dig a "tunnel of fire" in Jupiter's atmosphere, explode and send a spectacular fireball back into space through the newly excavated cavity. David A. Crawford and Mark B. Boslough of Sandia National Laboratories believed a tremendous plume of hot gas would erupt chiefly from the upper part of the tunnel.

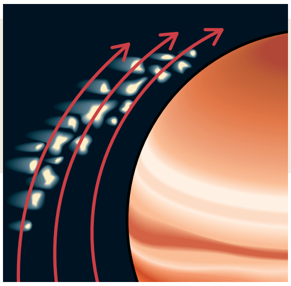
But even if most of those forecasts were right, would the astronomical community get to see any of this display? The answer hinged on just where on Jupiter the nuclei would hit. Early calculations were not encouraging: the comets were predicted to strike well over on Jupiter's nightside, where they would be hidden from the earth's view by the body of the planet. Jupiter would have to rotate eastward for at least an hour before any remains could be visible from the earth. Nature was to put on the biggest impact extravaganza in history, and it seemed that our seat was to be behind a post.

We accepted this assessment through the summer and fall of 1993; Jupiter and the sun were too close to each other in the sky for any further observations of S-L 9 to take place. But in early December, Scotti obtained new positions for the comet fragments as Jupiter rose just before dawn. From these measurements came another revelation: the comets would strike Jupiter much closer to the side facing the earth.

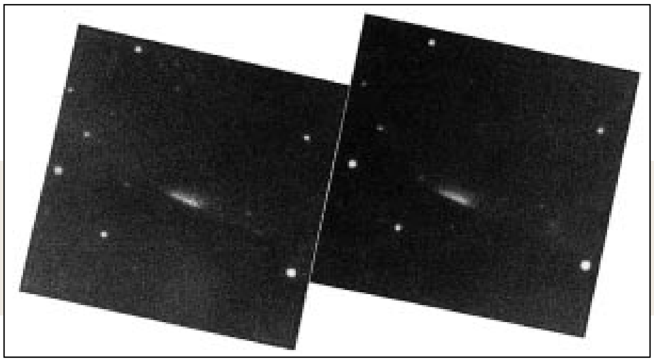
A Global Observing Session

As "impact week" approached in the summer of 1994, it became clear that this event was so extraordinary that it deserved observation time on as many telescopes as possible. Just as extraordinary was the good fortune that events had allowed astronomers a full 14 months to coordinate their programs. Heading the list of powerful telescopes to be aimed at Jupiter was the *Hubble Space Telescope,* whose newly corrected optics had already captured the comet

1992: During a highly elliptical orbit, Comet Shoemaker-Levy 9 passes within 20,000 kilometers of Jupiter and breaks into a string of fragments from the effects of the planet's gravity.



JARED SCHNEIDMAN/JSD



EUGENE SHOEMAKER, DAVID LEVY AND CAROLYN SHOEMAKER

1993: Carolyn Shoemaker finds what looks like a "squashed comet" on a pair of telescopic photographs that cover a section of the sky close to Jupiter. You can view the three-dimensional effect by holding the page close-up and merging the two images.

1993: Astronauts working from the space shuttle *Endeavor* repair the defective and ailing *Hubble* while orbiting some 600 kilometers above the earth.

NASA

nuclei with amazing clarity. For a team led by Harold A. Weaver of the Space Telescope Science Institute in Baltimore, *Hubble*'s wide-field planetary camera would monitor the comet nuclei as they moved closer to Jupiter. A group led by Heidi B. Hammel of the Massachusetts Institute of Technology used the telescope to take detailed images of the entire planet on the day before the first collision, to compare with later views to come during the week. The telescope would also collect spectrographic signatures of elements and gases released during the explosions. That is, of course, if something could still be seen when the impact sites rotated into the earth's view.

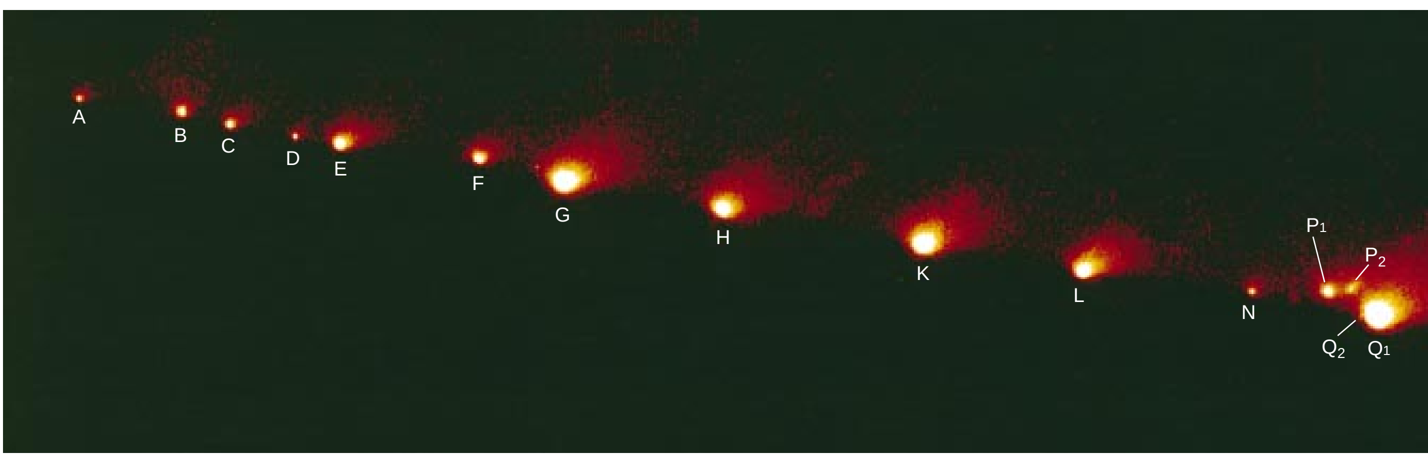
But even if the nightside strikes were to be invisible from the earth, there was another means to examine them. On its way toward a rendezvous with Jupiter, the *Galileo* space probe was in a position that would give its cameras and other instruments a direct view of the impact sites. Controllers at the Jet Propulsion Laboratory instructed the spacecraft to collect and return data on several of the impacts.

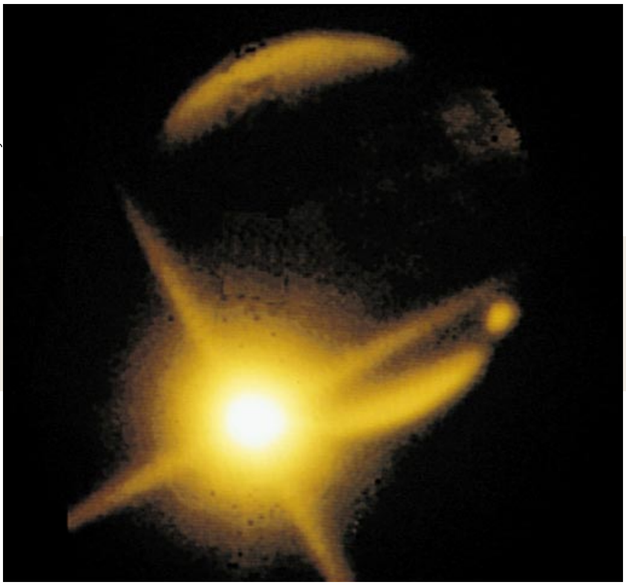
Many of the world's great telescopes were destined to play a vital role in recording the strikes and the related phenomena. The collisions would occur over a period lasting almost six days; thus, telescopes spread over the globe were needed. Palomar's venerable five-meter telescope, other large telescopes in Spain, Chile, Hawaii and Australia, and a host of smaller telescopes participated. The NASA *Kuiper Airborne Observatory,* flying out of Melbourne, Australia, captured key spectroscopic measurements. In addition, teams of radio astronomers monitored Jupiter for the effects of the impacts on the Jovian magnetosphere.

Using the Keck Observatory's giant 10-meter telescope atop Mauna Kea in Hawaii, Imke de Pater of the University of California at Berkeley and her colleagues planned to record infrared images in the wavelengths of light absorbed by cold methane gas. Because Jupiter's methane-rich atmosphere absorbs these wavelengths, filters that pass light only in the "methane band" would darken the face of the planet and highlight anything happening very high in or above the planet's atmosphere. These measurements, Imke and others reasoned, should be sensitive enough to catch any spots left by the collisions and, possibly, the impact plumes themselves. The South Pole Infrared Explorer telescope (SPIREX) was primed to make similar observations.

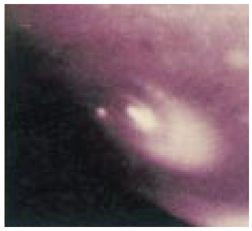
July 16, 1994: Show Time

After 14 months of waiting, the first word was electrifying: Calar Alto Observatory in Spain had recorded the infrared signature of a collapsing plume from the first impact (Nucleus A). The detection was confirmed by the European Southern Observatory in Chile. Not only was the impact detectable, it was spectacular. As we were soon to find out, the plume shot some 3,000 kilometers above the clouds of Jupiter. But even with this news, for astronomers





PETER J. MCGREGOR AND MARK ALLEN *Australian National University*



HEIDI B. HAMMEL AND NASA

1994: Over a period of nearly six days, the 21 fragments of the comet plummet into Jupiter and explode. In particular wavelengths of light, some of the plumes from these bursts outshine the entire planet (*left*). As Jupiter rotates, the scars from the backside collisions move into the earth's view (*above*).

1994: Astronomers at the Space Telescope Science Institute in Baltimore receive *Hubble's* images of the giant explosive plumes and spots on Jupiter and begin the process of deciphering the data on these spectacular collisions.

SPACE TELESCOPE SCIENCE INSTITUTE AND NASA

awaiting the first data from *Hubble,* tension was high. The telescope employed different filters and detectors from those used at the observatory in Spain, and everyone wondered what the mighty eye in space would record.

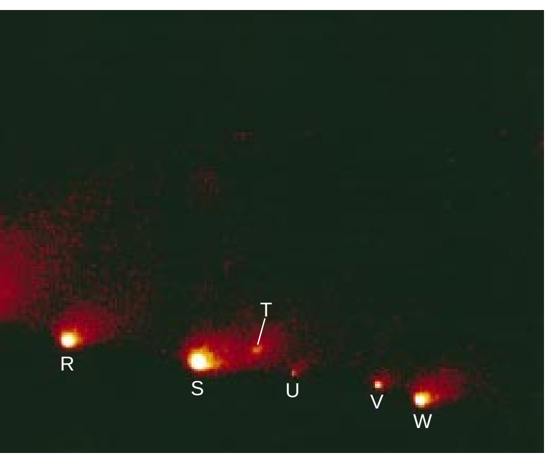
The entire *Hubble* comet team huddled around a single video monitor at the Space Telescope Science Institute shortly after the first images had been returned. The first few had not shown any obvious disturbance, and anxiety mounted. But then a spot appeared above the edge of the planet, and everyone in the room began to breathe again. The next image showed the plume rising and brightening over Jupiter. The fireworks were in clear view, and the comet team erupted in celebration.

By that first magical day, it was clear that the meticulous planning had paid off handsomely. The international collection of observatories, on the earth and in space, was responding like a symphony orchestra, with Marsden's frequent electronic messages acting as conductors. They allowed observers to know what everyone else was doing so that their programs could be altered to keep up with the emerging picture.

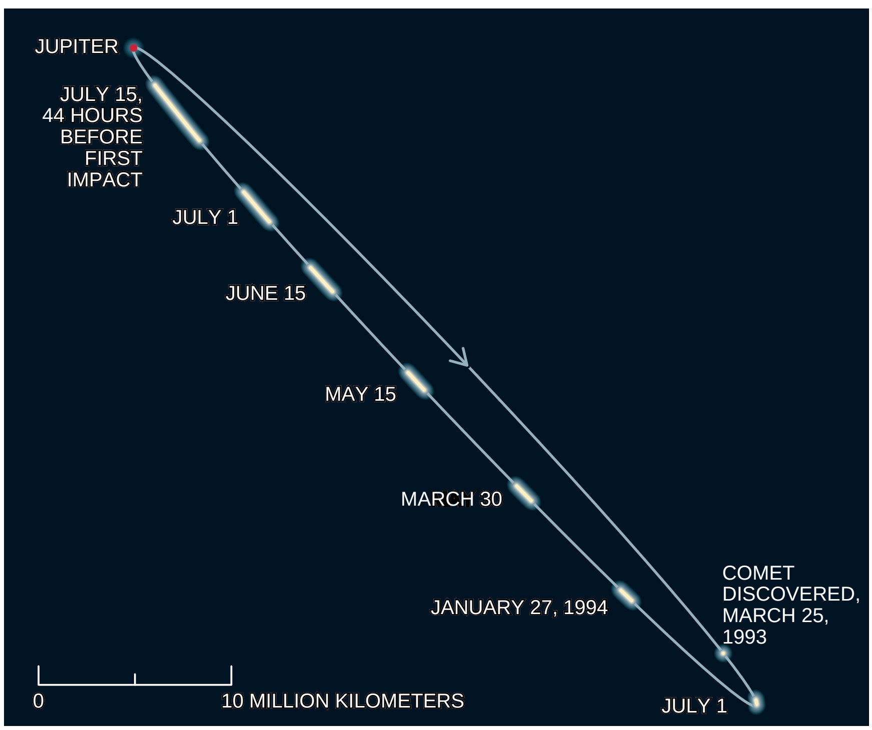
A Battered Planet

From the outset the performance of the comets was intriguing. As Jupiter rotated, a large spot left by Nucleus A came into view. It was made up of three distinct parts: a central streak, an expanding ring and a peculiar crescent-shaped outer cloud. In the visible part of the spectrum, the markings looked extraordinarily dark, but in the infrared light of a methane absorption band, the spot appeared bright against the dark planet. The entire spot was as large as the earth. Several hours later Nucleus B struck Jupiter with quite different ef-

FRAGMENTS OF THE COMET remaining after its near miss with Jupiter in 1992 show delicate comae in an image from the *Hubble Space Telescope* (*left*). The 21 nuclei are labeled with letters of the alphabet (I and O were not used to avoid confusion with one and zero). Numerical subscripts on fragments P and Q denote nuclei that broke apart after the main disintegration. The train of fragments grew continuously in length from the time of discovery in 1993 to the final collisions in 1994 (*below*).



HAROLD A. WEAVER AND T. ED SMITH *Space Telescope Science Institute and NASA*



JARED SCHNEIDMAN/JSD; SOURCE: PAUL W. CHODAS

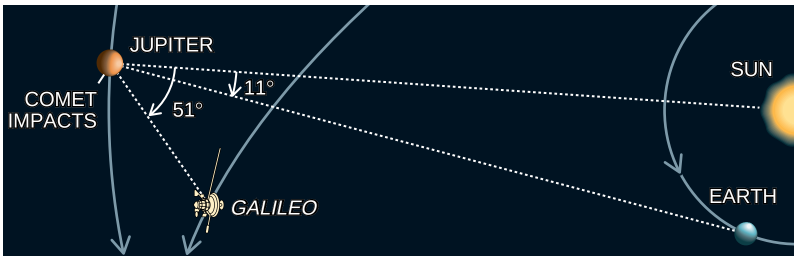
Diary of a Flung Pearl

I have been fascinated by the similarity of the large collisions and what the sequence of events surrounding each of these blasts demonstrates. Before the impact, a storm of small particles first penetrated Jupiter's atmosphere. This string of fine debris produced the dull infrared glow that could be seen from the earth over the visible edge of the planet, above the impact site. Next, the main mass struck Jupiter's atmosphere in full force and generated a brilliant meteor. That meteor was hidden from the *Hubble Space Telescope* and terrestrial telescopes but was detected by *Galileo* (*below*), which fully imaged the crash of W (*left*).

JET PROPULSION LABORATORY

As a nucleus plunged deeper into Jupiter's atmosphere, a rising, incandescent fireball emerged. Hot gases shot out of the "tunnel of fire" at velocities that exceeded 10 kilometers per second. This jet produced an enormous plume that eventually reached some 3,000 kilometers above Jupiter's ammonia cloud tops. As the plume grew, its temperature plummeted, dropping as low as a few tens of degrees above absolute zero. Submicroscopic particles condensed and made the plume visible in reflected sunlight as it rose into view from the earth, and above the shadow of Jupiter.

About six minutes after a collision, the plume that had erupted upward began to fall back. It continued to descend for some 10 minutes. The collapsing plume and underlying atmosphere grew hot as these gases became compressed and began to release sustained flashes of infrared energy. This burst was the main bright event.



JARED SCHNEIDMAN/JSD

VIEWING GEOMETRY from the* Galileo *space probe, on its way to Jupiter, allowed scientists a direct view of the collisions.

Working with Paul J. Hassig, then at the Titan Corporation, and David J. Roddy of the U.S. Geological Survey, I have studied the physics of such plumes using a numerical computer model. Our work helps to explain the dark clouds seen in the first two hours after impact. The computer simulation (*far right*) re-creates many features of an evolving plume, such as those of Nucleus G, which was so clearly captured by *Hubble* (*right*).

A key observation in both the computer modeling and *Hubble* images is that as each

fects. Even though B had been brighter than A, the plume that rose from its impact was so much smaller that only the largest telescope in the world, the 10-meter Keck, recorded it easily. Nucleus B may have consisted of a swarm of small house-size subnuclei that split off from Nucleus C sometime after the initial breakup. An observer on Jupiter would have seen a fabulous storm of meteors, but little was detected from the earth.

Nuclei C and E crashed with much the same effects as A. Two days later there was great anticipation as Nucleus G—which had a bright coma and presumably large mass—made its final descent. *Hubble* had a clear view of Jupiter, but that night all the big telescopes at Mauna Kea Observatories were closed because of fog and drizzle. Yet miraculously, only a minute before the impact, the clouds above Mauna Kea parted. The observatory domes raced open, and the telescopes captured images of the strike before more fog and rain forced them to close again only 10 minutes later. They were lucky to get a view: Nucleus G hit with such tremendous energy that the collapsing plume was much brighter than the entire planet in the infrared methane band. Nucleus G left the same imprint as the earlier major impacts of A, C and E, but the scar was much bigger. The great flash of energy was well recorded in Australia and at the South Pole.

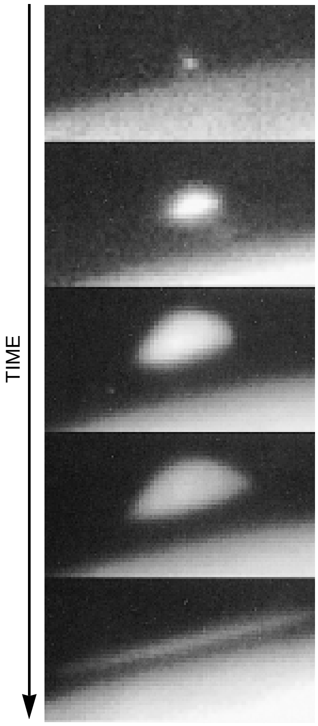
At this point, *Hubble* had detected expanding rings from impacts A, E and G in the clear regions between the inner dark core clouds and the outer dark crescents. It was found that these were expanding outward at about 450 meters per second. Interpretation of these features fell to Andrew P. Ingersoll of Caltech. Soon after impact week, Ingersoll realized the rings were not moving out fast enough to be sound waves—they were not the "boom from the plume," as he had originally thought. But the speed of the waves was the same for all impacts. Ultimately, Ingersoll and Hiroo Kanamori, also at Caltech, found that an "internal gravity" wave had been produced, somewhat like the waves formed by a stone thrown into a pond.

As impact week continued, Nucleus L left the largest spot yet, once again complete with a central core and outer, crescent-shaped cloud. By this time amateur astronomers around the world had found that these dark features on Jupiter were so large and dense that they could be seen by using small telescopes. The nuclei of H, K and L were all preceded by a long train of particles whose entry into the atmosphere produced a rising infrared glow before the arrival of the main part of the nucleus. The *Galileo* spacecraft took an engaging series of "snapshots" of the brilliant meteor and incandescent rising plume from the impact of W, the final nucleus, as it tore into Jupiter. The *Hubble* image sequence of the same fall ended with a view of the plume collapsing directly on top of the spot made earlier by Nucleus K.

Reviews Still Coming in

Despite the many observations of this dramatic episode, important questions are not yet fully answered. How large were the nuclei? Were they mostly swarms of small bodies, or were there large individual fragments? How much energy did they release when they hit? The diversity of effects and the sheer mass of data—more than for any other single event in the history of astronomy—preclude a simple analysis. Just as scientific discussions and meetings before the impact emphasized the need to coordinate observations, sessions convened afterward have concentrated on comparing the data to see which ideas fit best.

Comet S-L 9 probably began its wanderings in the outer solar system beyond the orbit of Neptune. A series of close encounters with Jupiter gradually altered its orbital period from one revolution about the sun every several



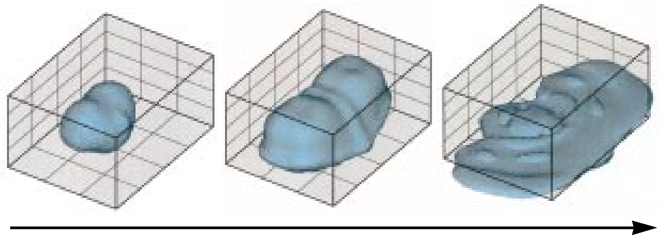
HUBBLE SPACE TELESCOPE COMET TEAM AND NASA

***EXPANDING PLUME** from Nucleus G is revealed in a sequence from* **Hubble.**

major plume fell back toward the planet, its base developed a crescent-shaped "skirt" that expanded sideways. That feature was distinctly asymmetrical because material shot outward from the inclined tunnel of fire primarily in the "backfire" direction. Lateral flow continued across the top of the atmosphere for about 45 minutes as the leading edge of the lobe traveled a distance greater than the radius of the earth.

Much of the incoming comet mass ultimately ended up scattered in the outer, crescent-shaped cloud, along with shocked gases from the upper part of the tunnel punched in Jupiter's atmosphere. Detailed images of the spot from Nucleus G show 16 distinct radial lines dissecting the crescent. These streaks may have been produced by 16 fragments in the nucleus.

The aftermath of each of the large collisions showed that extremely dark clouds also formed an inner core. That central spot marked a tall column that reached from Jupiter's troposphere into its stratosphere. The dark core probably contained constituents dredged from deep within the planet's atmosphere—perhaps from the layer of ammonium hydrosulfide clouds that lies hidden under the upper, ammonia cloud deck. Why did a transparent zone form between the crescent and the inner core? The mechanism remains unknown, as does the composition of the dark particles that made the impact clouds so visible. But scientists can readily speculate.



EUGENE SHOEMAKER, PAUL J. HASSIG AND DAVID J. RODDY

***COMPUTER MODELING** simulates the evolution of a plume.*

Clifford N. Matthews of the University of Chicago has proposed that the dark matter is a brown polymer called poly-HCN. I believe that the dark material of the inner clouds may have contained sulfur-bearing compounds and that the transparent zones were composed of gases from regions of Jupiter's atmosphere above the ammonium hydrosulfide cloud layer. That composition could then explain the bull's-eye pattern of the spots: the lateral zonations represent vestiges of the layer-cake structure of Jupiter's atmosphere after it was excavated by the comet and blasted outward. *—E.M.S.*

thousand years to about once a decade. The latest orbital calculations, by Paul W. Chodas of the Jet Propulsion Laboratory, indicate that probably about 1929 (the year an unrelated crash hit the earth's stock market) the comet made a slow approach to Jupiter that allowed the planet to capture the comet as a moon. The resulting two-year-long orbit about the planet was, however, unstable. Some revolutions followed narrow ellipses; others were roughly circular. In 1992, when the orbit was highly elliptical, the comet passed so close to Jupiter that it was broken apart.

The initial disintegration dispersed the cometary material into a long swarm of debris. Erik I. Asphaug of the NASA Ames Research Center and Willy Benz of the University of Arizona have shown that the loose string of rubble could have then coalesced into a set of distinct nuclei under the mutual gravitational attraction of the fragments. We suspect that large coherent pieces of fractured comet were present in some nuclei but not in others.

After the main disruption event, additional nuclei split from some of the earlier formed nuclei. Just how this later fracturing occurred is not understood. Possibly internal gas pressure ruptured large chunks, or perhaps the force of collisions between fragments traveling in the swarm knocked them apart. The largest individual nuclei in the entire train probably were no more than a kilometer or two across. These nuclei did not complete even one more orbit before striking Jupiter's flank. When they hit, the energy from each of the largest impacts probably equaled hundreds of thousands of large hydrogen bombs exploding simultaneously.

The great dark scars left on Jupiter gradually spread, merged and slowly faded in the months after the impacts. Yet as this article goes to press, almost a year after the collisions, a faint dark band along the line of impact sites is still visible through even small telescopes. Such dark clouds have never been seen on Jupiter before, and one wonders just how rare such a dramatic event must be.

The frequency of impacts depends on the scale of the body involved, and we are still uncertain about the size of this comet before it broke apart. But by making some reasonable assumptions, we can estimate that the crash of a string of nuclei such as S-L 9 probably occurs less than once every few thousand years. Thus, we feel fortunate to be living at this moment, to have found the comet on its way toward Jupiter and to have witnessed its demise in a blaze of glory.

The Authors

DAVID H. LEVY, EUGENE M. SHOEMAKER and CAROLYN S. SHOEMAKER have been searching the skies together since 1989. Levy writes and lectures and is also an avid amateur astronomer. He has written 15 books—somewhat fewer than the number of comets he has discovered. Eugene and Carolyn Shoemaker have been working as a husband and wife team since 1982. Eugene served as a geologist for the U.S. Geological Survey from 1948 to 1993, where he organized the Branch of Astrogeology. He is now scientist emeritus with the U.S.G.S. and holds a staff position at Lowell Observatory. Carolyn, too, is on the staff of Lowell Observatory. She also works as a visiting scientist at the U.S.G.S. and is research professor of astronomy at Northern Arizona University.

Further Reading

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Lost Science in the Third World

Many researchers in the developing world feel trapped in a vicious circle of neglect and—some say—prejudice by publishing barriers they claim doom good science to oblivion

by W. Wayt Gibbs, *staff writer*

Luis Benítez-Bribiesca waxes nostalgic as he recalls the early years of *Archivos de Investigación Médica,* the Mexican medical journal of which he is now editor in chief. Soon after the publication was founded in 1970, the Institute for Scientific Information, a private firm in Philadelphia, agreed to include the journal in its Science Citation Index. The SCI lists articles from roughly 3,300 scientific journals selected from the more than 70,000 that are published worldwide. Inclusion in the SCI and a few other top databases guarantees that a journal's articles will be seen when scientists search the literature for new discoveries in their field and decide which previous work to cite in their own papers.

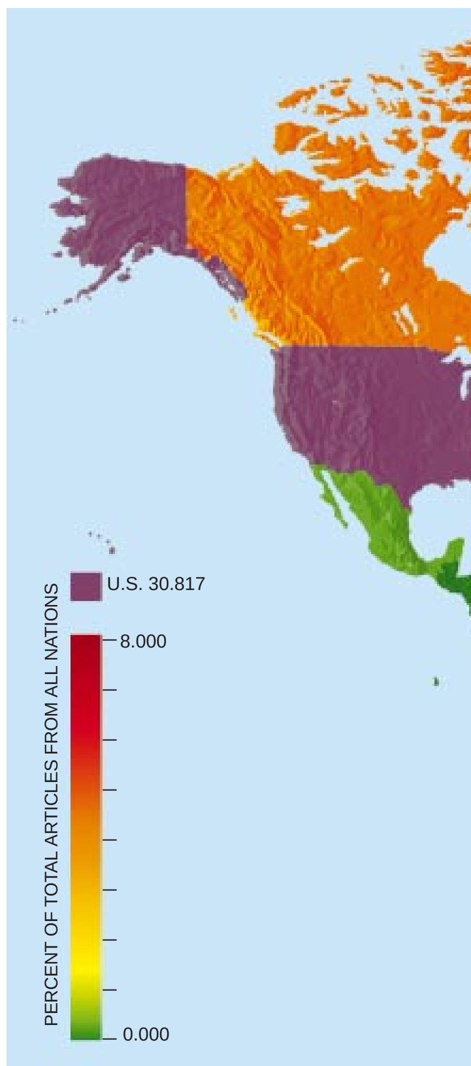
Of course, there were conditions: to remain in the SCI, *Archivos* had to publish its issues on time, provide English abstracts for its Spanish articles—and purchase a $10,000 subscription to the index. All of which the journal did, until

SHARE OF MAINSTREAM JOURNAL ARTICLES (PERCENT OF TOTAL FOR ALL NATIONS)

U.S.	30.817
JAPAN	8.244
U.K.	7.924
GERMANY	7.184
FRANCE	5.653
CANADA	4.302
RUSSIA	4.092
ITALY	3.394
NETHERLANDS	2.283
AUSTRALIA	2.152
SPAIN	2.028
SWEDEN	1.841
INDIA	1.643
SWITZERLAND	1.640
CHINA	1.339
ISRAEL	1.074
BELGIUM	1.059
DENMARK	0.962
POLAND	0.913
TAIWAN	0.805
FINLAND	0.793
AUSTRIA	0.652
BRAZIL	0.646
UKRAINE	0.578
NORWAY	0.569
SOUTH KOREA	0.546
NEW ZEALAND	0.426
SOUTH AFRICA	0.415
GREECE	0.411
HUNGARY	0.398
ARGENTINA	0.352
[SLOVAKIA, CZECH REPUBLIC]	0.332*
MEXICO	0.332
EGYPT	0.280
TURKEY	0.243
BULGARIA	0.220
HONG KONG	0.205
PORTUGAL	0.201
SINGAPORE	0.179
CHILE	0.176
NORTHERN IRELAND	0.140
SAUDI ARABIA	0.129
VENEZUELA	0.093
THAILAND	0.086
[NIGERIA, KENYA]	0.073*
MALAYSIA	0.064
PAKISTAN	0.063
[ROMANIA, SLOVENIA, CROATIA, SERBIA, BOSNIA AND HERZEGOVINA, ALBANIA, MACEDONIA]	0.053*
PUERTO RICO	0.050
LEBANON	0.041
PHILIPPINES	0.035
KUWAIT	0.034
[MOROCCO, ALGERIA, LIBYA, TUNISIA]	0.033*
[LITHUANIA, LATVIA, ESTONIA, BELORUSSIA]	0.032*
[IRAN, IRAQ]	0.030*
CUBA	0.029
ICELAND	0.029
JAMAICA	0.029
[MOLDOVA, KAZAKHSTAN, TAJIKISTAN, TURKMENISTAN, UZBEKISTAN, KYRGYZSTAN]	0.024*
[ZIMBABWE, SENEGAL]	0.024*
[JORDAN, SYRIA]	0.021*
GEORGIA	0.021
[COLOMBIA, ECUADOR, PERU]	0.019*
SRI LANKA	0.019
TRINIDAD AND TOBAGO	0.013
[PARAGUAY, URUGUAY]	0.013*
INDONESIA	0.012
[NEPAL, MYANMAR, BANGLADESH]	0.012*
BAHRAIN	0.011
BOLIVIA	0.010
[MALI, NIGER, SUDAN, ETHIOPIA, SOMALIA, GHANA, ZAIRE, CONGO, CAMEROON, UGANDA, TANZANIA, ZAMBIA, NAMIBIA, MOZAMBIQUE, BOTSWANA]	0.009*
[YEMEN, OMAN, U.A.E.]	0.008*
[GUATEMALA, HONDURAS, NICARAGUA, COSTA RICA, PANAMA]	0.007*
[CAMBODIA, LAOS, VIETNAM]	0.006*
[GABON, GAMBIA, BURUNDI, CENTRAL AFRICAN REPUBLIC, CÔTE D'IVOIRE, BENIN, RWANDA, TOGO]	0.005*
MONGOLIA	0.004
U.S. VIRGIN ISLANDS	0.002
[HAITI AND DOMINICAN REPUBLIC]	0.001*
GREENLAND	0.001
BAHAMAS	0.000
AFGHANISTAN	0.000

*Average for countries in this group.

SOURCE: 1994 Science Citation Index; SCIENTIFIC AMERICAN *research.*



MAINSTREAM SCIENCE, viewed through the astigmatic lens of the most influential journals, gives a colored picture of the world. Analysis of the papers published in 1994 by some 3,300 journals included in the Science Citation Index, a commercial database widely used by researchers, yielded the table above. Countries in the map were then shaded to reflect their participation in the so-called international scientific literature. The near invisibility of less developed nations may reflect the economics and biases of science publishing as much as the actual quality of Third World research.

1982. “But then the country went through a terrible economic crisis, resulting in a delay of publication for six months,” Benítez recalls. Although the editors explained the situation to ISI and pleaded with its managers for patience, “they couldn’t care less,” he says. “We were out of the database.”

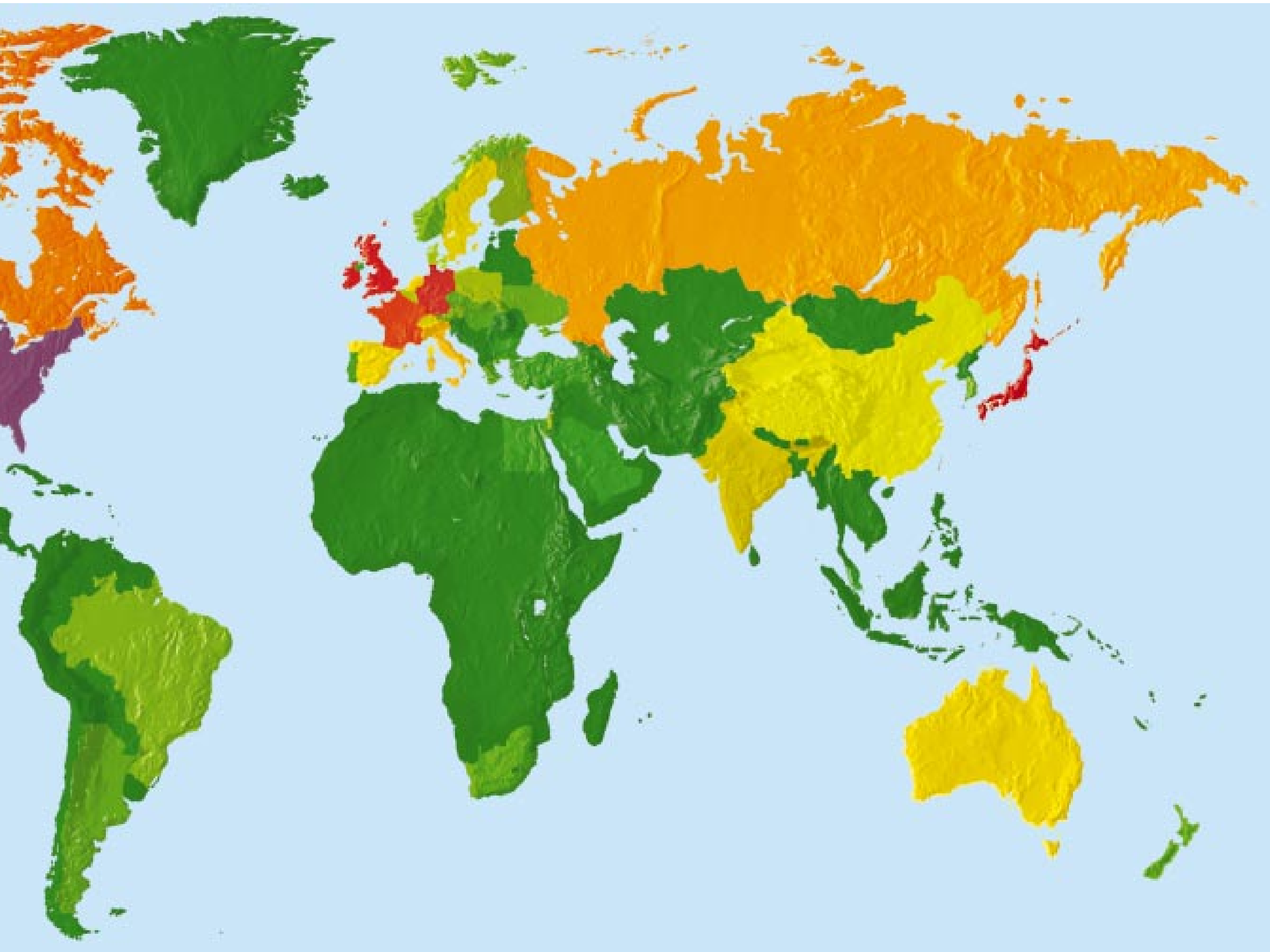
Since then, the journal has struggled to make itself attractive enough to be allowed back into the inner circle of science. It ran English translations beside every Spanish paper. Then it stopped publishing the Spanish versions altogether. Finally, it hired an American editor, insisted that all authors write in English to avoid translation errors and changed its name to *Archives of Medical Research.* Meanwhile the journal assembled an editorial board of top Mexican researchers and an international review committee of 15 American, Canadian and European scientists. Last December the Mexican national science agency gave the journal its highest rating. And despite a devaluation of the peso in January that has raised the journal’s costs by 40 percent, this year *Archives* released its summer issue a month early.

“But ISI says we still don’t meet their criteria,” Benítez laments. The scientists on his journal’s editorial board, he has been advised, have not been cited often enough. (Thanks to citation databases like the SCI, many researchers are now rated by the number of times their papers have been listed as references in other articles.) “Our editorial board was selected by choosing the 13 highest-cited biomedical scientists in Mexico,” he argues. “Why are we held to such a high standard when new American journals, announcing in *Science* or *Nature* that their first issue will be appearing in six months, can advertise already that they will be indexed in the SCI?”

Benítez is not alone in his frustration. Throughout the developing world, many of the more than 100 scientists and journal editors interviewed for this article point to structural obstacles and subtle prejudices that prevent researchers in poor nations from sharing their discoveries with the industrial world and with one another. Although developing countries encompass 24.1 percent of the world’s scientists and 5.3 percent of its research spending, most leading journals publish far smaller proportions of articles by authors from these regions [*see table on page 97*].

The invisibility to which mainstream science publishing condemns most Third World research thwarts the efforts of poor countries to strengthen their indigenous science journals—and with them the quality of research in regions that need it most. It may also deprive the industrial world of critical knowledge, observes Richard Horton, editor of the *Lancet.* “One of the reasons why infectious diseases such as the Ebola virus are emerging is that economic changes in developing countries are bringing humans into contact with previously isolated ecosystems,” he says. “The only way to understand that process and its effects is to publish work from local researchers.”

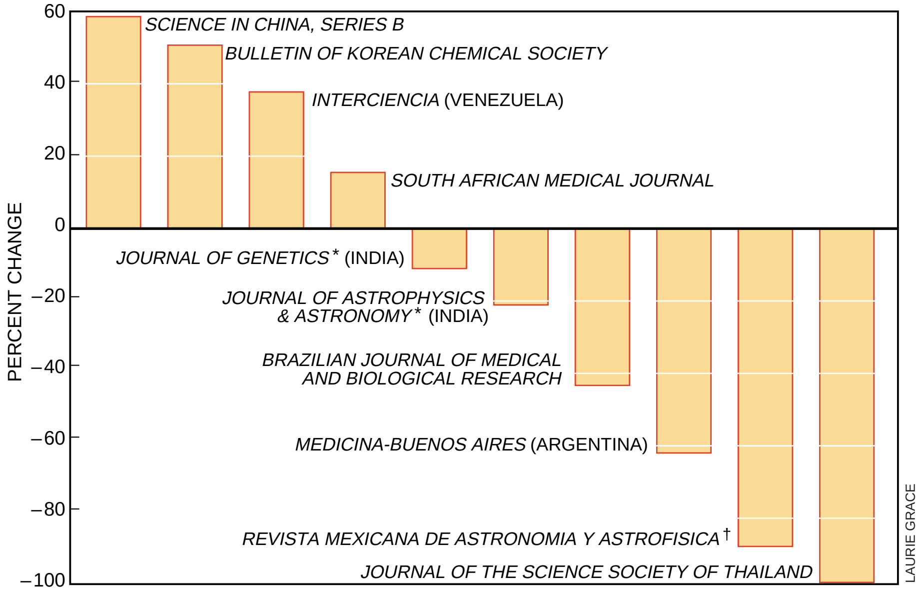
Although the proportion of mainstream science coming from underdeveloped nations has hardly grown in two de-



LAURIE GRACE

Third World Journals: From Mainstream to Slipstream

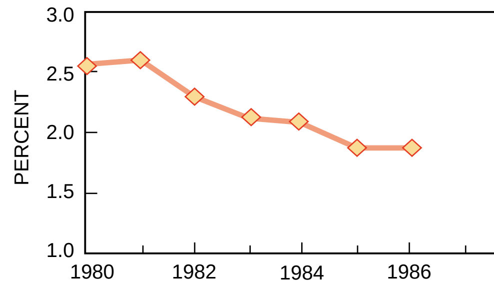
CHANGE IN IMPACT FACTOR OF 10 THIRD WORLD JOURNALS, 1983–1992



* Since 1988. † Since 1985. *SOURCE:* Journal Citation Reports; SCIENTIFIC AMERICAN *research.*

Although many developing nations have been increasing their investment in scientific research in recent years, Third World journals are struggling just to remain on the margin of the international scientific community. The fraction of those journals among the publications covered by the influential Science Citation Index—never a large proportion—has fallen by 40 percent

THIRD WORLD JOURNALS IN SCIENCE



SOURCE: 1994 Science Citation Index; SCIENTIFIC AMERICAN *research.*

cades, several initiatives may help change that. The United Nations has sponsored three commercial indexes of Third World journals. A number of developing countries have set aside money to reward their scientists for publishing and their local journals for maintaining lofty standards. But the change that holds most promise for linking scientists in the Third World with those in the First—the rapid movement of scientific communication onto the Internet—may also perversely widen and fortify the information gap between the poorest countries and the rest of the world.

Circles within Circles

Benítez says he will continue to apply to ISI for admission into "the Club," as the collection of so-called international journals published largely in the U.S. and western Europe is sometimes called in less industrial regions. Although he realizes that his chances are slim—the number of Third World journals covered by the SCI has declined from 80 in 1981 to 50 in 1993—he also recognizes that until *Archives* is indexed, work published in its pages will reach few.

Rogerio A. Meneghini of the University of São Paulo showed just how few when he studied the papers published by 487 Brazilian biochemists over a 15-year period. The articles they sent to international journals had received 7.2 citations each, on average. Those sent to Brazilian journals, only three of which are included in the SCI, garnered one ninth as many. Such low visibility is the norm: 70 percent of Latin American journals are not included in any index, according to a study by Virginia Cano of Queen Margaret College in Scotland. They thus "are condemned to a ghostlike existence," Cano wrote.

Unfortunately, since database publishers rely on citation rates to select the journals they include, "this is a vicious circle," Benítez observes. "We don't get many citations, because the journal is not well known because it is not in the international indexes." Bypassing the databases and going straight to library shelves is not an option, adds Christopher T. Zielinski, director of biomedical information for the World Health Organization's Eastern Mediterranean Regional Office. "Since Western research libraries acquire only journals with a high impact, they do not subscribe to journals outside the magic circle of citation analysis. It is clear that we have a self-perpetuating and closed system of review and citation."

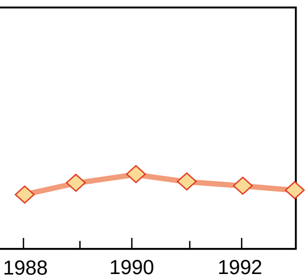
"Being unrepresented in the SCI or MEDLINE or INSPEC or many other databases is just another cruel fact of the way science in the world works at the moment," responds David A. Pendlebury, an analyst at ISI. Ten years ago, recalls Eugene Garfield, the company's former chairman, an opportunity to change that fact passed untaken. "I sponsored a meeting at which the Rockefeller Foundation and the National Science Foundation proposed raising the $250,000 necessary to pull in some 300 Third World journals," he says. "I thought it was a fantastic idea. But neither Rockefeller nor the NSF nor anybody else would come up with funds to index the additional journals." Still, he adds hastily, "if anything really significant is discovered [in a developing country], it gets into the mainstream journals that we are indexing."

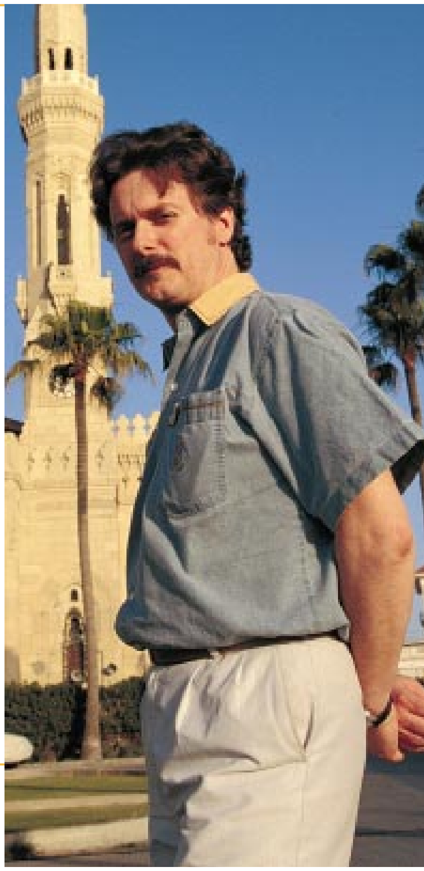
Benítez and others challenge that assertion. "Take cholera, for example," Benítez says. "Right now cases are increasing in Mexico. Our researchers have interesting findings about some new strains. International journals refuse our papers because they don't consider cholera a hot topic. But what if these strains spread across the border to Texas and California? They will think it important then. Meanwhile the previous knowledge about the disease will have been lost. Scientists searching the literature will not find the papers published in Mexican journals, because they are not indexed."

Equally important, Horton points out, "it is vital that developing countries communicate their research to one another. And it is hugely unethical not to have a way for [Third World] researchers to share ideas with the medical infrastructure."

Of course, not all local journals are competent to serve that role. "Many do since 1981. A number of the top journals from less developed nations have seen their impact factor, a measure of how often their articles are cited in other journals, decline sharply over the past decade.

CITATION INDEX





TOM HARTWELL SABA

“The 2 percent participation in international scientific discourse allowed by Western indexing services is simply too little to account for the scientific output of 80 percent of the world.”

Christopher T. Zielinski,
World Health Organization

not deserve, from the scientific perspective, to be published,” points out Manuel Krauskopf, a biochemist at the University of Chile who has studied Latin American science publishing for many years. “We need to face the fact that some journals contaminate the endeavor with their poor quality.”

According to K. C. Garg of the National Institute of Science, Technology and Development Studies in New Delhi, only 20 percent of the more than 1,500 journals published in India are refereed and appear regularly. Meneghini reports that “virtually all of the about 400 Brazilian scientific journals have either a very lenient editorial policy or none at all.” In such gray literature, as it is known, “correctness of methods and the author’s knowledge of scientific literature are seldom checked because we are short of qualified referees and because the journals’ limited accessibility discourages foreign experts from serving as referees,” says Flor Lacanilao, former chancellor of the University of the Philippines in the Visayas. “Philippine journals may even be harmful by perpetuating the wrong research practices. Although it is hard to admit, through them much of our research funds are wasted.”

Such indictments have stirred debate throughout the Third World about how to encourage and identify the good science that is too often tossed out with the bad—and how to share it with researchers in other poor countries as well as with the Club. “Research results such as the lessons learned from Senegal and the Gambia about the effectiveness—in the field—of oral and injectable polio vaccines are potentially also relevant in South Asia, for example,” suggests Esther K. Hicks, general secretary of the Advisory Council for Scientific Research in Development Problems in the Netherlands. But such lessons, if published at all, rarely cross national borders.

To change that, several institutions have launched incentive programs that reward scientists for publishing in peer-reviewed journals, with some success. “At the Southeast Asian Fisheries Development Center [SEAFDEC], I introduced the requirement of publication in journals covered by ISI for promotion in 1986 and for a cash incentive—50 percent of the researcher’s annual salary—in 1989,” Lacanilao reports. By 1993 the average number of publications per scientist had increased sevenfold. Manuel Velasco, who heads Venezuela’s Research Promotion Program, boasts that SCI-listed articles are up 57 percent since his program began in 1990. Brazil’s research funding agency, which offers lucrative fellowships to scientists who publish in international journals, has seen the number of papers from Brazilians working with colleagues in the U.S. or Europe quadruple since 1980.

The reward programs have had their drawbacks. “Desirable as these incentives are, they may also breed shabby research, ‘least publishable units’ [minor papers produced by stretching a single research finding] and redundant papers in the race toward publication,” warns Teodora Bagarinao of SEAFDEC. Already in the Philippines, two scientists have been caught publishing essentially the same paper in one journal. “Another problem,” says Enrique M. Avila, a marine biologist at the University of Philippines in Cebu City, “is stale publication. I know of two or three recent cases in which data from the 1970s were retrieved and published so the researchers could receive incentives.”

More ominously, some scientists warn that by favoring papers published in international journals—in Brazil, South Africa and the Philippines such papers are awarded twice as many points as those published domestically—incentive programs may forever doom local journals to leftovers. Hebe Vessuri, a sociologist of science at the Venezuelan Institute of Scientific Research, recalls a UNESCO meeting to analyze the weakness of Latin American journals. The specialists concluded that “the publications were locked up in a classic vicious circle: domestic journals did not gain prestige and international circulation because scientists published their best results abroad, but Latin American researchers published abroad because domestic journals did not take their results to the scientific world.”

That meeting was held in 1964. In 30 years, Vessuri notes, little has changed, except that tremendous growth and specialization of knowledge make foreign journals ever more attractive. Benítez admits that even the doctors on the editorial board of *Archives* send about 70 percent of their reports to SCI-listed journals in the U.S. or Europe.

National science councils in Brazil and Mexico are trying to break the cycle by ranking their journals and throwing all their support behind those at the top. In Brazil the initial evaluation deemed 83 percent of domestic titles to be irrelevant. Some fields fared worse than others: less than 7 percent of the existing agricultural journals made the cut. Mexico, in a similar exercise, last year identified 20 "Mexican Journals of Excellence." The SCI covers two of them.

When many of the best and the brightest journals in developing countries are excluded, "the 2 percent participation in international scientific discourse allowed by Western indexing services is simply too little to account for the scientific output of 80 percent of the world," editorialized Zielinski this past June in the *British Medical Journal.* "This is particularly true in fields such as medicine, where diseases are no respecters of frontiers, especially with increased air travel and the resurgence of communicable diseases such as measles and tuberculosis. These diseases, as well as unique information on such topics as AIDS, tropical biodiversity and traditional medicine, are particularly well covered in the local journals."

Under Zielinski's leadership, WHO has formed a consortium of publishers of 223 medical journals, nearly all of them from less developed countries. With the British firm Informania, last July the consortium began producing a monthly CD-ROM index called ExtraMED that contains more than 8,000 images of full pages scanned from the most recent issues of the journals. At a price of $750 for Third World subscribers (twice that in richer countries), the database is substantially more affordable than the SCI, which at $10,990 is beyond the reach of nearly all libraries in underdeveloped areas. (ISI does sometimes offer discounts to customers in poor nations.)

Because profits will be split among the participating journals and researchers need not pay royalty fees to print copies of articles from the disks, "this is likely to provide much needed stimulus—and funds—to enhance the quality of the journals," Zielinski says. "We hope to bring developing country health journals into the mainstream of research literature." And not just health journals: Informania has secured agreements with the U.N.'s Food and Agriculture Organization to produce a similar CD-ROM of 500 agricultural journals and with UNESCO to produce ExtraSCI, containing 500 periodicals from all fields of science and technology.

Zielinski concedes that the Third World market may be limited for some time, because fewer than one library in 10 has a computer, let alone a CD-ROM player. But the index may help bring science from the developing world to the attention of researchers in the U.S. and Europe. And the disk's search engine is designed to monitor which articles are read and to report these statistics back

Editing Science

Scientists often rely on the process of elimination when forming theories. No surprise, then, that journals select articles the same way. But in their zeal to filter bad research from the scientific mainstream, editors and reviewers seem to catch a disproportionate number of papers from researchers in underdeveloped countries in their nets.

The journal *Science,* for example, has seen the trickle of submissions from authors in a dozen of the most scientifically prolific developing nations nearly double since 1991. But last year the journal accepted just 1.4 percent of such papers—the same as in 1991. It published about 21 percent of submissions from the U.S., in contrast.

Science is hardly unusual; leading journals in most fields publish far fewer than the 5.3 percent of articles expected as the fruit of that fraction of the world's research investment spent in less developed countries [*see table below, right*].

JESSICA BOYATT

Richard Horton, **Lancet**

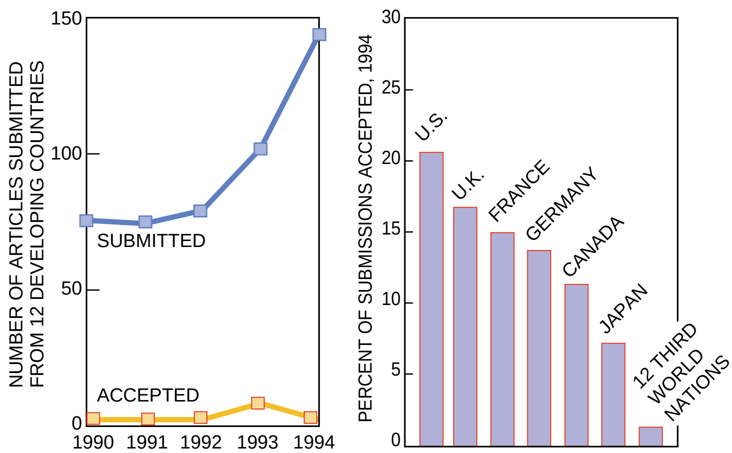
Many editors believe the low representation accurately reflects the poor quality of science in poor nations. "Environmental science in developing countries is indeed lagging behind the rest of the world, just as you would expect," says William H. Glaze, the editor of *Environmental Science and Technology*. "Not only is it old-fashioned, but sometimes it's just not very well done. The documentation is poor, and the experimentation doesn't meet our standards."

Many Third World authors, editors note, are tripped up by language. "If you see people making multiple mistakes in spelling, syntax and semantics," says Floyd E. Bloom, the editor of *Science*, "you have to wonder whether when they did their science they weren't also making similar errors of inattention." It is interesting, however, that acceptance rates for papers from India, where English is widely spoken, still tend to fall far below those for French and German articles.

There are some editors who believe the world would be richer if Third World science were given more attention. A few are trying to boost such research in their journals without lowering their standards. "We are very interested in serving environmental scientists all over the world, and it's clear we're not," Glaze admits. So he is recruiting retired scientists as mentors to help non-English speakers prepare their manuscripts for publication.

Richard Horton, editor of the *Lancet,* has a similar idea. As chair of the World Association of Medical Editors, Horton is assembling a global network of researchers who will assist editors of Third World medical journals in establishing peer-review processes. He hopes the network will also sensitize the editors of international

ARTICLES ACCEPTED BY *SCIENCE*



SOURCE: Science.

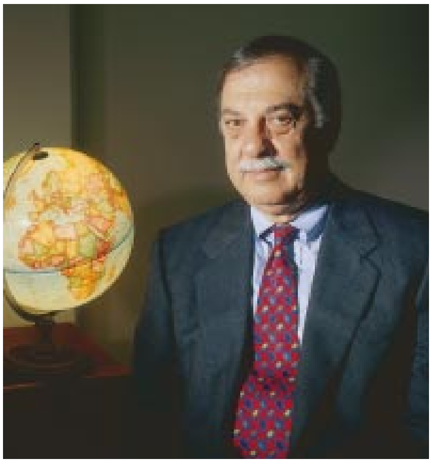
ARTICLES BY THIR

FIELD
MATHEMATICS
ENGINEERING
FORESTRY
AGRICULTURE
PHYSICS
OCEANOGRAPHY
ZOOLOGY
BOTANY
CHEMISTRY
BIOLOGY
ENVIRONMENTAL SCIENCE
GENERAL SCIENCE
MEDICINE
GENERAL SCIENCE
BIOCHEMISTRY
ECOLOGY

journals to cultural differences that he believes are often misinterpreted as bad science.

Not everyone likes this idea. Jerome P. Kassirer, editor in chief of the *New England Journal of Medicine,* has refused to join the association, asserting that the group is taking the wrong approach. Kassirer suggests that developing countries should receive guidance on nutrition and immunizations before getting advice on medical editing. "Very poor countries have much more to worry about than doing high-quality research," he says. "There is no science there."

Yet an editorial in Kassirer's own journal this past May praised a study by doctors at the Kenya Medical Research Institute that arrived at a simpler and more accurate way to diagnose malaria, which still kills more than 3,000 people daily. The advance will help save malaria patients, 90 percent of them African children. "It makes me very sad to hear someone in a position of [Kassirer's] authority make that kind of comment," Horton responds. The underrecognition of developing science, he says, represents "ethnocentrism at its worst."

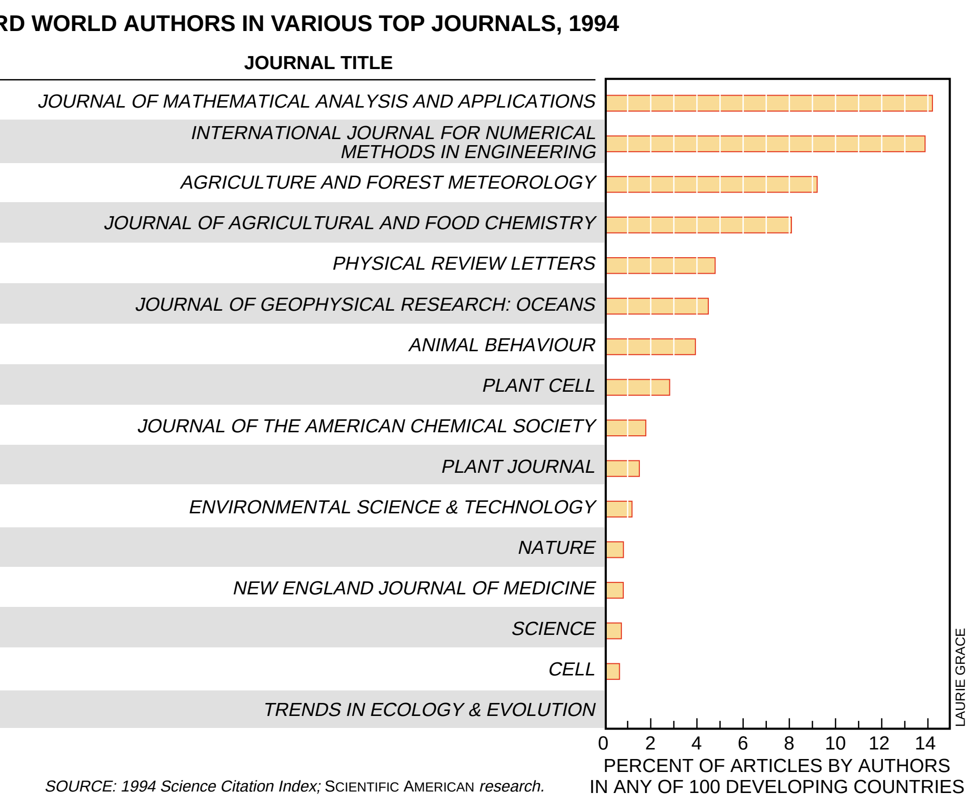


JESSICA BOYATT

Jerome P. Kassirer,
New England Journal of Medicine

Acceptance rates at the *Lancet* and the *New England Journal of Medicine* seem to reflect the difference in their editors' views. The *Lancet* accepted about 8 percent of the submissions it received from developing countries last year, whereas the *New England Journal* accepted only 2 percent.

Editorial philosophy may also explain why more than 20 percent of all the articles *Forest Science* published last year came from underdeveloped countries. Bill Hyde, the journal's former editor, worked in poor nations. "I learned to treat scientists in developing countries as I would treat my next-door neighbor," he says. "My neighbor is a horticulturist, not an economist. If I treat him like he's stupid because he doesn't know what I know, I don't gain all of his insights, and anything I do about the economics of apple trees is likely to be totally incorrect. But if I recognize that he has good insights that are just different from mine, then the two of us can supplement each other. Then you can go someplace." —*Brenda DeKoker*



SOURCE: 1994 Science Citation Index; SCIENTIFIC AMERICAN *research.*

to the consortium. "With this," Zielinski wrote, "perhaps some of the inequities of indexing and citation analysis can begin to be redressed."

The Matthew Effect

Such optimism may be premature. Many Third World researchers—about half those interviewed for this article who were willing to comment on the subject—are convinced that the reviewers and editors of mainstream scientific journals are more likely to reject a paper from an institution in an underdeveloped country than an article of equivalent quality from an industrial nation. More important, they say, even when their articles are published in prestigious journals, their Northern colleagues tend to ignore their work or to cite later papers by American or European scientists who have followed in their footsteps.

"Most people in Africa and Asia will say there is a tremendous bias against them, while most Americans and Europeans will say it is not true," observes Subbiah Arunachalam, who studies the publishing success of scientists in India at the Central Electrochemical Research Institute. "I have heard the allegation myself, and I have no real sympathy for it," counters Floyd E. Bloom, editor of *Science.* "In high-quality journals where I have been an editor or reviewer, we lean over backwards to help science being presented from developing countries whenever it is possible."

Statistical evidence of reviewer bias is skimpy, because collecting it would require tracking all articles rejected by one journal to see how many are then accepted by another of equal caliber. "It is like knowing your wife is being unfaithful but having no means of proving it," quips one South American researcher. Nevertheless, some highly respected scientists assert that bias exists.

"There is no question in my mind that there is some inherent prejudice in the minds of some referees in the West about authors from Third World countries," says C.N.R. Rao, president of the Jawaharlal Nehru Center for Advanced Scientific Research in Bangalore. "Referees tend to feel that good work could not have been done in a developing country. I have published in major journals of the world for the past 40 years, but even now I face some prejudice from referees. This is not infrequent."

Some scientists who have moved from industrial to less developed countries have found that the address change makes a difference to reviewers. "When I was a resident in Boston, I was able to publish papers in the *American Jour-*

nal of Pathology with a couple of well-known American pathologists," Benítez says. "They flew through to publication with no problem. After that, I went to the University of Bonn in Germany and published two papers in *Nature.* Then I came back to Mexico with more experience and maturity. But now when I have sent papers to the same journals, they have been rejected immediately."

"The quality of the peer review we receive in core life science journals is appalling," comments Wieland Gevers, a biochemist at the University of Cape Town in South Africa. "It smacks of First Worldism. They seem to expect even more from us than from American or European researchers."

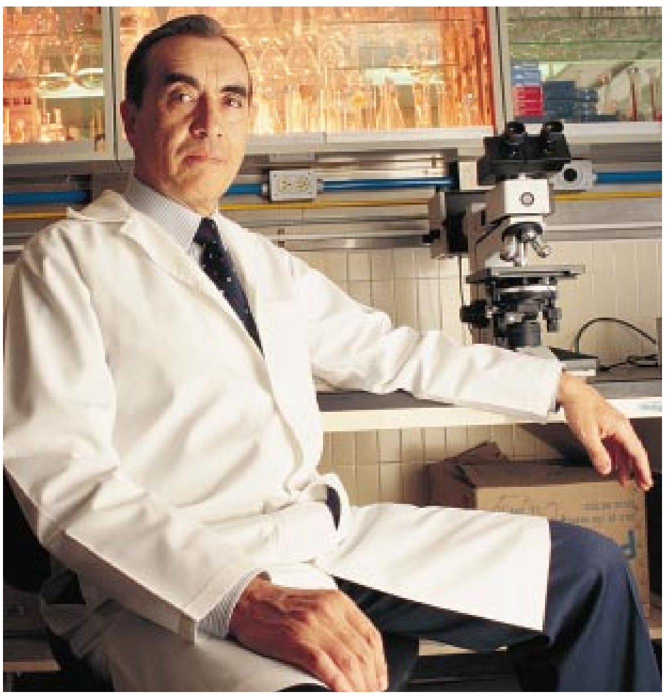
In some cases, this delays the publication of important results, Gevers asserts, pointing to "three breakthroughs that weren't taken seriously when we presented them to core journals." The first found that the anticancer drug 5-azacytidine can direct certain embryonic cells to become either muscle or fat, depending on conditions; the other two concerned the metabolism of low-density lipoprotein particles within the body. "These papers were sent from pillar to post for many months before they were finally accepted, even though editors described the work as well executed," Gevers says.

Many other articles, especially those in the applied fields to which developing countries devote most of their science funding, can find no audience at all among mainstream researchers. "I see a long-term, dangerous problem in the bias of a lot of the academic world against applied research," says George F. R. Ellis, a leading cosmologist at the University of Cape Town. "There is a kind of pecking order that places theoretical physics at the top and applied fields at the bottom. But it is right and fitting for scientists in Third World countries to be doing more applied research," Ellis argues. "The onus is on the international scientific community to recognize the results that are of high quality."

Recognition includes citations by those who build on one's work. But after studying the publications of 207 scientists working in Asia, Latin America and Africa, Jacques Gaillard of ORSTOM, the French international aid agency, concluded that scientists in developing countries "are caught in an especially vicious circle, because even when their findings are published in highly influential, prestigious scientific journals, they are, all told, far less often cited than writings by their colleagues from [industrial nations]."

> *"There is no question in my mind that there is some inherent prejudice in the minds of some referees in the West about authors from Third World countries."*
>
> C.N.R. Rao,
> *Jawaharlal Nehru Center for Advanced Scientific Research*

Meneghini has found that Brazilian papers, for example, are cited about 60 percent less than American papers in the same journal. Studies of citation rates for other developing countries show similar patterns. "More than prejudice, this is a sort of sociological phenomenon," he asserts.



KEITH DANNEMILLER *SABA*

RETURN ADDRESS can make a difference, says Luis Benítez-Bribiesca. Top journals accept his papers less frequently since he moved from Europe to Mexico.

Indeed, back in 1968 Robert K. Merton of Columbia University noticed that in science, credit for a discovery tends to go to the most famous researcher associated with it rather than to the most deserving one. In a classic paper in *Science,* Merton dubbed the phenomenon "the Matthew effect," after a verse from the biblical book of Matthew: "Unto every one that hath shall be given…but from him that hath not shall be taken away even that which he hath."

Rao notes that the Matthew effect "is not uncommon even for work done in advanced countries but hurts a person in a developing country much more because he does research with great difficulty. Sometimes it takes many years to complete the work. To then get no credit is very disappointing and frustrating."

Some Third World scientists perceive motives that derive more from malice than Matthew. Pushpa Mittra Bhargava recalls a paper he published not long ago in the *Indian Journal of Biochemistry and Biophysics.* "One fine day I got a reprint from a European author. [His article described] my work with just a different microbe—and no citation of my publication. There was a note attached to the reprint that said, 'Enjoyed reading your paper.' That was too much for me," says Bhargava, founder and director of the Center for Cellular and Molecular Biology in Hyderabad, India.

To reduce the Matthew effect, some journals have begun removing the names and affiliations of authors from papers before sending them to reviewers, a process known as blind reviewing. Gevers believes that "blind reviewing would level the playing field enormously. It would remedy many of the problems in the system." Although several controlled studies have shown that blind reviewing can slightly improve the quality of a journal's papers, so far none has examined the effect on submissions from less developed countries.

Simply inviting more scientists from undeveloped regions to act as reviewers might help as well, Arunachalam suggests. But the slow mail systems and unreliable fax lines that still plague much of the developing world complicate that solution. "One of our concerns is how quickly we could get papers to them and how quickly they would be able to respond," says

Bloom of *Science,* which has no reviewing editors outside of the U.S., Europe and Japan.

Barbed Wires

The movement of mainstream scientific publishing onto the Internet promises to free some Third World researchers from their isolation. "With delayed or nonexistent circulation of scientific journals [in developing countries], electronic communication can be a vital link in maintaining contact with peers, exchanging data sets and accessing the services of remote computers," observes Michael Jensen of the International Telecommunication Union.

A blue-ribbon panel of 13 experts commissioned by UNESCO Director-General Federico Mayor concurred. In a report issued last summer, it suggested that UNESCO ensure that scientists in all countries can get full Internet access at the lowest possible rates—if necessary, by selling such services itself. The panel also urged UNESCO to encourage "a rapid global shift to electronic publication of scientific research."

But some worry that UNESCO is not up to the first challenge and is not needed for the second. Pushed by market forces and pulled by the ability to share data and simulations that are too large or too dynamic to fit on a page, scientific communication is already moving at blazing speed onto the Internet [see "The Speed of Write," by Gary Stix; SCIENTIFIC AMERICAN, December 1994]. UNESCO, meanwhile, has not yet secured basic journals and databases for many Third World research libraries. Connecting individual researchers to the Internet may be far beyond its means—and, some fear, beyond the means of national governments as well, especially in Africa and the poorest parts of Asia.

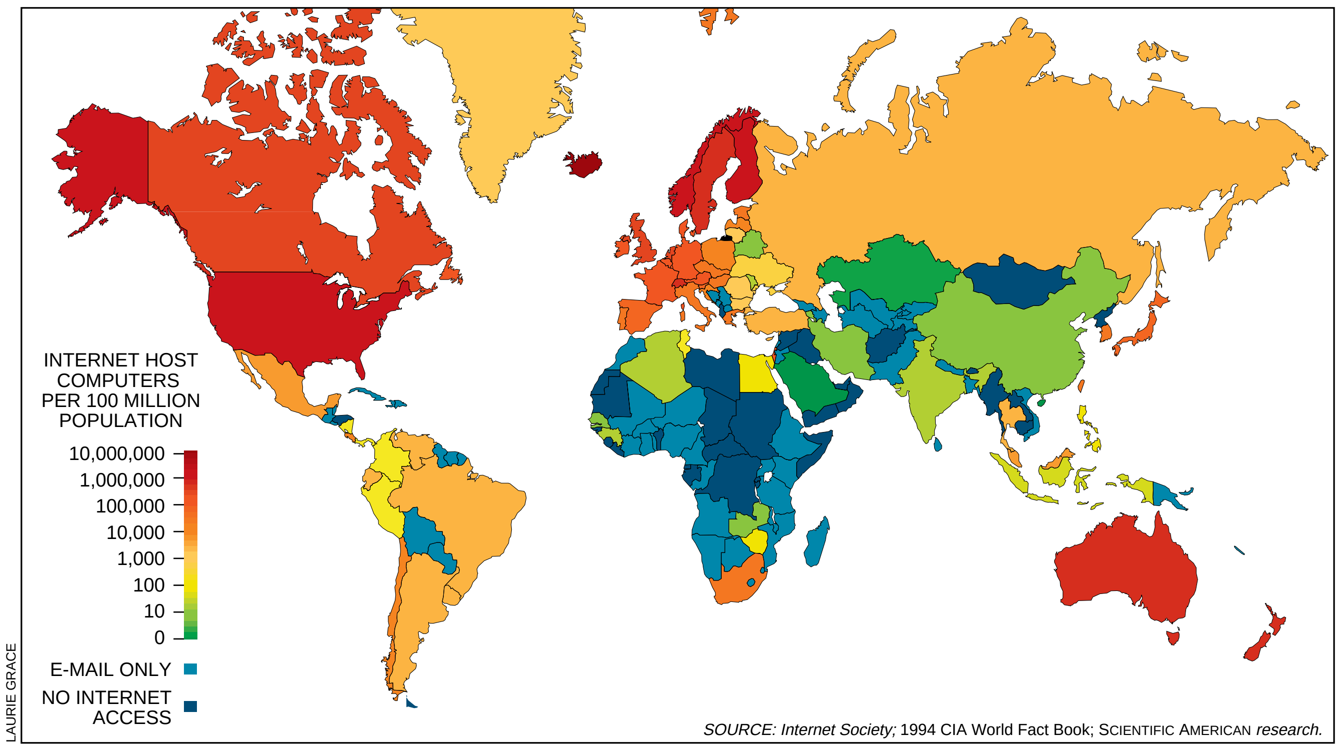
In these regions, telephone lines are too rare, unreliable and expensive to support the high-speed communication demanded by Internet applications. The entire continent of Africa, Jensen notes, contains fewer telephones than does Manhattan. African customers who sign up for service today are put on a waiting list 3.6 million people deep; in sub-Saharan regions the wait is currently about nine years.

Resources so scarce command high prices. A 1993 survey of five African countries from different regions found that the average price of an outgoing international call was $5 a minute—in some areas, faxes cost $30 a page. The average salary for a university lecturer, in comparison, is about $100 a month. So although about half the African nations can offer a daily E-mail service to at least some researchers, leased lines for Internet access—which can support only minimal data rates and cost up to $65,000 a year—are uncommon and likely to remain that way for some time.

"The huge danger is that the Internet might create a global impoverished class that doesn't have access to information systems," warns Martin Hall, an archaeologist at the University of Cape Town who often collaborates with researchers in other parts of Africa. "In five years we will be dealing with mostly paperless journals. Right now many African researchers depend on charity for their printed journals; paperless journals will be completely denied to these scientists. Africa has been impoverished of academic leadership in many areas, and that will probably be exacerbated by this growing information gap."

Unless it is breached. Three companies—AT&T Submarine Systems, Alcatel and FLAG—have separately proposed encircling Africa with an undersea fiber-optic cable that would connect every coastal country to the Internet. It is not yet clear when, or whether, there will be enough demand to cover the $2- to $6-billion cost. But if the ring is built, it may reinvigorate a continent of scientists who, says Amy A. Gimbel, director of the Sub-Saharan Africa Program at the American Association for the Advancement of Science, "are very battered and demoralized right now."

Providing the ability to reach out to scientists in the richer countries as well as in other regions that share their priorities, to present their discoveries, participate in dialogues and collaborate in experiments, this is one circle that would be decidedly virtuous.



GLOBAL INTERNET is transforming scientific communication. But the network has been slow to penetrate the Third World, leaving many researchers in poor nations isolated from informal contact with colleagues in more industrial regions.

Detecting Signals with Noise

For the most part, noise is a dirty word in electronics, appearing even in the most carefully crafted component. The temperature of the environment causes electrons to move about randomly, a process that introduces voltage shifts that can be heard as hiss and rumble. In certain instances, however, noise can be useful, even critical, for the transmission of information. Essentially, it can boost an otherwise weak signal above the threshold of detection. During the past 10 years, researchers have begun to recognize how the phenomenon, called stochastic resonance, may play a role in many diverse events, from the occurrence of ice ages to neuron signaling [see "The Benefits of Background Noise," by Frank Moss and Kurt Wiesenfeld, page 66].

We will describe two experiments. The first shows the utility of noise in bringing out a signal; the second illustrates the remarkable ability of the brain to home in on one conversation in a crowded restaurant—that is, to extract data from background noise.

WAYNE GARVER and FRANK MOSS collaborate at the University of Missouri at St. Louis. Garver is a senior scientist there and, when not constructing electronic circuits for demonstrations, likes to design and build sports-related timing and telemetry systems. Moss co-wrote the article on stochastic resonance that accompanies this project.

The key device we will build is a threshold detector (which provides the simplest manifestation of stochastic resonance). Such an instrument sends out a signal only if it receives an input of sufficient intensity. The project also needs two other devices: a signal generator and a noise generator. Besides these three modules, you will need a source of music (an ordinary tape player, say) and a set of headphones. The two generators and the detector can easily be built from inexpensive electronics parts; the total cost should be less than $100. (One source is Digi-Key Corporation, 701 Brooks Avenue South, Thief River Falls, MN 56701-0677; 1-800-344-4539.) The components can be assembled either on a breadboard (a plastic panel with many sockets that allow connections without soldering) or on printed circuit boards (which we recommend). The crucial components are integrated circuits called operational amplifiers, or op-amps.

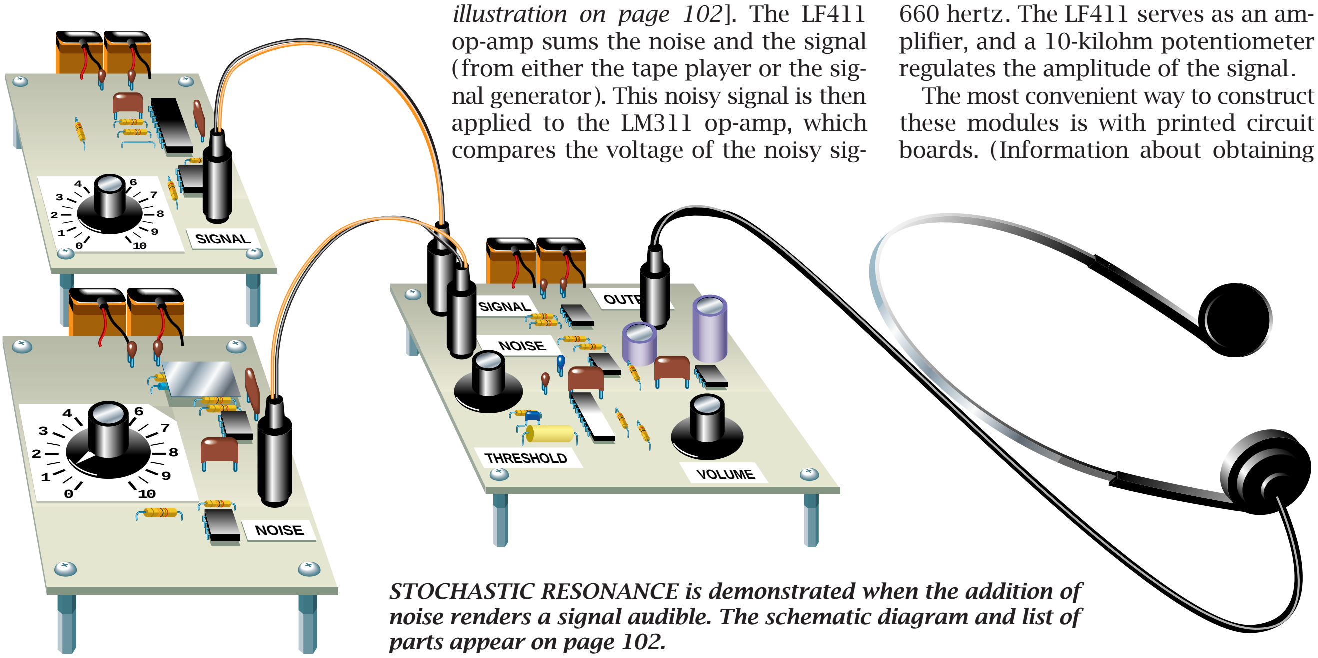
The threshold-detector module requires the largest number of parts [*see illustration on page 102*]. The LF411 op-amp sums the noise and the signal (from either the tape player or the signal generator). This noisy signal is then applied to the LM311 op-amp, which compares the voltage of the noisy signal to a threshold voltage. This voltage is adjusted with the one-kilohm potentiometer (an adjustable resistor).

When the noisy signal is less than the threshold, the output of the op-amp is −9 volts. It rapidly swings to +9 volts when the noisy signal crosses the threshold. The LM2917 op-amp measures the average rate at which these swings occur and converts it into a voltage that is amplified by the LM386 op-amp. The output of the LM386 is connected to the headphones. The potentiometer connected to the LM386 controls the volume of the sound.

The noise generator relies on the thermal agitation of the electrons in a megohm resistor. This large resistor is connected to the plus input of the LF411 op-amp at terminal 3, where fluctuating voltage, called Johnson noise, appears. This resistor and its amplifier must be shielded from extraneous signals, such as the 60-hertz power lines in your house. Covering them with a small piece of steel cut from a can lid should work. The shield must also be grounded: solder it to the ground plane on the printed circuit board underneath the resistor. The three LF411 op-amps function as high-gain amplifiers. The noise level can be adjusted with the 10-kilohm potentiometer.

In the signal-generator module, an ICL8038 chip generates a sinusoidal voltage signal with a frequency of about 660 hertz. The LF411 serves as an amplifier, and a 10-kilohm potentiometer regulates the amplitude of the signal.

The most convenient way to construct these modules is with printed circuit boards. (Information about obtaining



STOCHASTIC RESONANCE is demonstrated when the addition of noise renders a signal audible. The schematic diagram and list of parts appear on page 102.

ANDREW CHRISTIE

these boards appears at the end of this article.) Audio cables for connecting the threshold-detector module to the tape player and the signal and noise modules are available from electronics supply stores. You will need two such connecting cables that have miniature headphone male jacks (the type that plug into portable cassette players) on both ends. Each module will need two 9-volt batteries, one for the plus and one for the minus supply voltages.

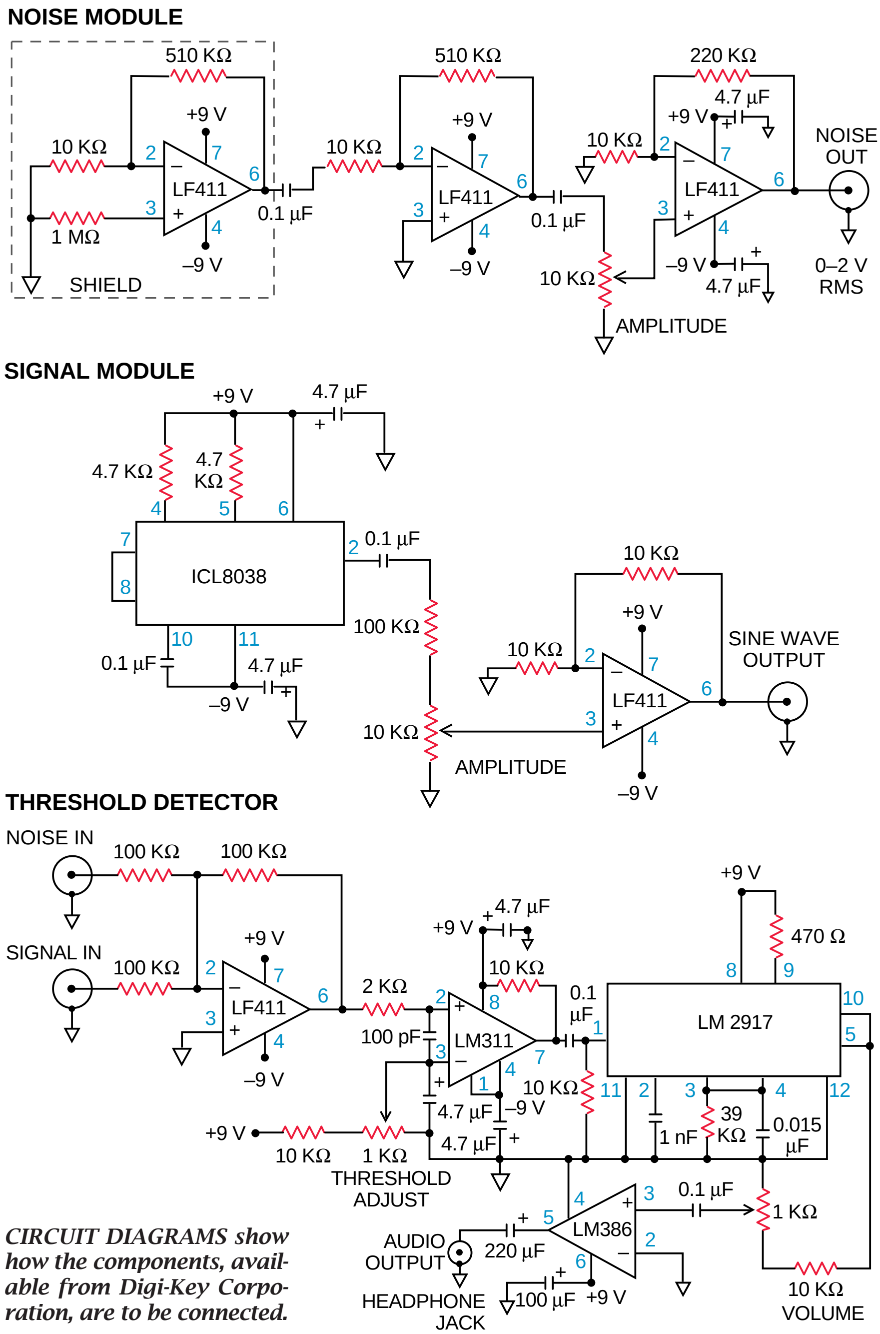
The first experiment makes use of the tape player and the noise module connected to the threshold-detector module. Connect the output of the tape player to the terminal marked "signal" on the threshold-detector module. Use the other cable to connect the noise module to the "noise" terminal on the threshold-detector module. Finally, plug in the headphones to the output.

Turn on the tape player and increase its volume to a somewhat large value—say, two thirds of maximum. Set the volume adjustment on the threshold-detector module about halfway between zero and the maximum. With the noise level at zero, adjust the threshold until you can just easily hear the music (it will sound distorted because of the nature of the circuit). Once set, the threshold adjustment does not need to be changed again. Next, turn down the volume on the tape player until you can no longer hear the music. The sound is now a weak, or subthreshold, signal.

Now you are ready to add noise to recover the music. Slowly turn up the noise-amplitude control. At first, you will hear unintelligible sounds, but as you boost the noise level, you will begin to perceive the music. Beyond that point, however, the noise will start degrading the music until once again all you hear is the noise. You can experiment with different threshold settings. Generally, the lower the threshold, the less noise will be required to produce an intelligible response.

In the second experiment the 660-hertz signal generator replaces the tape player. The idea is to measure a person's threshold of perception of a signal embedded in various amounts of noise. You will need to add gradations on all the potentiometer dials; number the range from 0 to 10 at regularly spaced intervals. You will also need a piece of ordinary graph paper to plot the noise level against the signal.

Put the headphones on and set the noise dial to 0. Turn up the signal dial to 8. Then, without looking at the dial, set the threshold to the point at which you can barely hear the 660-hertz tone. You can use these settings as your first data point (noise = 0, signal = 8).

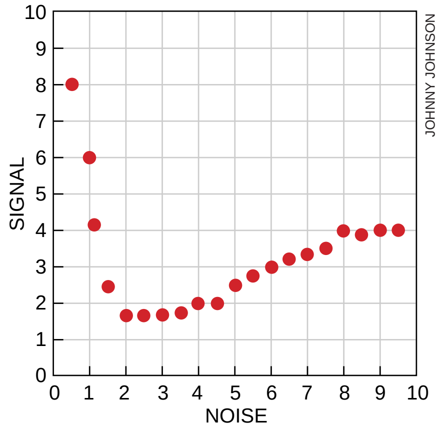


CIRCUIT DIAGRAMS show how the components, available from Digi-Key Corporation, are to be connected.

COMPONENTS SHOPPING LIST

QTY.	PART	DIGI-KEY NO.	QTY.	PART	DIGI-KEY NO.
5	LF411 INTEGRATED CIRCUIT	LF411CN	2	510 KΩ 1/4 W RESISTOR	510KQBK
1	LM311 INTEGRATED CIRCUIT	LM311N	2	10 KΩ POTENTIOMETER	308N103
1	LM2917 INTEGRATED CIRCUIT	LM2917N	2	1 KΩ POTENTIOMETER	308N102
1	LM386 INTEGRATED CIRCUIT	LM386N-1	1	0.015 µF 100 V CAPACITOR	EF1153
1	ICL8038 INTEGRATED CIRCUIT	ICL8038CCPD	6	0.1 µF 100 V CAPACITOR	E1104
1	1 MEGOHM METAL FILM RESISTOR	1.00MXBK	7	4.7 µF 25 V CAPACITOR	P2047
			1	220 µF 16 V CAPACITOR	P6621
4	100 KΩ 1/4 W RESISTOR	100KQBK	1	100 µF 16 V CAPACITOR	P6620
1	39 KΩ 1/4 W RESISTOR	39KQBK	1	1 nF 60 V CAPACITOR	P4812
1	2 KΩ 1/4 W RESISTOR	2KQBK	1	100 pF 60 V CAPACITOR	P4800
9	10 KΩ 1/4 W RESISTOR	10KQBK	5	3.5 MM JACK	MJ-3536
2	4.7 KΩ 1/4 W RESISTOR	4.7KQBK	6	9 V BATTERY CLIP	72K
1	220 KΩ 1/4 W RESISTOR	220KQBK	4	KNOB	8558K
1	470 Ω 1/4 W RESISTOR	470QBK	12	SPACER STANDOFF	J176

JOHNNY JOHNSON



SENSITIVITY TO A 660-HERTZ TONE is most optimal when the noise-level dial is set to between 2 and 5, where the signal does not have to be strong to be heard.

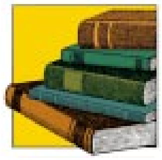
Now turn up the noise dial to 1. Adjust the signal dial (not the threshold dial) until you are barely able to perceive the tone; plot that point. Repeat this procedure for all noise dial settings up to 10 [*see illustration above*]. On the graph, you should notice that the data pass through a minimum at a noise setting in the range of 2 to about 5. This level is the optimum noise for detection of the 660-hertz tone. Note that the detailed shape of this data set may depend on the individual ability to perceive the signal amid the noise. Try to make the same measurements on several friends and plot the data from each on separate graphs. Are there any notable differences? Does the ability to detect the signal in the noise depend on age or hearing ability? For variation, try altering the 660-hertz tone by changing the 0.1-microfarad capacitor, located between pins 10 and 11 of the ICL8038 op-amp. The frequency equals 6.3829×10^{-5} divided by the value of the capacitor (more specifically, frequency = $0.3/(RC)$, where R is 4,700 ohms and C is the capacitance in farads.

For prefabricated circuit boards and additional construction tips, send $12 to Wayne Garver, Department of Physics and Astronomy, University of Missouri at St. Louis, St. Louis, MO 63121; E-mail: swpgarv@slvaxa.umsl.edu. This offer expires January 31, 1996.

FURTHER READING

THE SIGNAL VALUE OF NOISE: ADDING THE RIGHT KIND CAN AMPLIFY A WEAK SIGNAL. Ivers Peterson in *Science News*, Vol. 139, No. 8, page 127; February 23, 1991.

BRINGING MORE ORDER OUT OF NOISINESS. John Maddox in *Nature*, Vol. 369, page 271; May 26, 1994.



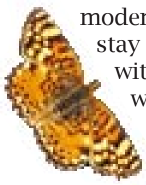
REVIEWS

Six Legs Good

Review by George C. McGavin

BUGS IN THE SYSTEM: INSECTS AND THEIR IMPACT ON HUMAN AFFAIRS, by May R. Berenbaum. Addison-Wesley, 1995 ($25).

Found everywhere from the poles to the equator, from sea level to the highest peaks and from deserts to rain forests, insects are all around us. They are extremely abundant: at any time, there are somewhere around 10 quintillion individual insects on the earth. And they are persistent, having been around for more than 400 million years. It can be argued that insects are the most successful life-form that has ever arisen on this planet. The modern urban dweller might prefer to stay cocooned from direct contact with six-legged creatures, but it would be foolish to ignore them. For every human being alive today, there are more than one billion insects, and we need them more than they need us.



More than half of all known species, and three quarters of all known animal species, are insects. Small size, a waterproof cuticle, phenomenal powers of reproduction and the power of flight all combine to give "bugs" (a term that, more strictly, refers specifically to insects of the suborder Heteroptera) a considerable edge over other animals. And there are, of course, many more insect species than those to which we have given names. By various reckonings there are anywhere from three to 30 or more unknown species for every one known. So it is with ample justification that May Berenbaum takes a good, hard look at the negative and positive impact of insects on human affairs and demonstrates just how important insects are to our continued existence.

Bugs in the System begins, not unreasonably, with classification. No, read on—some of this stuff really is fun. Things need names, after all. Thousands of new insect species are described every year; the sheer abundance inevitably makes for a few good stories. While I was aware that romantically inclined entomologists have named new species in honor of sweethearts (a lasting and less embarrassing tribute than a tattoo), I had no idea that a small fly had been given the specific name *thanatogratus* after the Grateful Dead. I need not explain the etymology of *Heerz lukenatcha.*

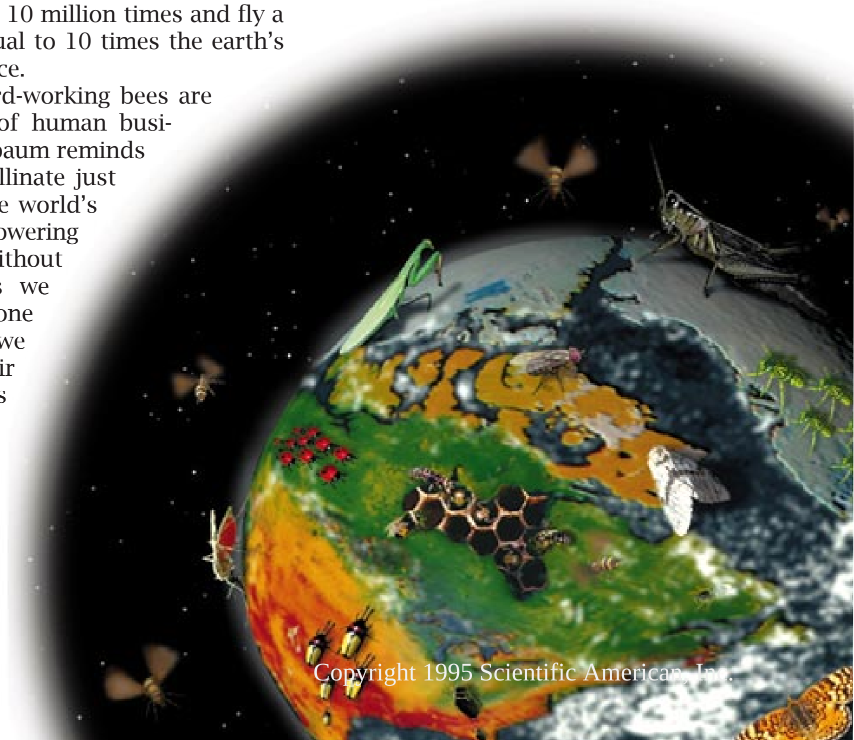
Chapter after chapter reveals astonishing facts and striking interrelationships between our world and that of insects. Berenbaum skillfully imparts her wide-ranging knowledge and infectious enthusiasm for bugs on every page. When it comes to sex, insects show off some of the more startling instances of political incorrectness in the natural world. Male bedbugs, for instance, have dispensed with the niceties of arthropod foreplay and simply stab their intended through the cuticle with a spike-like penis. And let us not forget the intriguing story of the predatory female firefly who has learned to lure the males of other closely related species to their death by imitating the sexual flashing signal of that species and not her own. It's a jungle out there.

Insects contribute to our lives in surprising ways. Even silk aficionados might be startled to learn that what feels so exquisite against the skin is nothing more than insect saliva. Chocoholics can discover how tiny midges play a vital role in the production of their preferred foodstuff. Honey lovers will be pleasantly disgusted to learn that they spread the regurgitated stomach contents of thousands of bees on their breakfast toast. The amount of effort involved in the process is quite remarkable: in order to create one kilogram of honey, worker bees have to visit flowers 10 million times and fly a distance equal to 10 times the earth's circumference.

Those hard-working bees are a big part of human business, Berenbaum reminds us. They pollinate just about all the world's species of flowering plant; without their labors we would lose one third of all we eat. For their part, insects eat almost anything: detritus, carrion, dung, fungi, blood, other insects and, of course, plants, dead or alive. Probably a little under half of all insects are herbivores. Actually, plants are not particularly easy or rich sources of sustenance, but insects have evolved numerous ways of overcoming plant defenses and poor food quality.

As part-time herbivores ourselves, we often run into a conflict of interests. The way we grow our food only exacerbates the problem; insects have not been slow to cash in on the seemingly endless acres of uniform crops we plant every year. On average, we probably lose around one fifth of all that we grow to munching insect mandibles. Why not get some of our own back and eat them? For those inclined to take the question seriously, *Bugs in the System* gives us the lowdown on rustling up some grubs. Insect bodies contain decent concentrations of fats, proteins, carbohydrates, vitamins and minerals. The food value of certain species compares more than favorably with—dare I say it?—hamburgers. More than 500 kinds of insect are regularly eaten by people all around the world, so there is no reason not to get your wok down off the shelf and start cooking. After all, most animals on the earth include some insects in their diets. If insects were to vanish, countless thousands of other animal species would go with them.

No matter how you look at it, insects make ecosystems work. Besides the vital job of pollination, they recycle nu-



trients, enrich soils and dispose of carcasses and dung. And insects are inextricably wound into human society. In addition to silk and honey, they provide us with waxes, medicines, dyes and other useful products. We use them to convict murderers, to catch fish, to rid us of pest insect species and weeds. We use them as model systems to help us understand the many complexities of biology, from behavior to genetics.

There is also the all-too-familiar downside to our buggy companions. Insects are major vectors of animal and plant diseases. Berenbaum shows only too clearly how the ravages of insects have changed the short course of recorded human history. Diseases such as louse-borne typhus have influenced the outcome of wars much more decisively than have weapons. The world has seen three pandemics of plague, the second of which killed one third of the population of Europe.

We are well aware now that plague is caused by a species of bacterium carried by fleas that live on black rats and that bite, among other things, humans. But it was not always so; enlightenment was a long time coming. The first pandemic struck in A.D. 541, and it was not until the early 1900s that the whole picture of plague finally came together. Berenbaum's text brings history to life. The war against insect-borne diseases is, of course, far from over; several million human beings still die every year as a result.

In short, this book is a tremendously good read, packed with information that will appeal equally to biologists and laypersons, students and teachers. Each chapter, on such broad topics as insect physiology, behavior and sociality (there is even a chapter entitled "Appreciating Insects"), takes the reader on a voyage of discovery and ends with a carefully arranged list of references, inviting further exploration. At the department of zoology here at Oxford, we hold a popular, annual bio-trivia quiz. I have already extracted numerous excellent questions with which to test this year's participants.

Another entomology book? Yes, but one with a difference. If you really don't like bugs, pick the book up anyway—it might bite you. Newcomers will be fascinated and intrigued. For old hands at the game, this kind of book reminds us why we took up entomology in the first place and still find the subject so engrossing.

GEORGE C. MCGAVIN is assistant curator of entomology at the Oxford University Museum and lecturer in zoology at Trinity College, Oxford.

Sex Matters

Review by Vern L. Bullough

THE SOCIAL ORGANIZATION OF SEXUALITY: SEXUAL PRACTICES IN THE UNITED STATES, by Edward O. Laumann, John H. Gagnon, Robert T. Michael and Stuart Michaels. University of Chicago Press, 1994 ($49.95). **SEX IN AMERICA: A DEFINITIVE SURVEY,** by Robert T. Michael, John H. Gagnon, Edward O. Laumann and Gina Kolata. Little, Brown and Co., 1994 ($22.95).

These two books, the first the actual study and the second a popular distillation of it, represent the latest and most comprehensive manifestations of what has become an American institution—the sex survey. They may not be great literature, but they do offer a provocative look at the methodology and social influences that color what we know about sex.

Despite the fanfare that accompanied the publication of the books, it is best to approach them with caution, if only because of the rocky history of studies of sexuality. The first published sex survey, conducted by Max Exner and issued in 1915, reported on the masturbatory practices of 948 male college students. It was a poorly designed study, even by the standards of its time, and was further handicapped by the author's belief that "morbid curiosities" should be curbed and sexuality erased from the consciousness of young men. By the 1930s and early 1940s some kind of sex survey appeared almost every year, but none of them claimed to be comprehensive. Even today most so-called sex studies are nonscientific surveys of the readers of certain popular magazines.

Research into sexual practices received a great boost in 1921, when John D. Rockefeller, Jr., established the Committee for Research in the Problems of Sex. When the pioneering work of Alfred Kinsey came to its attention in 1939, the committee offered financial support. But his controversial conclusions instigated a congressional investigation of the foundations that supported such allegedly immoral research. In 1954 the Rockefeller Foundation withdrew from the committee, bringing an end to funded sex surveys. During the 1960s, the National Institute of Mental Health briefly attempted to underwrite some sex studies, but it, too, was forced to retreat from the field.

The lack of national statistics on the incidence of various sexual behaviors became especially critical in the early 1980s, when an epidemic of AIDS appeared imminent. No reliable information existed on the prevalence of homosexuality in the U.S.—and indeed, the extent is still far from settled. In 1987 the National Institute for Child Health and Human Development announced support for two research projects, one on the sexual practices of adults and one on those of teenagers. The institute selected a team at the University of Chicago to carry out the adult survey. Before the institute could award final grants, however, Senator Jesse Helms of North Carolina attached an amendment to a Senate appropriations bill to prohibit the government from financing national sex surveys.


STEPHANIE RAUSSER

SEXUAL BEHAVIOR is a central aspect of our lives, yet data about it remain distressingly hard to find.

Discouraged but not defeated, the Chicago group reorganized its study, cutting the number of subjects from 20,000 to 3,432 people between the ages of 18 and 59. The team also broadened its focus, adding questions and cutting down on the planned epidemiological emphasis. A consortium of private foundations, including the Rockefeller Foundation, funded the project. The results of that work form the body of the books discussed here.

The title of the Chicago survey, the "National Health and Social Life Survey," reflects the theoretical outlook of one of the authors, John H. Gagnon, who believes that sexual practices should be studied in a social context. Kinsey concentrated on sexual behavior. The Chicago researchers seem to be far more interested in the social data than in the sexual data; they have much more information on gender, age, marital status, religious beliefs, acquaintance patterns and other sociological variables than on how their respondents view and practice sex.

The Chicago authors differ from Kinsey in other ways. Kinsey believed that not all people were willing to talk about sex, so he relied heavily on volunteers and included a number of checks for accuracy. In contrast, the University of Chicago team assumed that people would talk openly about their sexuality and that the interviewer could ascertain their honesty without conducting rigorous cross testing. For questions regarding masturbation, a behavior the Chicago group considered to be disapproved of by much of society, the researchers asked the respondent to write down his or her answers and put them in a sealed envelope.

Interestingly, Gagnon and his co-workers took no such precautions for questions about homosexuality. As a result, the survey probably underestimates the extent of homosexuality. There is also the basic problem of how to define homosexuality. The authors used various measures: self-identification (about 1.4 percent of all women and 2.8 percent of the men), homoerotic fantasies (about 5.5 percent of the women and 6 percent of the men) and actual practice (5 percent of the men said they had had same-gender sex at least once since they turned 18, and 9 percent responded that they had had sex with a man at least once since puberty). Percentages for women in the last two categories were about 4 percent.

The uneven geographic distribution of homosexuality complicates establishing its incidence. More than 9 percent of the men in the nation's 12 largest cities identified themselves as gay, compared with 1 percent in rural areas. Because gays, like African-Americans, tend to concentrate in certain areas in a city, special care must be taken to include them in surveys. This compensation was done for African-Americans but not for gays. All we can say with any certainty about the statistics on same-sex activities is that the numbers in *Sex in America* represent the minimum.

From the general sexual practices reported in the study, Gagnon and his colleagues conclude that HIV infection rates will be much lower than those usually predicted. That assessment is based on their finding that couples living together tend not to have other sex partners and that people usually have sex with and marry people of the same race, religion, social class and educational levels as themselves.

The survey yielded some unsettling statistics on the extent of misunderstanding between the sexes. Only 3 percent of the men reported ever having forced a woman to do something sexually she did not want, and more than 97 percent of the men indicated that forced sex did not appeal to them. Yet 22 percent of the women in the study said they had been forced to do something sexual at some time in their life, as compared with just 3 percent of the men. The questionnaire did not clearly define forced sex, but the term did not necessarily constitute rape either legally or in the minds of the female respondents. In most cases, such sex involved individuals they knew.

The Chicago researchers also weighed in on the subject of child sex. Some 12 percent of the men and 17 percent of the women reported they had been sexually touched when they were children. The reported sexual contacts of the women were primarily with males. Men who reported sexual encounters as children had them with both males and with females, but the females were themselves usually teenagers or younger.

In general, the results presented by the University of Chicago paint a comparatively conservative, family-centered portrait of the typical American, an image widely reinforced in the media. But a close reading of the two books suggests that staid image is probably misleading. The investigators steered clear of the most controversial topics. Only one question dealt explicitly with pornography. There were no queries about prostitution, pedophilia, sadomasochism, cross-dressing or any of the dozens of other paraphilias. And in a startling omission, the researchers totally excluded people living in institutions, defined as prisons, army camps and college dorms; the last two of these groups encompass the most sexually active segments in American society.

The Chicago survey reads less as a study of American sex practices than of American social life and health in a sexual context. Even so, it makes an important addition to the data bank on sexual practices. The frustration is that it leaves us realizing how much more there is to know.

VERN L. BULLOUGH is a visiting professor in the department of nursing at the University of Southern California.

Gauging the Heavens

Review by Jay M. Pasachoff

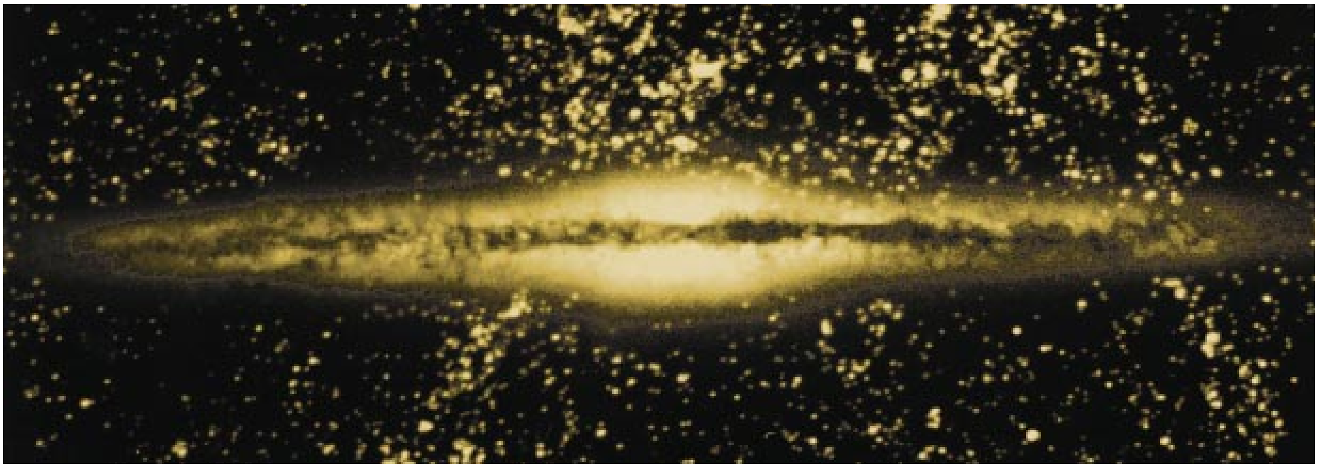
VOYAGE TO THE GREAT ATTRACTOR: EXPLORING INTERGALACTIC SPACE, by Alan Dressler. Alfred A. Knopf, 1994 ($25).

If the title of this book carries a whiff of science fiction, that is understandable. *Voyage to the Great Attractor* is very much a journey into uncharted realms of outer space. Alan Dressler, a young and respected astronomer at the Carnegie Observatories (better known by its ancestral name, the Mount Wilson Observatory), takes us with him as he becomes one of astronomy's "Seven Samurai," a group of scientists searching for nothing less than the structure of our universe. The trip is all the more remarkable because every detail of it is real.

Dressler's voyage parallels the maturation of cosmology into a quantitative science. An important step in this process took place in the 1920s and 1930s, when Edwin P. Hubble and his associates discovered the redward shift of light from distant galaxies, a finding now understood as a consequence of the expansion of the universe. Astronomers have since learned to work backward, deducing the approximate distance to galaxies by measuring how much their light has been stretched, or redshifted. With that information, we can break out of the two dimensions that we see in the sky and begin to get a full, three-dimensional view of the universe.

Dressler and his colleagues set out to chart our section of the universe by studying in detail the distribution of bright elliptical galaxies. Ever since the time of Hubble, our mind-set has been to think of the universe as expanding uniformly. But as Dressler explains, his team was forced to break with that paradigm when it found groups of galaxies whose redshifts seemed unexpectedly large given their brightness—that is, they seemed to be expanding away too quickly.

This startling finding soon garnered Dressler and his six collaborators (Sandy Faber, Donald Lynden-Bell, Roberto Terlevich, Dave Burstein, Gary Wegner and Roger Davies) the Seven Samurai nickname. Then, much like D'Artagnan joining the Musketeers, Ofer Lahav of the University of Cambridge became the eighth samurai when he provided a map that revealed a vast clumping of galaxies, qualitatively different from any known cluster. The gravity from this cosmic gathering seemed to be accelerating all the surrounding galaxies in its



GREAT ATTRACTOR shows up as a concentration of galaxies (white dots) *cutting across the image of a galaxy that represents the Milky Way.*

direction, causing the anomalous redshifts. In an offhand comment during a press conference, our author referred to the galactic pileup as the "Great Attractor," a flashy name that captured attention within and well beyond the astronomical community.

Perhaps such a term is necessary these days when people also hear astronomers talk about an immense "slice of the universe" and its "Great Wall," although Dressler reflects on the negative as well as the positive points of having such a simplistic peg on which to hang a mental image. Indeed, we see how Dressler and his co-workers feel left behind by the immediate shift in public interest to the Great Wall of galaxies discovered by a Harvard-Smithsonian team. Time and again *Voyage to the Great Attractor* brings us behind the scenes to reveal the feelings of the scientists as their work progresses, sometimes one step back for every two or three forward.

Dressler introduces us, but not too deeply, to his fellow samurai. We see how they interact, as well as how they clash for personal and scientific reasons. From his position at the Carnegie Observatories, Dressler was able to contribute time on his institution's telescope in Chile, in addition to his own ideas and approach to research. He describes the evolution of the data sets that eventually brought him and his collaborators to the revolutionary idea that our universe's expansion is far less regular than astronomers once thought. Large regions of the cosmos are held back from the overall expansion (known as the Hubble flow) by the gravity of massive collections of objects like the Great Attractor. Such large-scale structures and motions surprised cosmologists, because other evidence indicates that the universe was very smooth soon after the time of the big bang.

In recounting the tortuous path toward the discovery of the Great Attractor, Dressler wends through a wide variety of today's cosmological thought. We face the uncertainties, errors and problems of interpretation that affect real scientific data. Philosophers of science may not be able to define precisely what the scientific method is, but readers of this book will understand better by the end how science is done.

Dressler often explains by analogy. In one passage he recounts spending the night at the observatory with an assistant, clicking off the redshifted spectrum of a new galaxy every five minutes: "I, the telescope, and the computer, were chugging along like some infernal contraption; charts flying, motors whirring, computer beeping, and, at the heart, two humans piloting their way through deep space at a madcap pace. I can think of no better image than Toad in his motorcar in Disney's animated version of Kenneth Grahame's *The Wind in the Willows*—eyes lit up like headlights, bouncing, exulting, merrily on his way to 'nowhere in particular.' "

Dressler paints an honest picture of cosmology, describing its problems as well as its successes. He includes the viewpoint of those who object to the idea of the Great Attractor and evaluates their reservations. He leaves the reader in good shape to understand the methodology and importance of results now flowing in from the *Hubble Space Telescope,* most notably the much discussed recent measurements of the expansion of the universe that seem to leave our universe younger than some of its parts. Dressler's lucid explanations benefit from the well-chosen graphs and diagrams scattered throughout.

In retrospect, the evidence for the Great Attractor has held up well, although doubters remain. Some observers have reported what might be called an "Even Greater Attractor." Above all, astronomers now widely accept the once radical idea that huge mass concentrations distort the (overall) uniform Hubble flow.

I agree with Dressler that he has earned the right, at the end of the book, to "speculate with something less than the full scientific rigor required for the body of the paper." He expounds on the nature of the scientific enterprise and on the value of science for society. He is an optimist in some general sense, remembering that "millions of people live more comfortable and healthy lives than any Pharaoh ever did."

Dressler's most interesting reflections concern the broader implications of his work. He concludes that "in all likelihood, *our* universe contains all that we will ever know; the *universe* of other realms of existence that lies beyond is inaccessible, probably forever. If this is true, then it is not outrageous to believe that we can know 'all there is to know.' " (Although the book is, on the whole, carefully put together, I would have been happier with fewer italics and with a proper distinction made between "enormity" and "enormousness." The forthcoming paperback edition will incorporate some of these changes.)

After a few hundred pages of scientific and personal details, Dressler returns to earth with his thoughtful conclusion that "it is time to take full stock of the discovery that life is the most complex thing we know of in the universe, and, as such, most worthy of our admiration." We have traveled outward from our galaxy to the largest known structures in the universe. It is refreshing to be reminded that our own brains provide the ship for the voyage.

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by Abigail Zuger

The High Cost of Living

We see all comers in the mid-Manhattan HIV clinic where I work, from healthy asymptomatic carriers of the virus to emaciated men and women suffering from the late stages of AIDS. The sick and the well mingle in the cramped waiting room and try not to meet one another's eyes. I have gotten used to reassuring the healthy patients who burst out, "Am I going to look like that?" as soon as they sit down in my room. "Soon, I hope, we'll have treatments to keep you as well as you are for a long time," is my usual, careful response.

What I still have not gotten used to are healthy patients who spend their time with me not affirming their health but instead trying to convince me of how ill they are. These visits, more frequent as government benefits for people infected with HIV become more generous, never fail to give me pause.

My session with Dominique a few months ago was typical of such encounters. A plump woman in her early twenties, Dominique was born to drug-using parents, weathered a stormy adolescence in one of the city's worst neighborhoods and found she was HIV-infected after a series of short liaisons with drug-using partners. The group home for young runaways, where she is slowly stabilizing, sends her to our clinic for periodic blood tests and checkups. The visits are usually fairly cursory: despite her positive HIV test, Dominique is entirely healthy. On a cellular level, her immune system is waging an all-out battle against the virus, but it is still managing to hold its own. All her tests of immune function are normal.

"How's my *T* count?" Dominique demanded. Most of our patients keep a close eye on their helper *T* cell count, the most commonly used indicator of the health of their immune system.

"Still completely normal!" I always enjoy being able to deliver *some* good news in the course of a day.

"Oh." Dominique frowned a little. I stared and waited for what came next.

"I thought it would be low, since I got the thrush so bad."

"You do?" Thrush is a patchy-white fungal infection of the palate and gums that often develops in HIV-infected people when their immune system begins to fail. I rapidly tried to remember my last view of Dominique's mouth. When treating people whose *T* cell counts are normal—Dominique's, at 1,050 per cubic millimeter, is right on the mean—and whose chances of acquiring thrush are essentially nil, I often cut a few corners on the exam.

"Yep." She nodded emphatically. "Real bad."

"Let's take a look."

"You don't have to look. I'm telling you, it's real bad."

"Let's take a look," I repeated. She climbed up onto the examining table, and I shone a light into the crenated pink canyons of an entirely normal mouth.

"It looks just fine. Don't worry, there's no thrush in there."

I was not entirely surprised when she frowned again, headed for the mirror over my sink and opened her mouth wide. She gestured at the row of papillae at the very back of her tongue.

"There. You see—there. Those big bumps. Those are the thrush, right?"

"Those are just your taste buds, I'm afraid."

"You sure?"

I was sure.

Far from kissing me with joy and relief, Dominique stalked out of my office without even saying good-bye. A few minutes later her clinic social worker handed me a form to fill out and confirmed what I had already figured out—with a diagnosis of thrush Dominique would have had a much better shot at getting a subsidized apartment of her own than she has as a healthy person. Now she will be discharged from the group home back to her aunt's overcrowded apartment, back in the very neighborhood that brought her to so much grief.

Dominique is not the first patient I have known to try to barter health for food, clothes or shelter; patients like her have anxiously assured me and my colleagues that they have everything from nonexistent diarrhea and weight loss to nonexistent HIV infection. The phenomenon never fails to startle and sadden us, although we know perfectly well that malingering is an inevitable part of medical practice. As Hector Gavin wrote in 1843 in his 400-page history *Of Feigned and Factitious Diseases,* "The monarch, the mendicant, the unhappy slave, the proud warrior, the lofty statesman, even the minister of religion... have sought to disguise their purposes, or to obtain their desires, by feigning mental or bodily infirmities."

This time-honored modus operandi takes on a heightened pathos and complexity in the context of HIV. It does so partly, I suppose, because the machinators are eventually so likely to develop precisely the symptoms they now feign. But more than that, their behavior clearly illuminates the dismal context of urban HIV infection, in settings where even the jerry-built social supports set up for those infected with the AIDS virus are a prized source of security. Those of us who work regularly with HIV-infected people know well the instinctive tenacity with which they cling to their health. It is painful to imagine the desperation that would induce someone like Dominique to do otherwise.

Dominique and the others cast us into roles that none of us had bargained for when we took on this work: police rather than physicians, antagonists rather than advocates. Medical schools omit these other aspects of our careers from their curriculums, leaving us free to figure out our parameters for ourselves. I have colleagues who cheerfully, even aggressively, embroider their patients' documents with all manner of lavishly bestowed misdiagnoses. If their mission is to care for the whole patient, they reason, then surely the securing of food and shelter is as central to their job as anything else.

I see their point, but I am still not quite ready to take that leap and diagnose the vallate papillae of the tongue as thrush. I gave Dominique a perfect bill of health on her housing form. She has not been back to see me since.

ABIGAIL ZUGER is an infectious disease specialist in New York City. Her book, Strong Shadows: Scenes from an Inner-City AIDS Clinic, *will be published by W. H. Freeman and Company this coming fall.*