HOW THE BODY KNOWS LEFT FROM RIGHT • A CLEVER SEARCH ENGINE

SCIENTIFIC AMERICAN

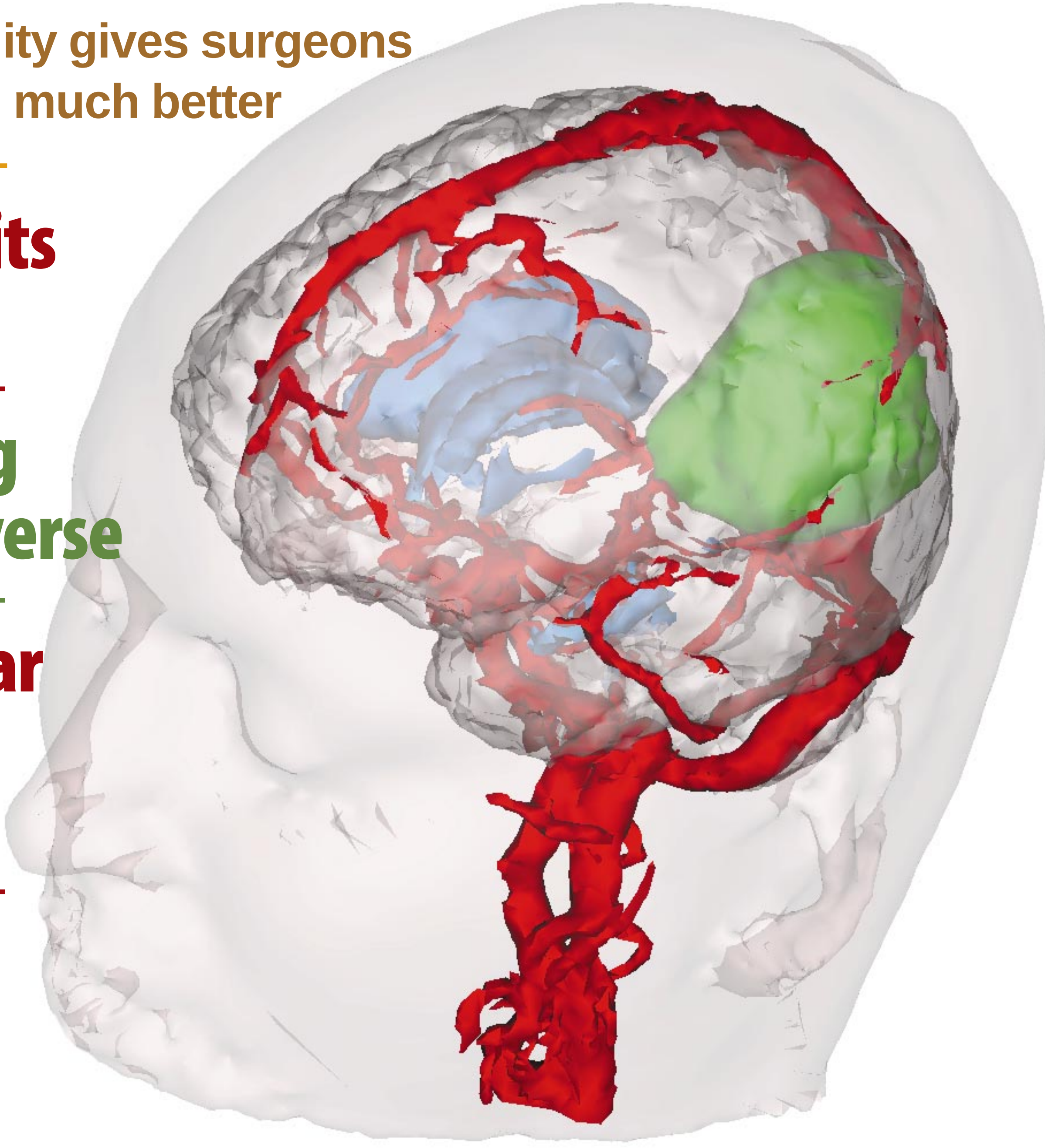
JUNE 1999 $4.95 www.sciam.com

EXPEDITIONS: THE BATS OF BELIZE

Scanners and Scalpels

X-ray vision?

Virtual reality gives surgeons something much better



The Limits of Logic

Mapping the Universe

Germ War against Crops

SCIENTIFIC AMERICAN

June 1999 Volume 280 Number 6

Scientific American (ISSN 0036-8733), published monthly by Scientific American, Inc., 415 Madison Avenue, New York, N.Y. 10017-1111. Periodicals postage paid at New York, N.Y., and at additional mailing offices. Canada Post International Publications Mail (Canadian Distribution) Sales Agreement No. 242764. Canadian BN No. 127387652RT; QST No. Q1015332537. Subscription rates: one year $34.97 (outside U.S. $49). Institutional price: one year $39.95 (outside U.S. $50.95). Postmaster: Send address changes to Scientific American, Box 3187, Harlan, Iowa 51537. Reprints available: write Reprint Department, Scientific American, Inc., 415 Madison Avenue, New York, N.Y. 10017-1111; fax: (212) 355-0408 or send e-mail to sacust@sciam.com **Subscription inquiries: U.S. and Canada (800) 333-1199; other (515) 247-7631.** Printed in U.S.A.

About the Cover
This three-dimensional model of a patient's head and brain was assembled from medical scan data. The green area represents a tumor. Image courtesy of Michael Leventon of the Artificial Intelligence Laboratory, M.I.T.

From the Editors

The Adventures of Bat Men

Glenn Zorpette is either going to outlive the rest of Scientific American's Board of Editors, or he's going to perish way ahead of schedule; I can't decide which. He keeps his diet estimably rich in vegetables and spends lunch hours at the gym. When he wrote last year about exercise and body image, his own published statistics ("5′ 10½″, 167 lbs., 7% body fat") attracted considerable mail, some of it asking for dates.

On the other hand, Glenn also volunteers for assignments that risk raising our insurance premiums. Consider that he dove more than 150 feet down, and suffered severe nitrogen narcosis, in the crater of Bikini Atoll to discover how it has recovered from H-bomb testing [see "Bikini's Nuclear Ghosts"; Scientific American Presents: *The Oceans,* Fall 1998]. That intrepidness makes him a natural contributor to our Expeditions feature, in which journalists report from the field about researchers' experiences.

STEVE WINTER

ABOARD THE* MEDDY BEMPS, *Glenn Zorpette found harsh conditions and new foods.

For the latest installment, Glenn and photographer Steve Winter hitched along with Bruce W. Miller and Michael J. O'Farrell as they took ultrasonic recorders into Belize's remote, unspoiled Toledo district to count and classify bats on the wing. Roads in Toledo are few and far between, so the scientists conducted their survey along two rivers on board a former lobstering boat, the *Meddy Bemps.*

"The trip was almost over before it started," Glenn recalled, back in our offices. Entering the mouth of the Sarstoon River, the border between Belize and Guatemala, the *Meddy Bemps* grounded repeatedly on the shifting patchwork of shoals. In desperation, the motorman had finally approached some fishers on the Guatemalan side to ask where the deeper water was. "The color suddenly drained out of Miller's face, and I realized the boat was flying a Belizean flag and we were technically in Guatemala without permission," Glenn said. "Relations between Belize and Guatemala could be better, and the boat might have been confiscated if the Guatemalan military had been around."

Fortunately for bat buffs, an international incident was avoided. For the next week, the team instead endured mosquitoes, barking spiders, doctor flies, stormy waves, cramped conditions, spotty food supplies, a case of giardiasis, cold weather and warm beer. But one night, 12 miles up the Temash River, they happened on a "hot spot," the bat equivalent of a feeding frenzy. Miller and O'Farrell are fairly sure that among the species gorging on insects was the northern ghost bat, a creature as elusive as its name suggests. Glenn relates the adventure, beginning on page 82.

John Rennie

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

SCIENTIFIC AMERICAN®
Established 1845

John Rennie, EDITOR IN CHIEF

Board of Editors
Michelle Press, MANAGING EDITOR
Philip M. Yam, NEWS EDITOR
Ricki L. Rusting, SENIOR ASSOCIATE EDITOR
ASSOCIATE EDITORS: Timothy M. Beardsley; Gary Stix
W. Wayt Gibbs, SENIOR WRITER
Kristin Leutwyler, ON-LINE EDITOR
EDITORS: Mark Alpert; Carol Ezzell; Alden M. Hayashi; Madhusree Mukerjee; George Musser; Sasha Nemecek; Sarah Simpson; Glenn Zorpette
CONTRIBUTING EDITORS: Marguerite Holloway; Steve Mirsky; Paul Wallich

Art
Edward Bell, ART DIRECTOR
Jana Brenning, SENIOR ASSOCIATE ART DIRECTOR
Johnny Johnson, ASSISTANT ART DIRECTOR
Bryan Christie, ASSISTANT ART DIRECTOR
Heidi Noland, ASSISTANT ART DIRECTOR
Mark Clemens, ASSISTANT ART DIRECTOR
Bridget Gerety, PHOTOGRAPHY EDITOR
Richard Hunt, PRODUCTION EDITOR

Copy
Maria-Christina Keller, COPY CHIEF
Molly K. Frances; Daniel C. Schlenoff; Katherine A. Wong; Stephanie J. Arthur; Eugene Raikhel; Myles McDonnell

Administration
Rob Gaines, EDITORIAL ADMINISTRATOR
David Wildermuth; Eli Balough

Production
Richard Sasso, ASSOCIATE PUBLISHER/VICE PRESIDENT, PRODUCTION
William Sherman, DIRECTOR, PRODUCTION
Janet Cermak, MANUFACTURING MANAGER
Carl Cherebin, ADVERTISING PRODUCTION MANAGER
Silvia Di Placido, PREPRESS AND QUALITY MANAGER
Georgina Franco, PRINT PRODUCTION MANAGER
Norma Jones, ASSISTANT PROJECT MANAGER
Madelyn Keyes, CUSTOM PUBLISHING MANAGER

Circulation
Lorraine Leib Terlecki, ASSOCIATE PUBLISHER/VICE PRESIDENT, CIRCULATION
Katherine Robold, CIRCULATION MANAGER
Joanne Guralnick, CIRCULATION PROMOTION MANAGER
Rosa Davis, FULFILLMENT AND DISTRIBUTION MANAGER

Subscription Inquiries
U.S. AND CANADA 800-333-1199; OTHER 515-247-7631

Business Administration
Marie M. Beaumonte, GENERAL MANAGER
Constance Holmes, MANAGER, ADVERTISING ACCOUNTING AND COORDINATION

Electronic Publishing
Martin O. K. Paul, DIRECTOR

Ancillary Products
Diane McGarvey, DIRECTOR

Chairman
John J. Hanley

Co-Chairman
Rolf Grisebach

President and Chief Executive Officer
Joachim P. Rosler

Vice President
Frances Newburg

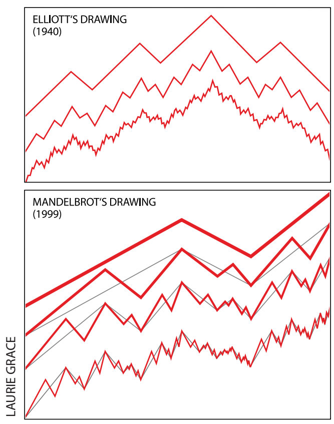
Scientific American, Inc.
415 Madison Avenue
New York, NY 10017-1111
(212) 754-0550

Benoit B. Mandelbrot's article "A Multifractal Walk down Wall Street" in the February issue elicited myriad responses from readers. Robert Ihnot of Chicago found the article rather bewildering. "If we know that a stock will go from $10 to $15 in a given amount of time," he writes, "it doesn't matter how we interpose the fractals, or whether the graph looks authentic or not. The important thing is that we could buy at $10 and sell at $15. Everyone should now be rich, so why are they not?" Additional comments are included below.

FRACTALS AND FINANCE

I am impelled to point out that most of the ideas presented in Benoit B. Mandelbrot's article "A Multifractal Walk down Wall Street" [February] originated with Ralph Nelson Elliott, who put them forth more comprehensively and more accurately with respect to real-world markets in his 1938 book *The Wave Principle*. Figure 1 shows an illustration from Elliott's literature depicting the multifractal nature of markets; figure 2 shows Mandelbrot's exposition. Slight differences in the specific pattern used in these diagrams are irrelevant because Mandelbrot is not arguing a specific form, just multifractal self-affinity. For a detailed response to Mandelbrot's article, please visit http://www.elliottwave.com/response.htm on the World Wide Web.

ROBERT R. PRECHTER, JR.
President, Elliott Wave International
Gainesville, Ga.



SUSPICIOUSLY SIMILAR? Benoit Mandelbrot begs to differ.

As a member of the financial services industry, I agree with many of Mandelbrot's observations of the market's uncertainty and volatility. But I disagree with the article's findings for a couple of reasons. First, with regard to modern portfolio theory (MPT), Mandelbrot only used single security positions to illustrate his point. I don't believe any practitioners of MPT would use it to predict the outcome of a single position such as Alcatel or the dollar–deutsche mark exchange rate. The article would have carried more validity if the comparison had been set against a portfolio of diversified assets. Second, Mandelbrot is correct that MPT accounts for 95 percent of all probable market outcomes, leaving unaccounted for those rare events at the extremes. Throughout history our financial markets have been hit with extreme events, and this is built into the universe of statistical data. But what has been accomplished by testing the realm of the remaining 5 percent? What assets should make up a portfolio for events that history has never seen?

WILLIAM M. LAVANNE
Lake Zurich, Ill.

Mandelbrot replies:

At some point Ralph Elliott's "principle" and my cartoon simulations both use recursive interpolation in which each part is a reduced-scale version of the whole. The idea is ancient, but his use and mine stand in absolute contrast. Elliott drew a certain nonrandom "wave" that he claimed "really forecasts" every real-world market; however, this simplistic wave was first stretched, squeezed or otherwise adjusted by hand. In contrast, fractal or multifractal models must follow firm mathematical rules that allow quantitative developments throughout, as mine do. In any event, the random or nonrandom cartoons themselves are of no interest; they serve only to introduce the subtle quantitative properties and tools of my model of price variation—fractional Brownian motion in multifractal time. The rules of this model are not recursive but fully specified mathematically and can be adjusted to fit the historical financial data.

Lavanne acknowledges that modern portfolio theory (MPT) discards 5 percent of the evidence but ends by asserting that the effects of the disregarded extremes are never seen in history. Of course they are. They include the "10 sigma" storms (market fluctuations greater than 10 standard deviations) that dwarf everything that MPT considers and are continually blamed for portfolio failures.

WASHING THE LUNGS?

I read with interest the report "Breath of Fresh Liquid," by W. Wayt Gibbs [News and Analysis, February], which discussed the use of perfluorocarbon liquids in the treatment of lung ailments. It raised a question that has been niggling at my hindbrain for some time. Some contaminants, such as vapors or metal fumes, are instantly absorbed by the bloodstream. But particulates such as asbestos fibers, lead paint dust, or even relatively nontoxic dusts and soot just physically clog the lungs. Yet there is generally no immediate treatment aside from pure oxygen. Could oxygenating liquids like perfluorocarbons be used to clean such particles from the lungs, or does the fact that they generally evaporate instead of being coughed out preclude this as a treatment method?

ROBERT L. CARLSON
Green Knight Environmental
Consulting Services
via e-mail

Pediatric surgeon Ronald B. Hirschl of the University of Michigan replies:

Many investigators have been interested in the application of perfluorocarbons as lung-washing, or lavage, agents. One of our first adult patients who underwent partial liquid ventilation had aspirated charcoal slurry, which resulted in lung failure. The perfluorocarbon mobilized the charcoal into the patient's central airways where it could be re-

OTHER EDITIONS OF SCIENTIFIC AMERICAN

Spektrum der Wissenschaft
Verlagsgesellschaft mbH
Vangerowstrasse 20
69115 Heidelberg, GERMANY
tel: +49-6221-50460
redaktion@spektrum.com

Pour la Science
Éditions Belin
8, rue Férou
75006 Paris, FRANCE
tel: +33-1-55-42-84-00

LE SCIENZE
Le Scienze
Piazza della Repubblica, 8
20121 Milano, ITALY
tel: +39-2-29001753
redazione@lescienze.it

Investigacion y Ciencia
Prensa Científica, S.A.
Muntaner, 339 pral. 1.ª
08021 Barcelona, SPAIN
tel: +34-93-4143344
precisa@abaforum.es

Majallat Al-Oloom
Kuwait Foundation for
the Advancement of Sciences
P.O. Box 20856
Safat 13069, KUWAIT
tel: +965-2428186

Swiat Nauki
Proszynski i Ska S.A.
ul. Garazowa 7
02-651 Warszawa, POLAND
tel: +48-022-607-76-40
swiatnauki@proszynski.com.pl

Nikkei Science, Inc.
1-9-5 Otemachi, Chiyoda-ku
Tokyo 100-8066, JAPAN
tel: +813-5255-2821

Svit Nauky
Lviv State Medical University
69 Pekarska Street
290010, Lviv, UKRAINE
tel: +380-322-755856
zavadka@meduniv.lviv.ua

ΕΛΛΗΝΙΚΗ ΕΚΔΟΣΗ
Scientific American Hellas SA
35–37 Sp. Mercouri St.
Gr 116 34 Athens GREECE
tel: +301-72-94-354
sciam@otenet.gr

Ke Xue
Institute of Scientific and
Technical Information of China
P.O. Box 2104
Chongqing, Sichuan
PEOPLE'S REPUBLIC OF CHINA
tel: +86-236-3863170

moved via routine suctioning. And studies suggest that perfluorocarbons may aid in clearing the lungs of patients suffering from diseases such as cystic fibrosis in which the lungs are filled with large amounts of mucus and other inflammatory debris. Extending this concept to include the lavage of inhaled fibers, dust or soot is reasonable and may prove beneficial in the future.

TRAPPING ANTIPROTONS

In her box entitled "Reaching for the Stars" ["The Way to Go in Space," February], Stephanie D. Leifer states that the first steps toward determining the feasibility of antimatter propulsion are being taken "under NASA sponsorship," citing the design and construction of a "device in which antiprotons could be trapped and transported" by researchers at Pennsylvania State University. In truth, cold antiprotons were first trapped in 1986 by researchers at Harvard University, the University of Washington and the University of Mainz. We stored the antiprotons using electrical and magnetic fields in a device called a Penning trap, which was intrinsically portable. Over the past decade, nearly a million antiprotons have been stored in our apparatus and used to compare precisely the charge and mass of the antiproton and proton. Without debating the merits of antiproton propulsion, it seems inappropriate to pretend that the research program mentioned by Leifer is doing anything more than playing catch-up. We've been there and done that long ago.

GERALD GABRIELSE
Harvard University

Editors' note:

Leifer's original manuscript referred to an article Gabrielse wrote for Scientific American ["Extremely Cold Antiprotons," December 1992] on this research, but space limitations did not permit us to include that reference in her short piece.

Letters to the editors should be sent by e-mail to editors@sciam.com or by post to Scientific American, 415 Madison Ave., New York, NY 10017. Letters may be edited for length and clarity. Because of the considerable volume of mail received, we cannot answer all correspondence.

50, 100 AND 150 YEARS AGO

SCIENTIFIC AMERICAN

JUNE 1949

NEURAL TECHNIQUE—"Two University of Chicago physiologists, Ralph W. Gerard and Robert T. Tschirgi, have succeeded in keeping a large section of a rat's spinal cord alive and functioning outside the animal's body. Placed in a trough after dissection, it is supplied with blood or an artificial nutrient through the spinal-cord arteries. Gerard and Tschirgi have already found five distinct substances capable of furnishing energy for nerve. (Glucose had previously been considered the only energy source.) They have also been able to demonstrate that spinal-cord function—in apparent contrast to accepted theories of brain function—can be restored after as much as 30 minutes of oxygen or glucose deprivation."

ANCIENT SLAVERY—"During the past century and a half the civilized world has rightly come to regard slavery as a degradation of human values and an economic and social stupidity. For 3,000 years of pre-Christian history, on the other hand, no ethical misgivings can be detected in the legislation set up to control slave systems, whether old Babylonian, old Hittite, Assyrian, or the Hebrew of the Old Testament. Our illustration reproduces a bas-relief on the tomb of the Pharaoh Harmhab, who lived around 1350 B.C. The bas-relief shows a group of Negro captives guarded by Egyptian soldiers. At the right a scribe keeps tally of the prisoners, captured by Harmhab after one of his military expeditions in surrounding countries."

Ancient Egyptian bas-relief depicting slavery

JUNE 1899

MIND AND MEDICINE—"Dr. Edward C. Spitzka, of New York, the noted alienist, has recently given several really remarkable instances of the power of mental suggestion. 'In the graver forms of hysteria,' says Dr. Spitzka, 'when loss of sensation occurs in exactly one-half the body, you can lay a piece of tinted paper on the sensitive side; then suggesting it to be a mustard plaster, a red area will appear on the corresponding unsensitive side.' Such blisters have produced permanent scars in similar cases. It is quite possible that the extent to which this mental suggestion may be advantageously employed is not fully appreciated by the medical profession."

TIME, MOTION, MONEY—"A true comparison of the relative cost of operation of cable, electric, and horse traction for street railways points unmistakably to the great superiority of electricity over both horses and cable, not only in traffic-handling capacity, but in economy. On January 1, 1893, the entire street railway system of New York City was operated by horses. The latest report shows that the company operated 27.2 per cent of its car mileage by the cable system, 33.7 per cent by horses and 39.1 per cent by the electric system, and at an operating expense per mile of 17.55 cents, 17.89 cents and 10.06 cents, respectively. It overturns all established ideas to find that the cheapness of electric traction is in the greater speeds that are possible with the cars."

MESOPOTAMIAN MEDICINE—"Until recently, the only evidence about medical knowledge in ancient Babylonia and Assyria was the so-called magical cuneiform tablets—conjurations against diseases and the demons supposed to be responsible. However, Dr. Christopher Johnston has found, from the library of [King] Assurbannipal, several letters from physicians. One interesting tablet may describe a facial erysipelas [a streptococcal infection]: 'All goes well in regard to that poor fellow whose eyes are diseased. I had applied a dressing covering his face. Yesterday, undoing the bandage which held it, I removed the dressing. There was pus upon it the size of the little finger tip. All is well. Let the heart of my lord the king be of good cheer.'"

JUNE 1849

THWARTING FRICTION—"Messrs. R. L. and B. F. Stevens have constructed an iron vessel which is now in this City [New York] to test the principle of their new invention, which they have patented. The principle of the invention consists in applying air to the immersed surface of a vessel in motion, and thus interposing, by a continuous or intermittent supply, a stratum of air between the immersed surface of the vessel, and the water, for the purpose of reducing the friction of the water."

GLASS-WEAR—"At the Polytechnic Institution in London is exhibited one pound of glass, spun by steam into four thousand miles, and woven with silk into beautiful dresses and tapestry."

HONEST ABE'S INVENTION—"Patents issued from the United States Patent Office for the week ending May 22, 1849: . . . 'To A. Lincoln of Springfield, Ill., for improved method of lifting vessels over shoals.'"

NEWS AND ANALYSIS

IN FOCUS

EXPLOSIVE REACTIONS

A backlash from a nuclear espionage case might hurt science and do little to bolster national security

All the headlines, political finger-pointing and demands for tightened access seemed inevitable in the wake of the purported spying incident at Los Alamos National Laboratory. Several reports have called it the worst instance of espionage since the Rosenberg case. Senator Richard C. Shelby of Alabama, chair of the Senate's Select Committee on Intelligence, called for banning foreign scientists from visiting any U.S. nuclear labs to prevent the "hemorrhaging" of bomb secrets.

But whether the responses are in line with the espionage threat is debatable, many arms-control experts say. Moreover, draconian measures, such as barring foreign visitors, could hamper U.S. science and defeat a basic goal of the nation's labs: maintain the global nuclear balance.

The furor began on March 6, when the *New York Times* reported that the U.S. was investigating a Los Alamos scientist who, in the mid-1980s, may have passed to China secrets of the W-88—the thermonuclear warheads in Trident II submarine-launched ballistic missiles. The suspicion stemmed from seismic readings of China's underground nuclear tests, which strongly resembled the rumblings produced by the W-88. More important, a Chinese document (obtained through U.S. espionage) contained a specific reference to the Los Alamos–born device. With W-88 technology, China could produce warheads small enough so that it could fit several onto a single missile, as the U.S. does now with its arsenal. Largely from circumstantial evidence, suspicion fell on Wen Ho Lee, a U.S. citizen born in Taiwan—China's bitter adversary.

Legislators and others pounced on the Clinton administration, which waited more than a year before acting on the spying report delivered in 1996 by Department of Energy counterintelligence. The speculation is that the White House avoided the issue so as not to harm its policy of "constructive engagement" of China. Politicians also jumped on word of less than stellar security at the labs, citing a DOE review giving Los Alamos a "marginal" rating (the middle of a three-tiered scale) and a General Accounting Office finding that the backgrounds of only 5 percent of scientists visiting from "sensitive" countries were checked. Several panels and committees announced plans to examine lab security.

ERIC O'CONNELL

ACCESS DENIED: the classified section of Los Alamos National Laboratory is generally off-limits to foreign nationals.

While recognizing the danger of leaks, many arms-control observers think the U.S. is overreacting. "There's some piling on going on here," remarks Christopher E. Paine of the Natural Resources Defense Council in Washington, D.C. "People were hammering the labs because they allowed [foreign] delegations to visit."

Closing off these institutions would undermine the labs' efforts with former enemies to help stabilize the nuclear balance of power. The visits began after the cold war, when the Bush administration sought to stem the outflow of Russian weapons scientists. Collaborating on basic science, noted former Los Alamos director Siegfried S. Hecker in a *Washington Post* editorial, "opened the door for discussions of nuclear materials security"—first with Russia, then with China. John C. Browne, Los Alamos's current director, echoed that philosophy in congressional testimony on October 6, 1998: "To perform the lab's national security mission, it is vital that the lab interacts with the best scientists in the world."

The current media frenzy has painted Los Alamos as "an open sewer," complains Dipen Sinha, one of the 7,000 or so full-time employees on the 43-acre campus. That foreign visitors could mill about freely or that scientists casually give away secrets over cafeteria food is "baloney," he says. If escorted visits are necessary, precautions such as draping computer screens are taken, explains Los Alamos spokesperson Jim Danneskiold.

Even so, during the past couple of years—and with greater urgency since the spy case became public—Los Alamos has been instituting stricter protocols. They include polygraph tests, additional guards, an on-site counterintelligence office and a restructuring of the unclassified computer network "so that the vast majority of it is behind a firewall," Danneskiold says. A temporary shutdown in April of the classified computers (which are separate from any external network) was to plug a few holes—preventing, for instance, the surreptitious transfer of disk contents from a classified machine to an unclassified one.


SARAH MARTONE *AP Photo*

BANNING FOREIGN VISITORS, a drastic step, was proposed by Senator Richard C. Shelby after his April tour of Los Alamos.

In any case, a crackdown on foreign nationals would not have saved the W-88 secrets. Officials think Lee revealed the technology on a trip to China in the 1980s. Lee says he refused to divulge information to an inquiring Chinese official. But because he failed to report this contact and was deemed deceptive during an interview by the Federal Bureau of Investigation, Browne and DOE secretary Bill Richardson fired him on March 8. Hoping to find evidence to bring charges, the FBI carted off boxes of material after searching Lee's house. (Banning foreign visitors, however, would have kept Lee from working in 1997 with a Chinese researcher, who the FBI later determined has no connection to Chinese intelligence.)

Foreign-born scientists make up a small but important population at Los Alamos. As of March, 185 of the 365 Los Alamos postdoctoral fellows were foreign nationals. This dependence is mirrored throughout the rest of U.S. science: the National Science Foundation estimates that one third of all Ph.D. science students come from outside the U.S. and that nearly two thirds plan to stay—thereby filling a gap left by U.S.-born students seeking other careers. Perhaps more disturbing, the concern with foreign nationals seems to be affecting other science forums: scientific societies charge that the State Department has increasingly delayed the visas for some foreign scientists, thereby preventing them from attending open meetings.

Whether restricting foreign access could have helped in other espionage cases, however, might be contained in a report initiated by an intelligence committee chaired by Representative Christopher Cox of California, which at press time was available only to Congress and executive-branch officials. The report supposedly details several instances of espionage and the transfer of computer and satellite technology. Besides the W-88, the nuclear secrets obtained include refinements for the neutron bomb, the basics of which China purportedly stole from the U.S. in the mid-1980s.

That the W-88 and other nuclear thefts occurred during the height of the cold war illustrates how hard it is to maintain absolute security. "No secret stays secret forever," remarks arms-control expert Frank N. von Hippel of Princeton University. He and Steven Aftergood, a secrecy analyst at the Federation of American Scientists, cite a July 1970 report by a task force that included such physics giants as Frederick Seitz and Edward Teller. It concluded that "it is unlikely that classified information will remain secure for periods as long as five years." One year is more likely. "These secrets are contained inside the heads of people," says historian Richard Rhodes, author of *The Making of the Atomic Bomb*. "I don't see how you can secure that."

Rhodes and others also insist that the transfer of the W-88 secrets in no way compares with the Manhattan Project espionage, in which Klaus Fuchs and others delivered plans of the atomic bomb to the Soviet Union via the Rosenbergs. One difference, Rhodes notes, is that the U.S. was a nuclear monopoly in 1945. China also has yet to show outward signs of exploiting U.S. miniaturization technology by, say, moving to a multiple-warhead system. "The incremental growth in threat to the U.S. to me seems vanishingly small," Aftergood remarks.

Paine asserts that other countries systematically gather up as much U.S. technology as possible and that France and Israel have stolen secrets. "The very people squawking about Chinese espionage are on the forefront of doling out billions to Israel," Paine says. "Is this really about national security, or cultural bias against the Chinese?"

In Paine's view, the reaction among some politicians reflects a naive, cold-war mentality. "It is a symptom of a lot of strategic confusion about the role of nuclear weapons," he concludes. "What are we trying to do? Preserve a nuclear monopoly indefinitely? Keep an advantage over other states? Is it the ultimate elimination of nuclear weapons?" Clarifying the question would certainly help determine how best to maintain the balance between national security and open science. *—Philip Yam*

MOLECULAR BIOLOGY

A DIABETES SWITCH?

Turning off a single gene protects mice against obesity and type II diabetes

The idea of a single pill that could allow you to eat a high-fat meal without gaining weight—and that could control type II diabetes to boot—sounds like fantasy. But research published in March suggests that such a drug may be closer to science fiction: unlikely perhaps, unquestionably difficult, but not theoretically impossible.

For around the labs of Brian P. Kennedy and his colleagues at the Merck Frosst Center for Therapeutic Research in Kirkland, Quebec, scurry genetically engineered mice that gain only half as much weight as their unaltered littermates when fed the same high-fat chow. After one of those calorie-rich meals, these mutant mice function normally, whereas their fatter brethren suffer the high blood sugar levels that are a hallmark of type II, or adult-onset, diabetes. The two groups differ by a single gene, which creates an enzyme called protein tyrosine phosphatase-1B, or PTP-1B. The fat, sick rodents have PTP-1B; the healthy mutants don't.

The research—which Kennedy and his collaborators at McGill University, led by Michel L. Tremblay, published in *Science*—is important for two reasons. First, the fact that an absence of PTP-1B protects against obesity is surprising, says Barbara C. Hansen, director of the Obesity and Diabetes Research Center at the University of Maryland. Based on what biologists have learned about PTP-1B over the past decade, most would have expected just the opposite.

The enzyme sits in cells all over the body. In muscle and liver cells, Kennedy explains, "it appears to function as an on/off switch" that controls how long insulin can coerce the cells into extracting sugar from the blood. "When insulin docks to its receptor on the outside of a cell, it causes the part of the receptor inside the cell to change shape," he continues. That in turn sets off a chain reaction in which phosphates and proteins clump together and open up the cells' membranes to receive sugar from the bloodstream. In type II diabetics, these cells resist insulin coercion, so too much sugar stays in the blood and not enough gets in to fuel the cells.

"We think PTP-1B strips the phosphates off an active receptor," stopping the effect of insulin after a certain amount of time, Kennedy says. So mice that have had PTP-1B knocked out are much more sensitive to insulin, because they lack a major means to turn the insulin signal off. "But if this increases insulin sensitivity to drive glucose into the cells, that should if anything increase fatness," Hansen points out. The most recent drug approved to treat type II diabetes, troglitazone, has only "a very modest effect" in reversing insulin resistance, she says, yet it often causes weight gain.

So what are the mutant mice doing with the extra calories, if not making fat? Kennedy says that recent experiments, still unpublished, suggest that "they are burning more calories." If so, then there may be a new way to fight obesity: suppress the body's production of PTP-1B.

The second important revelation from the experiment was that the knockout mice appeared healthy and long-lived despite a total lack of PTP-1B, raising the prospect of a drug that might be safer than existing diabetes and obesity drugs. Several such medicines have been withdrawn or restricted.

Clinical trials found the type II diabetes medicine troglitazone to be safe, for example. But the Food and Drug Administration estimates that since it was licensed in 1997 and prescribed to more than 1.6 million U.S. patients, 26 deaths and nine liver transplants have "probably" or "possibly" been caused by the drug. In late March an FDA appointed expert committee recommended that diabetics not rely on troglitazone alone and get regular liver tests while taking it.

A drug that inhibits PTP-1B would work differently. Merck is screening thousands of chemicals, but Kennedy admits that it will not be easy to find a drug that blocks PTP-1B but not other PTPs. The human genome is thought to contain up to 100 of these enzymes, each varying from the others only slightly in chemistry but vastly in function.

"One cannot predict the side-effect profile" of PTP-1B-suppressing drugs, points out Phillip Gordon, director of the National Institute of Diabetes and Digestive and Kidney Diseases. "It is, however, a very important target for drug design and may well offer promising mechanisms of weight control"—long known to be the best way to control type II diabetes.

And although PTP-1B makes a tempting target, Hansen cautions that "it is not very likely that attempts to suppress a single enzyme with drugs will be successful. But perhaps we may find two or three places where different drugs work independently, and we can combine them." So although it may not come in a pill, there is room to hope for the antifat, antidiabetes cocktail.

—*W. Wayt Gibbs in San Francisco*

STEPHEN FERRY *Gamma Liaison*

OBESITY AND DIABETES are two conditions that go hand in hand. Now studies in mice suggest there may be a new way to prevent both.

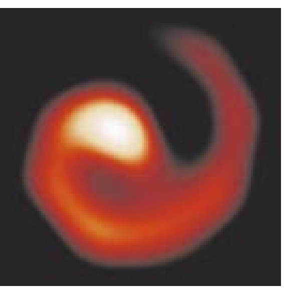
IN BRIEF

Tabletop Fusion

Researchers from Lawrence Livermore National Laboratory say in the April 8 *Nature* they have concocted a fusion reactor that fits on a laboratory bench top. They used a femtosecond laser—one that delivers a pulse of infrared in about 35 millionths of a billionth of a second—to zap clusters of deuterium atoms. The heated clusters exploded, and some atoms smashed into one another, fusing and releasing particles. The technology will not replace fossil fuels—it released only 10 millionths of the energy in the laser pulse. At less than $1 million, however, it may serve as an inexpensive alternative to $1-billion reactors for studying materials science and fusion physics. —*Gary Stix*

Stellar Pinwheel

No, it's not a spiral galaxy; it's a star. Wolf-Rayet 104, to be specific—one of a class of hot, massive stars that are 100,000 times brighter than the sun. This one, which is 4,800 light-years away, was detailed by astronomers from the University of California at Berkeley using the Keck I telescope in Hawaii. The spiral, which is 18 billion miles across, is created by the "lawn-sprinkler" effect: the star is spewing out gases while at the same time rotating around a unseen stellar companion. A "movie" is available at http://isi.ssl.berkeley.edu/wr104.html. —*Madhusree Mukerjee*



U.C. BERKELEY SPACE SCIENCES LABORATORY/ W. M. KECK OBSERVATORY

Wolf-Rayet 104

Blind Reason

That some Alzheimer's patients become lost in familiar surroundings may not arise from debilitating memory loss. Disorientation instead stems from "motion blindness," according to the March 23 *Neurology*. Optic-field cues, such as scenery rushing past, are interpreted by a region of the cerebral cortex and alert healthy people to the direction of their movement. By having subjects view moving dots on a screen—something like snowflakes swirling past a car's windshield—Charles Duffy and his colleagues at the University of Rochester found that these cues are muddled in the brains of some Alzheimer's patients. —*Jessa Netting*

More "In Brief" on page 20

ANTI GRAVITY

Semper Fly

As the son of a former U.S. Marine sergeant, I got quite used, whilst a feckless youth, to the charming and affectionate sobriquet "maggot." (And the marine in question was my mom. What I was called by my dad, also a former marine, would turn the air blue.) An almost familial pride therefore came over me when I saw some recent glowing press for actual maggots, specifically, the teeming, squirming, wormy offspring of blowflies.

The larval lauding appeared as a letter, entitled "Maggots Are Useful in Treating Infected or Necrotic Wounds," in the March 20 *British Medical Journal*. The maggots' beneficent medical potential comes from the future flies' habit of chewing diseased and dead tissue while eschewing the healthy stuff. The letter noted that they might be put to especially good use against flesh-eating bacteria that have become resistant to conventional antibiotic treatment.

Many a patient might opt for salt in their wounds before maggots. An hour spent in the dusty stacks of journals at a nearby medical school library, however, revealed that maggots have a long and illustrious place, dating to quite recently, in the physician's treatment armamentarium.

The elegantly written "Maggot Therapy: The Surgical Metamorphosis" appeared in the journal *Plastic and Reconstructive Surgery* in 1983. Had they done nothing else, the authors, Edward A. Pechter and Ronald A. Sherman, earned everlasting esteem for calling the derivation of the word "blowfly" an "entomologic etymologic exercise." But they also explained that accounts of maggots' ability to debride a wound go back about five centuries. War is indeed hell, sometimes of the Hieronymus Bosch variety—most of the early observations of maggoty goodness seem to have been made at various battles, in which wounded soldiers became the unwitting objects of scientific discourse simply by lying there long enough to have flies lay eggs on or in them.

A Baltimore physician named William S. Baer did the first serious studies of maggots and wound therapy in the 1920s. His curiosity became aroused by the case of two World War I soldiers apparently saved from death by maggots that kept them, their broken legs and their abdominal wounds company on a battlefield for a week. In 1931 he reported successfully treating dozens of cases of osteomyelitis, a devastating bone infection, with maggots. The term "maggot therapy" was no bother to Baer, but others recognized it as a public-relations nightmare. A 1933 paper suggested "larval therapy," but even that made people's skin crawl. Nevertheless, maggots treated burns, abscesses, leg ulcers and gangrene through the 1940s before being discarded for the most part, a victim of people's prejudices against roiling masses of creepy, crawly insects dining on their necrotic flesh. Go figure.

And that's too bad. Especially since the creeping and crawling may actually be part of the therapy—some researchers think the constant movement of the little critters stimulates the growth of fresh, healthy tissue. Maggots may possibly even release their own special brand of antibacterial agents. If the thought of them happily munching away at raw infections wasn't so downright nauseating, they might be staples in medicine cabinets around the country. (Chances are, if you have them in your cabinet now, it's really time to clean out that cabinet.)

Shakespeare pointed out that "we fat ourselves for maggots." The worms will crawl in and the worms will crawl out eventually anyway. We may as well open our arms, and our open wounds, to them now. Perhaps the latest term designed to lessen the gag factor—"biosurgery"—will finally do the trick and give medicinal maggots their long overdue image makeover. Then again, probably not. —*Steve Mirsky*

"Let me take a moment to tell you about our diseased tissue."

MICHAEL CRAWFORD

In Brief, continued from page 18

Three's Company

Two teams have discovered the first extrasolar system. A planet three fourths the mass of Jupiter had been known to orbit the sunlike star Upsilon Andromedae; now two others—one twice Jupiter's mass, the other four times—have been detected in more distant orbits. The researchers, who include Geoffrey Marcy and R. Paul Butler of San Francisco State University, made the find after noticing orbital irregularities and an inexplicable tugging at the parent star. The mystery: how such Jupiter-size bodies exist so closely to their star. In our solar system, the two innermost ones would lie within Earth's orbit. The paper was submitted to the *Astrophysical Journal*. *—Philip Yam*

In with the Old

Traditional antidepressant drugs are just as effective as newer drug therapies such as Prozac, according to a study sponsored by the Agency for Health Care Policy and Research. The choice between the prescription of an older therapy, such as a tricyclic drug, and one of the new selective serotonin reuptake inhibitors (SSRIs) should be based, therefore, on relative advantages and risks. Side effects of the SSRIs may include insomnia, nausea and headache, whereas the traditional drugs may affect the heart and blood pressure. The report can be found at www.ahcpr.gov/clinic/deprsumm.htm. *—J.N.*

CATHERINE LAMBERMONT *Liaison International*

Antidepressing news

Scientific Discipline

All undergraduates should be required to study some science, mathematics, engineering and technology, states a March report by a committee of the National Research Council (NRC). Recent studies have shown that U.S. students have a poor understanding of basic scientific principles and their relation to everyday life. Currently science and technology courses account for less than 6 percent of the course load for the vast majority of students graduating from prestigious universities. The classes recommended by the NRC would emphasize basic concepts and the interconnection of science and technology with other disciplines. *—J.N.*

More "In Brief" on page 22

ASTRONOMY

THE LITTLE SPACECRAFT THAT COULD

After a string of remarkable discoveries, Lunar Prospector prepares for a spectacular finale

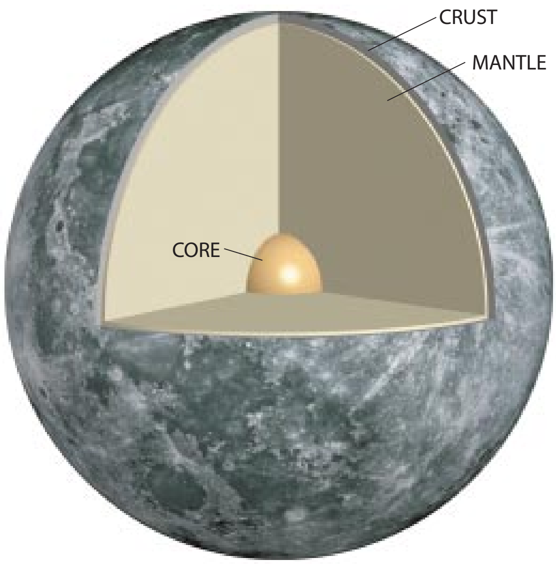
Lunar Prospector is not an impressive-looking spacecraft. Shaped like a soup can with its ends cut off, the 295-kilogram (650-pound) orbiter is not much larger than a washing machine. But as it nears the end of its 18-month mission, the plucky vessel continues to provide revealing glimpses of the composition and structure of the moon. The spacecraft first grabbed the public's attention in early 1998, when its instruments detected evidence of ice in the perpetually shadowed areas near the moon's poles. Now mission investigators have announced another important finding: measurements indicating that the moon has a relatively tiny core. The new data reinforce the theory that the moon was created by a cataclysmic collision between Earth and another body more than four billion years ago.

The investigators gauged the size of the moon's core in two ways. Because of the Doppler effect, which shifts the frequency of Lunar Prospector's radio signal as the spacecraft moves toward or away from Earth, researchers were able to identify slight variations in the craft's velocity as it orbited the moon. By carefully recording these variations, the scientists mapped the lunar gravitational field and calculated the moon's moment of inertia, which revealed the distribution of the body's mass. Assuming that the moon's core, like Earth's, is composed mostly of iron, researchers estimated that its radius must be between 220 and 450 kilometers (140 to 280 miles). The radius of the moon as a whole is 1,738 kilometers. "It's an indirect measurement, with a lot of uncertainties," says Alan B. Binder, the principal investigator for Lunar Prospector.

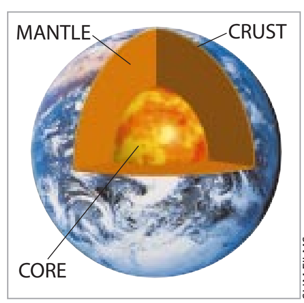
But Binder and his colleagues had an ingenious plan for refining the estimate. Although the moon's core does not generate a planetary magnetic field, as Earth's does, Lunar Prospector's magnetometer was able to measure the weak field induced in the moon's core when the body passed through the tail of Earth's magnetosphere. From these data, the scientists calculated a core radius of between 300 and 425 kilometers.

At this size, the moon's core would contain only about 2 percent of the body's mass. In contrast, Earth's core—which has a radius of about 3,400 kilometers—comprises about 30 percent of the planet's mass. The relative puniness of the moon's core suggests that the moon was born with a severe iron deficiency. Astronomers have theorized that about 4.5 billion years ago a rogue protoplanet, probably two or three times as massive as Mars, slammed into Earth and blasted a huge amount of debris into space. According to this theory, some of the debris clumped together to form the moon. Binder believes the impact occurred after most of Earth's iron had sunk to the planet's core. In that case, the debris expelled into space would have been mostly iron-poor rock from Earth's mantle and from the mantle of the protoplanet.

Lunar Prospector may find



***MOON'S CORE** holds only 2 percent of the body's mass* (left), *whereas Earth's core contains nearly one third of the planet's mass* (below).



SLIM FILMS

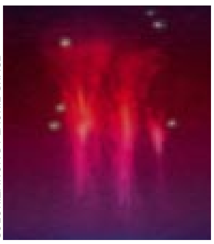
In Brief, *continued from page 20*

Suffer the Children

Maintaining a four-year decline, child abuse and neglect dropped to under one million cases by 1997, according to the U.S. Department of Health and Human Services statistics released in April. This represents a decrease of some 55,000 cases from the record high of 1,018,692 abused and neglected children in 1993. Parents continue to be overwhelmingly responsible for the mistreatment, and substance abuse was involved in a third of the cases. The report recommends incorporating substance abuse and mental health programs as integral parts of the child-protection system. —*J.N.*

Hunting of the Sprite

In what sounds like an improbable union of science and the supernatural, a report in the April 1 *Geophysical Research Letters* announced the development of the first reliable method for counting sprites. Sprites in this case are not the woodland beings of fairy tale but equally elusive electrical phenomena that appear as scattered red glows above thunderstorms. Steven Reising of the University of Massachusetts and his colleagues found that the radio signals emitted by lightning bolts accompanied by sprites were distinct from those that were not. Radio monitoring should be cheaper and more effective than recording sprites on video equipment. —*J.N.*



STEPHEN B. MENDE AND R. L. RAIRDEN; COLORIZATION BY LAURIE GRACE

High light

Insights into Angiogenesis

New understandings have emerged on the mechanisms that stop the blood vessel growth (angiogenesis) that nourishes tumors. A Duke University team reported in the March 16 *Proceedings of the National Academy of Sciences* that angiostatin shrinks blood vessel growth by binding to and shutting down ATP synthase, an enzyme on an endothelial cell's surface. It thereby cuts off the energy required for blood vessel growth. The finding could lead to small, nonprotein molecules that block angiogenesis and that are more readily manufactured than angiostatin, a complex protein. In related research, a group from Children's Hospital in Boston reports in *PNAS* a new angiogenesis inhibitor from human cartilage, called troponin I. —*G.S.*

SA

additional clues to the moon's origins in the last months of its mission. Earlier this year the spacecraft dropped from its 100-kilometer-high mapping orbit to a low elliptical orbit that brings it as close as seven kilometers to the moon's surface. The lower altitude allows the craft to take more accurate readings, although it must fire its thruster every four weeks to avoid hitting the moon.

A crash landing, however, is the craft's ultimate fate. On July 31 the mission runs out of funding, and eventually the orbiter will run out of fuel. But even the smashup may yield a scientific return: investigators hope to maneuver Lunar Prospector for an impact in one of the moon's permanently shadowed polar regions. Some scientists are still skeptical about the presence of ice in these areas; to strengthen the evidence, Binder and his colleagues would like to analyze the plume of material that would be ejected by the spacecraft's swan dive. Observatories in Earth orbit, including the Hubble Space Telescope, might be able to see traces of water vapor in the plume. "That would be an absolute confirmation of water," Binder says. Officials at the National Aeronautics and Space Administration have not yet approved the impact experiment. —*Mark Alpert*

PUBLIC HEALTH

IT CAME FROM THE DEEP

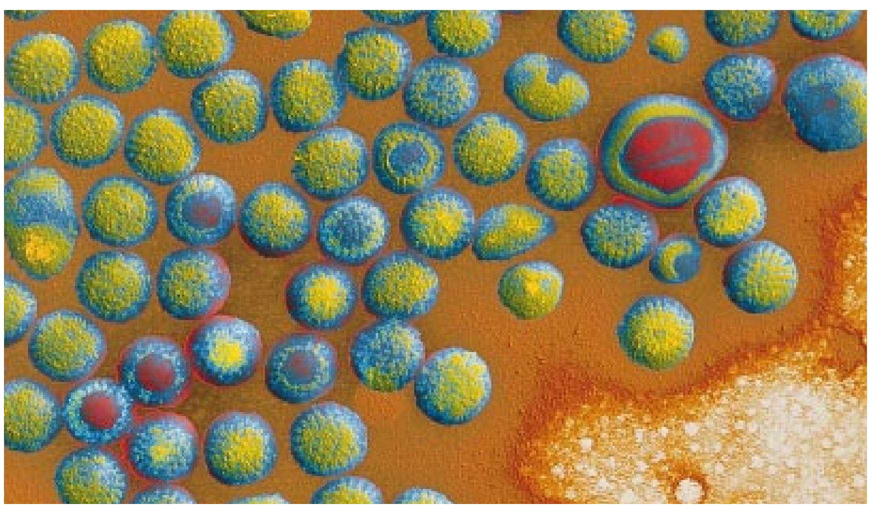
Scientists warn of outbreaks stemming from the ocean abyss

In December 1992 thousands of people on the southern coast of Bangladesh began vomiting and experiencing profuse, watery diarrhea that caused their tissues to lose so much fluid that their eyes appeared to sink within their sockets and the skin on their fingertips began to pucker. Within days, many had died of severe dehydration.

The scourge was not new: it was cholera, a waterborne infectious disease that had reached epidemic proportions there many times before. But scientists have noted that the outbreak was accompanied by an upwelling that brought deep-sea water to the surface near the Bangladeshi coast. They are now wondering whether it is a harbinger of what both the developed and the developing world can expect if humans continue to pump sewage—treated or not—into the oceans of the planet.

Increasingly, scientists are finding evidence of pathogenic microbes, many usually found only in human feces, at startling oceanic depths. "The deep ocean acts as a kind of refrigerator," says Rita R. Colwell, the director of the National Science Foundation. "It has been assumed that a human is not going to be exposed to these microbes if they're several thousands of meters below the surface, but currents carry waters such that they may appear on another shore," she says. "So it is always a possibility that these microbes—which are essentially lying there dormant—could at some point provide the entrée to an epidemic."

Marine scientist D. Jay Grimes of the University of Southern Mississippi says



E.O.S./GELDERBLOM *Photo Researchers, Inc.*

DEEP DANGER? Human pathogens such as this rotavirus can survive at great depths, possibly posing a health threat during ocean upwellings.

that a variety of viruses that infect the human gastrointestinal tract—including poliovirus and rotavirus—have been identified in ocean water samples taken below 1,000 meters (3,300 feet). And the microbes can last: in the late 1980s Sagar M. Goyal of the University of Minnesota isolated gut bacteria from samples obtained at sewage sludge–dumping sites more than 170 kilometers offshore from New York City—30 months after the sites had been closed to further dumping. The bacteria were resistant to several antibiotics, a clear sign that they originated from humans taking the drugs.

According to Grimes, researchers are just beginning to realize the implications of disease-causing microbes in the deep ocean. "But the studies proving a link between an upwelling and a human outbreak haven't been done yet," he says.

Public health expert Paul R. Epstein of Harvard University suggests a different scenario, based on prior studies by Colwell, for the 1992 outbreak in Bangladesh. An upwelling could have brought nitrogen and phosphorus, nutrients abundant in deep-sea waters, closer to the surface, where they could have prompted a plankton "bloom." That would have caused populations of small, plankton-eating sea creatures called copepods to flourish. And cholera bacteria thrive in the guts of copepods, so their numbers would in turn have increased. "It's certainly possible that cholera bacteria from the deep could get washed up and cause disease, but that would be hard to prove," he states.

Benjamin H. Sherman of the University of New Hampshire agrees that the presence of pathogenic microbes at great depths is a general warning sign of the degree to which humans can affect the earth's ecosystems. "The prospect that we have decades-old or hundreds-of-years-old pathogens in the deep blue is interesting," he comments. But he points out that a more immediate problem is sewage released in coastal waters.

Nevertheless, Epstein says he is "very much" concerned about the presence of pathogens in the deep ocean, especially considering the proliferation of projects such as one in Boston, where a 17-kilometer-long pipeline is being built to take sewage from the city out to sea. Although that sewage will be treated, he cautions that some microbes are insensitive to chlorine.

"We don't know the consequences" of adding sewage to the sea, Epstein warns. "We're just beginning to look at how climate change can affect ocean circulation and bring these bugs back to haunt us." —*Carol Ezzell*

ARCHAEOLOGY

Rediscovering the New World

About the time that Christopher Columbus made his discovery, the Incas performed a ritual sacrifice of two girls and a boy high atop an extinct volcano. In March a National Geographic Society–sponsored expedition to the top of 6,723-meter (22,057-foot) Mount Llullaillaco in northern Argentina reported unearthing the three mummified victims, surrounded by statues, tapestries and pottery. Five centuries of permafrost had left the mummies astonishingly well preserved. The joint American-Argentine-Peruvian team found blood in the hearts and lungs of two of the mummies, which retained intact internal organs. Fingernails and hairs on the arms had not decayed, either. Examining the corpses may broaden the understanding of diseases present in the Inca empire and the ties between the Incas and other populations. The mummies may also provide anthropologists with new knowledge about *capac cocha,* the Incas' ritual sacrifice of children. —*Gary Stix*

RICKEY ROGERS *Reuters/Archive Photos*

Mummified Incan child

NEUROBIOLOGY

GETTING WIRED

New observations may show how neurons form connections

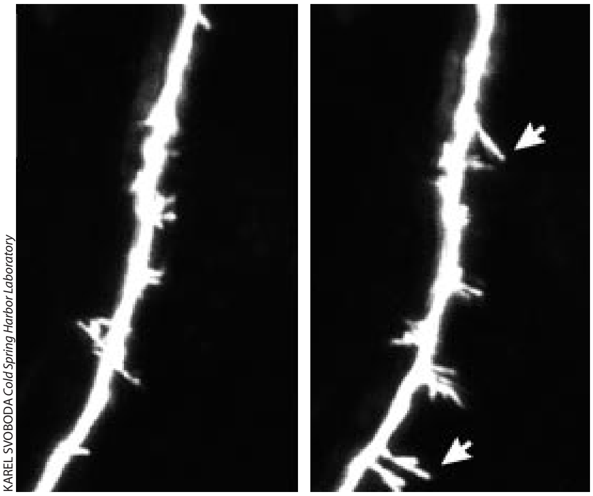
As brains grow and learn, connections called synapses form between the billions of brain cells, or neurons, that process information. Synapses play a crucial role in guiding thought, because they allow some excitations—but not others—to pass from one neuron to another. How exactly those synapses form, however, is a mystery, because they are exceedingly small, and although electron microscopes can observe them, the method works only with dead tissue.

Researchers at Cold Spring Harbor Laboratory have recently employed a new type of microscopy to observe electrically stimulated neurons in a slice of living rat brain in exquisite detail. Mirjana Maletic-Savatic, Roberto Malinow and Karel Svoboda were rewarded with some eye-opening observations of the dynamics of structures that seem to lead to synapses.

The technique involves infecting some neurons in a slice of brain with a benign virus that causes cells to produce internally a fluorescent dye. An infrared laser beam focused to a point then scans the slice in a three-dimensional pattern under a microscope. The energy of the laser is too weak to excite the fluorescent dye unless two infrared photons strike a dye molecule almost simultaneously. That is unlikely to happen except right at the focal point. When two photons do strike, though, the dye emits visible light. From that light an extremely high resolution image can be constructed, because the light all comes from a minute volume.

The researchers examined neurons from the hippocampus, a region of the brain known to be important in learning and memory. When they observed the neuronal dendrites—the data-input branches of neurons—they saw countless tiny fingerlike projections extending from the dendrites like tentacles. These projections, called filopodia, continually appeared, changed shape and disappeared on a timescale of minutes.

Filopodia have not been seen before in a way that allowed their behavior to be examined. Maletic-Savatic and her



KAREL SVOBODA *Cold Spring Harbor Laboratory*

RAT DENDRITES **(left)** ***grew microscopic protrusions called filopodia*** **(right, indicated by arrows)** ***25 minutes after electrical stimulation.***

colleagues used the opportunity to test the effect of electrically stimulating dendrites just as a nearby neuron might do when excited by a thought or a sight or a touch. Stimulation caused more filopodia to emerge close to the site of the stimulus and made existing ones grow longer. Some eventually generated bulbous heads, suggesting they were turning into dendritic "spines"—permanent structures that can link a dendrite to another neuron via a synapse. "It is very likely these are real synapses being formed," Maletic-Savatic says. These effects of stimulation were eliminated when the researchers bathed the neurons in a substance that blocks a specific cell-surface receptor long believed to play a role in synapse formation. The results were reported in *Science.*

The investigators could not observe new synapses forming directly, because the neurons being contacted by growing spines were not infected with dye-producing virus and so were invisible; moreover, synapses are even smaller than filopodia. Still, the results provide the clearest picture yet of how synapses may originate—and how brains change.

—*Tim Beardsley in Washington, D.C.*

BY THE NUMBERS

Income Inequality in the U.S.

For about three decades—roughly the period from the early 1940s to the early 1970s—the U.S. became progressively more egalitarian. This was a time of rapidly rising productivity and rising real wages. But by the early 1970s, productivity growth slowed and real wages declined, at least for the unskilled. Although average household income in real dollars rose by 41 percent from 1967 to 1997, those with low incomes—the two lowest groups on the chart—benefited little. Of course, from year to year, some households moved up the income scale, whereas others moved down.

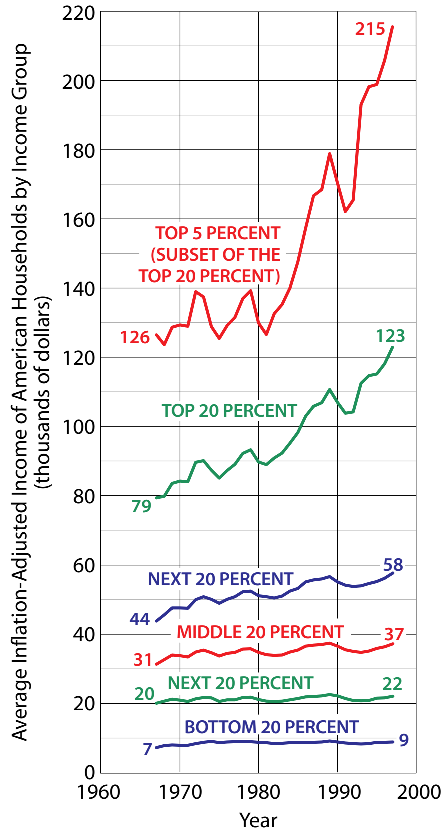
The growing inequality of the past few decades cannot be blamed solely on globalization of trade, although some economists believe it is the most important factor depressing wages and threatening the jobs of the less skilled. Other economists, including those in the Clinton administration, argue that technology, particularly computerization, is the chief villain. (But recently there have been signs that computers and the Internet may finally be contributing to an increase in U.S. productivity growth, which historically seems to coincide with rising equality.) The decline of American trade unions, which traditionally have reduced the gap between worker and manager incomes, is also a factor, as is the related drop in good-paying manufacturing jobs. Beginning in the 1980s, the supply of college graduates grew slowly, which led to a shortage of better-educated workers and consequently an increase in their earnings advantage over the less skilled. The rising number of single-parent households also contributed to inequality, and the influx of women into the job market may have depressed wages of the unskilled by increasing the supply of labor. In addition, the unskilled suffered from competition with immigrants and from the decline in the real value of the minimum wage.

Another reason for rising inequality was the dramatic surge, beginning in the early 1980s, in the share of income going to the top 5 percent of households. Lower tax rates introduced by the Reagan administration probably also contributed to inequality.

Income inequality is greater in the U.S. than in Europe—some of the most striking differences are found among the lowest paid. Globalization and new technology also affected the distribution of income in Europe, but in most cases, inequality did not rise as much as in the U.S. Countries with strong labor union movements were able to moderate the growth of inequality. In European countries the wage premium for a college education is less than it is in the U.S.

On average, the U.S. in the 1990s enjoyed greater growth and lower unemployment than did major European nations. Is the U.S. performance the result of greater inequality, with bigger rewards to the rich, who typically invest much of their surplus in job-producing enterprises? Is the lower growth in European countries the result of spending on social welfare, rather than investing in job-creating enterprises? Does the equalizing effect of stronger unions in most European countries contribute to lack of creativity and competition? Economists do not agree on the answers to such questions, but they do agree that investment in education, particularly for low-income children, would reduce income inequality. —*Rodger Doyle (rdoyle2@aol.com)*

SOURCE: U.S. Bureau of the Census. Numbers indicate mean incomes in 1967 and 1997 in thousands of 1997 dollars. Chart is based on money income before taxes and includes Social Security, public assistance and other government cash assistance programs but excludes capital gains and the value of noncash transfers such as Medicare, Medicaid and employer-paid medical plans. If data showing income after taxes, capital gains and noncash transfers were available, they would show roughly the same pattern, but with a lower level of inequality.



RODGER DOYLE

When Good Health Is Good Business

The new head of the World Health Organization, Gro Harlem Brundtland, argues that providing good health care can boost the bottom line

When Gro Harlem Brundtland began her term as the new director general of the World Health Organization (WHO) last July, she put forward an extraordinarily ambitious agenda for the agency: "We can combat ill health. We can do our part to combat poverty and suffering. Nothing in life—as I see it—has more meaning." The sentiment may sound like that of a naive idealist trying to save the world. But don't wait for Brundtland's speech about how noble it is to help those who are less fortunate. She would much prefer to discuss how she plans to get the job done: follow the money.

I'm scheduled to meet Brundtland at the headquarters of WHO in Geneva, a city with gorgeous views of the Alps and scores of jewelry stores, chocolate shops and, of course, Swiss banks. Despite this affluence, though, Geneva is also a city for the impoverished and suffering. In addition to WHO, numerous international relief agencies are based here, including the International Committee of the Red Cross and the United Nations High Commissioner for Refugees. This juxtaposition fits Brundtland's plans quite nicely. As she sees it, money invested in improving the plight of the world's poor is important for more than just humanitarian reasons—it's also good for business. She's taking this argument around the world, trying to convince governments and corporations that initiatives such as childhood vaccination programs can cut costs.

If the notion of playing to people's pocketbooks sounds like the tactic of a politician, that's no surprise. As a seven-year-old, Brundtland (who was born in Oslo in 1939) joined Norway's Labor Party and has been a member ever since. She served three terms as prime minister of Norway in the 1980s and 1990s. When she takes a seat at the large rectangular table in her meeting room at WHO, I can just picture the space filled with international heads of state, translators at their sides, arguing and negotiating well into the night. But now, in the early afternoon, the room is bright. The intense sunlight reflecting off snow-covered Mont Blanc, visible through the wall of windows across from me, is nearly blinding. Brundtland, with her back to the light, appears as a silhouette. But her voice is strong, clear and focused.

"I was a 35-year-old public health physician doing scientific work for my dissertation at that point," Brundtland recalls about her entry into politics in 1974. She had graduated from medical school in Oslo in 1963 and then earned a master's degree in public health from Harvard University. After that, she returned to Norway in 1965 and began work as a physician at the Norwegian government's Ministry of Health, where she dealt primarily with children's health. After nine years on the job, the prime minister of Norway made an interesting offer to Brundtland—he asked her to join his cabinet.

The call was "absolutely surprising to me," Brundtland remembers. "I said, 'Do you mean in the Ministry of Health?' And he said, 'No, I mean in the Ministry of the Environment.'" But Brundtland quickly saw the connection between the two: "What influences people's health is what they breathe, what they drink, what they eat. So the air, water, sanitation—all the qualities of the environment around us—are essential."

Brundtland accepted the position. One of her first tasks was to lead a conference of other European environment ministers on the contentious subject of acid rain, among other issues. The discussion focused on acid rain falling in Norway, caused by pollution released in England. "Many countries were against raising this whole debate because it implies that you are responsible for what happens outside your borders as a result of what you do in your own country," Brundtland says—an implication few politicians wanted to face at that time.

The ensuing political battle taught Brundtland an important lesson. "I realized that as long as we talked about the environment—acid lakes in the south of Norway and fish dying because of it—people who have an ecological awareness will understand this as a warning signal. But some people will say, 'Well, what does it matter if some fish die in Norway? We have to increase productivity, and this is just something we have to live with.'" The key, she realized, was attracting the attention of economic decision makers and convincing them that protecting the environment could be, in the long run, profitable. Her initial reasoning was that companies could benefit financially

ALAIN MORVAN *Gamma Liaison*

***EASING THE BURDENS OF POVERTY** and environmental degradation are keys to protecting the world's health, according to Gro Harlem Brundtland.*

by "improving their technologies and making better products" so that factories released less pollution. And Brundtland could point to some Norwegian factories that, after installing their own pollution-fighting devices, started making money by selling the equipment to other companies.

The idea of applying market forces to promote the conservation of natural resources attracted international attention in 1983, when Javier Pérez de Cuellar, then secretary general of the U.N., appointed Brundtland to establish and lead the World Commission on Environment and Development (WCED). WCED's mission was to explore how best to link economic concerns with environmental ones—an idea that became known as sustainable development. The 1987 recommendations of WCED, known informally as the Brundtland Commission, prompted the U.N. to call the Earth Summit in Rio de Janeiro in 1992, which attempted to encourage governments to approach economic development in environmentally sustainable ways.

During the 1980s and into the 1990s, Brundtland was also busy as prime minister of Norway. She first took office in 1981—elected in large part because of her popularity as environment minister. Over the next 15 years she held Norway's highest political office for a total of 10 years, focusing not only on environmental concerns but also on women's rights.

Now, more than 20 years after she left, Brundtland has returned to medicine. In July 1998 she began a five-year term as head of WHO, taking over from Hiroshi Nakajima, her unpopular predecessor often faulted for allowing the organization to become an inefficient and, at times, irrelevant bureaucracy. Brundtland has streamlined the agency, merging more than 50 programs (often focused on only one disease) into 10 new divisions that address such broad topics as communicable diseases, social change and mental health, as well as sustainable development and healthy environments.

This last category is by no means accidental. Brundtland now finds herself revisiting arguments she made earlier in her career, particularly about the importance of economic concerns. Just as she learned that discussions only about the tragedy of environmental degradation had little impact on political decision makers, she realized that the same held true for health. The frequently cited argument that everyone has a fundamental right to basic health care ("a very good argument," Brundtland notes—and WHO strongly supports the idea of universal coverage for basic health care needs) often does not work, especially in a country that has a weak human-rights record to begin with, she asserts.

One of Brundtland's first actions in office was to step up the war against malaria. According to Brundtland, the number of cases of malaria—currently some 300 million a year—has increased over the past 10 to 15 years, notably in Africa. (The situation is so grim, Brundtland comments, that many doctors she has met in Africa have told her that at present, malaria is a greater problem than AIDS. "That illustrates the dimension of malaria, but it also illustrates that the HIV/AIDS epidemic [in Africa] has not peaked yet," she warns.) Malaria's human and social costs can be seen in the resulting deaths, disabilities and devastated villages; the economic damage, perhaps not immediately obvious to some people, is clear to Brundtland: "If you don't have a certain level of investment in health in your country, you have terrible morbidity and mortality patterns, and it drains your potential for growth."

WIM VAN CAPPELLEN *Impact Visuals*

"ROLL BACK MALARIA," a new WHO program, includes the distribution of mosquito bed nets, such as this one being used in Myanmar (Burma).

The World Bank appears to agree with this financial argument—the organization is cooperating with WHO in its efforts to fight malaria. Specific projects of the "Roll Back Malaria" campaign include working with organizations such as UNICEF to distribute drugs and mosquito bed nets. And with an eye toward possibly eradicating malaria one day, WHO is also funding research into a vaccine.

Brundtland also wants to move quickly to spare the developing world—especially parts of Asia—the health problems caused by tobacco. Under her guidance, WHO has put together a second major effort: the Tobacco Free Initiative, designed to help countries pass laws controlling the advertising, sale and taxation of cigarettes. "We can do something about [this] before it costs a lot in human suffering and in hospital services," she suggests.

The success of sustainable development to remedy environmental concerns has been mixed. Although some companies have made a profit by, for instance, selling indigenous products from rain forests, others have foundered. Brundtland herself indicates that even though there "has been a considerable increase in government cooperation on sustainable development" in the past decade, "there's a lot more to be done." Could it be too much to ask that the world take on eliminating ill health, poverty and suffering, as Brundtland suggested when she started at WHO?

Jonas Gahr Støre, senior policy adviser to Brundtland, points out that the world already spends $2.3 trillion on health—all WHO needs to do is "marginally influence the way governments spend that huge amount of money"—money that now often does not reach the people who need it most. He argues that "even if you only have $10 [to spend] per person, per year, it matters how you spend those $10. For a basic package of immunization and primary health care, you can make a huge difference."

Brundtland also believes that smaller steps can add up quickly to solve big headaches, particularly because she sees so many of today's problems as closely intertwined. "The biggest threat to health is really the existence of poverty and the fact that in some areas, poverty has been gaining ground," she states. Furthermore, Brundtland argues that ill health itself actually contributes to poverty. And, of course, poverty can lead to—and result from—environmental degradation. "If you choose the right pattern of development, you take care of health, the environment and economics," she maintains. Brundtland's prescription may be one the world cannot afford to ignore.

—Sasha Nemecek in Geneva

CONSERVATION

TURTLE TRAGEDY

Demand in Asia may be wiping out turtle populations worldwide

In July 1997 William P. McCord, carrying a small camcorder, crossed from Hong Kong into mainland China. Word was that for the past several years, China's vast live food markets served as the final destination for hundreds of thousands of the world's wild turtles. McCord, a turtle expert from the East Fishkill Animal Hospital in upstate New York, recorded hours of painfully graphic videotape showing the slaughter of turtles, the arrival of transport trucks and the endless numbers of animals for sale. Many on the tape are banned from trade by the Convention on International Trade in Endangered Species (CITES), such as the Hamilton's terrapin and the Ganges soft-shell turtle. McCord's tape also revealed many American turtles caught in the wild—mostly, Florida soft-shells, red-eared sliders and snapping turtles. The size of the few markets he saw, McCord says, compares with that of New York City's Fulton Fish Market. "It's terrible," he groans, "and nobody's doing very much—if anything—to stop it."

After viewing the tape at a meeting, herpetologists despaired. "Given the volume of what was going on there, there are probably more individual animals of endangered species being killed for food every day than we could conserve in a lifetime," laments John Gramieri, curator of herpetology at Chicago's Lincoln Park Zoo. John L. Behler of the Wildlife Conservation Society, who chairs the World Conservation Union (IUCN) committee responsible for chelonian protection, estimated that at least 10,000 live turtles were present in that Guangzhou market on the day of McCord's taping.

Mature, wild-caught turtles are prized in Chinese markets because they are thought to confer wisdom, health or longevity when consumed. With increasing wealth and reduced trade barriers, people have more opportunities than ever to buy and sell. "This is an unfortunate combination of centuries-old tradition with newfound wealth," says Ross Kiester of the U.S. Forest Service, who helped to chart turtle trade routes in Southeast Asia. A turtle, he notes, "is the perfect gift to give an honored relative—the Chinese equivalent of giving your aunt a box of Godiva." Kiester saw a Vietnamese peasant receive $1,200 for a commercially extinct Chinese three-striped box turtle, believed to cure cancer. Fifteen years ago this turtle sold in Hong Kong for $10.

There are no hard numbers as to how many of these markets exist globally, but researchers believe that the trade is seriously affecting turtle populations worldwide. McCord estimates from his tape that "90 percent of the animals were from outside the country." Most Chinese species have become commercially extinct, and many Southeast Asian species are very nearly so. No definitive studies indicate the drain on American turtles. But according to a recent analysis by TRAFFIC, a wildlife trade-monitoring program of the World Wildlife Fund, 617 turtles of the tracked species were exported from the U.S. in 1985. By 1995, the number had increased to 154,681—an increase attributed largely to their demand as food in Asia. Behler estimates that 25 million were exported for the food and pet trade between 1993 and 1997.

"The problem we have now with the turtle trade is the sheer volume," says TRAFFIC's Craig Hoover. "There's a shipper in Indonesia who has a standing order for one ton of turtles a day to send to China. There's a turtle dealer in the U.S. with a standing order of at least one ton of turtles per week to be sent to China." The rate, researchers say, is unsustainable—particularly because the turtles being taken are the mature animals, those few who have made it through a dicey infancy and subadulthood to become reproductive stock.

In the U.S., the explosion of turtle exports has caught conservationists off-guard. For years, the task has been to stem illegal wildlife imports; export problems were generally considered less serious. But these days, estimates U.S. Fish and Wildlife Services (USFWS) special agent Joe Ventura, based at Los Angeles International Airport, some 40 to 50 crates of live turtles pass through that airport each week. Because few of these species are on the CITES list, Ventura can do nothing to stop them. Making accounting matters even more difficult, some turtles may be illegally packaged as "seafood" and thus escape USFWS scrutiny.

Exacerbating the problem for non-CITES species is the fact that the U.S. has no regulations concerning their humane transport. Robert Johnson, curator of reptiles at the Toronto Zoo, notes that turtles are dumped layers deep on top of one another, often with hooks in their mouths—probably from baiting. Johnson says that Canadian groups are "disgusted" and that officials are sending back some shipments because of the maltreatment.


WILLIAM P. McCORD

ENDANGERED TURTLES FOR SALE in China include CITES-listed species, such as these **Kachuga tecta**, *or Indian roofed turtles, in the wooden and green bins.*

Federal agent Ellen Kiley of the USFWS, stationed in Buffalo, N.Y., confirms the inhumane packaging, adding that agents currently have "no tool under our regulations as to transport, unless there's a significant mortality." Matters could be different: Ventura notes that "some of the European countries, a colleague of mine told me, enforce [CITES] regulations for all species. But this [approach] is not taken very seriously in the U.S."

A partial solution would be establishing humane transport regulations through the International Air Transport Association (IATA), a Montreal-based nonprofit agency, which has already held two meetings this year on the subject. The self-regulatory agency has established such standards for mammals and birds, thereby protecting them. Because most airlines abide by IATA decisions and because a large proportion of the turtles appear to be transported by air, strict humane regulations may make the animals simply too expensive to ship. Says Johnson: "If the U.S. would enforce humane shipping policies, that would cause the cost of the turtles to go up and the trade would likely disappear. We want to make the cost of humane treatment be borne by those who want to eat turtle meat. That's a fair way of treating the value of wildlife."

Mark Phillips of the USFWS Office of Management Authority notes that his agency is currently discussing regulations for reptiles similar to those for birds and mammals under the Lacey Act, first enacted in 1900 to protect wildlife from commerce. Phillips says that proposed regulations will most likely be published in the Federal Register sometime this summer. After a review period, those regulations will be enforceable. Unfortunately, the Lacey Act is generally assumed to pertain only to imported animals; legislative authority to control the export of live, non-CITES-listed animals is sketchy.

The deeper concern among conservationists is that the burgeoning turtle trade might be only the tip of a massive marketing of wildlife stimulated by borderless finance. The Internet, the explosive globalization of capital and its concurrent huge expansion of international transport make trafficking in protected animals more lucrative than ever before. "We better wake up and smell the coffee," Behler warns. —*Wendy Williams*

WENDY WILLIAMS, a wildlife journalist based in Cape Cod, Mass., is working on Green Turtle Soup, *a book about turtles and the new globalism.*

IMAGING

SEEING THE BREATH OF LIFE

Specially treated gases could soon bring a breakthrough in medical imaging

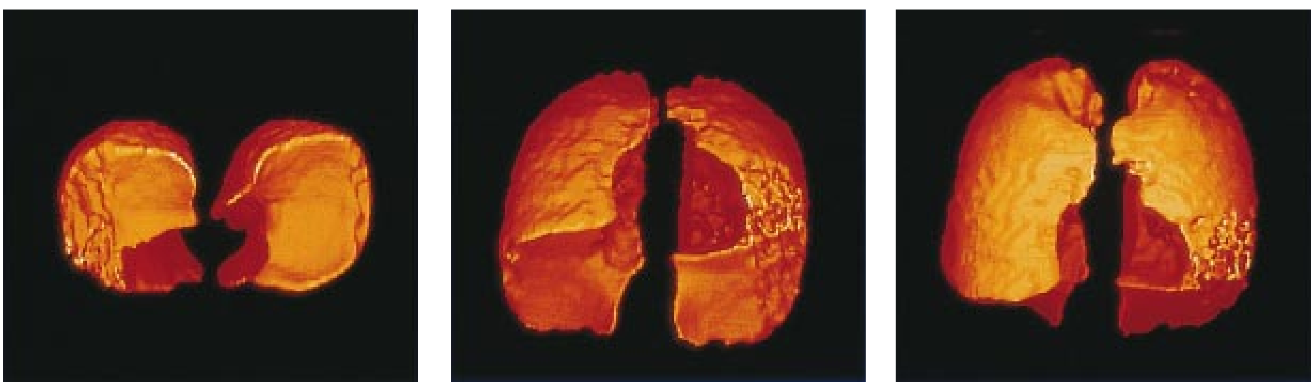
Images of structures inside the bodies of living patients obtained by nuclear magnetic resonance scanning have revolutionized medicine. But some parts of the body, such as the lungs, still cannot be visualized as clearly as physicians would like for assessing disease and planning treatments. That explains growing enthusiasm for a new type of magnetic resonance imaging (MRI) that can provide high-resolution scans of lungs and that shows potential for better imaging of the brain, colon and other organs.

Researchers at several centers in the U.S. and Europe have been exploring the technique. Volunteers inhale a lungful of an unusual isotope of either helium or xenon that has been "hyperpolarized." This means that a high proportion of the gas's atomic nuclei have their "spin"—a magnetic property of quantum particles—oriented in the same direction. Subjects then hold their breath for 10 seconds or so while they undergo an MRI scan in a specially tuned machine. Hyperpolarization makes the gas provide an MRI signal that is some 100,000 times stronger per nucleus than that produced by water, the substance normally visualized. The strong signal means internal spaces can be visualized at unprecedented resolution.

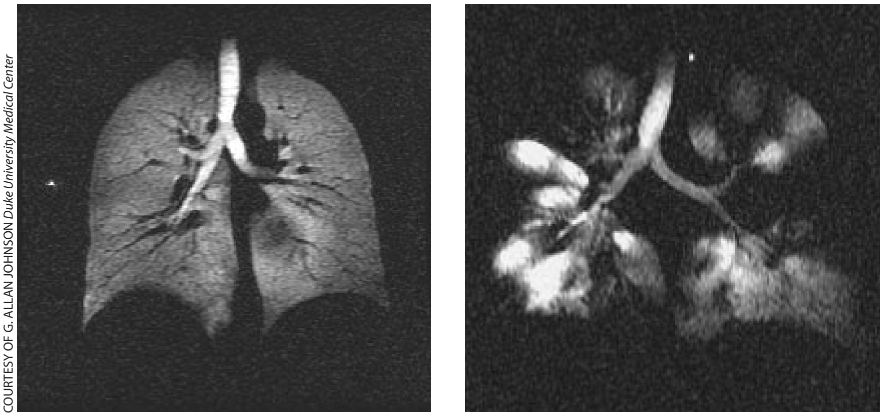
Researchers learned as long ago as 1960 that the nuclei of small quantities of helium 3 can be polarized with lasers. Later, others learned how to accomplish the same trick with xenon 129, the only other usable gaseous isotope. The hyperpolarized state can be maintained for hours, provided the gas is kept away from paramagnetic substances such as oxygen. The idea of using hyperpolarized gases in medicine is credited principally to William Happer and Gordon D. Cates, physicists at Princeton University, together with Mitchell Albert, now at Brigham and Women's Hospital in Boston. The technique is also proving useful in nonmedical research on foams and minerals.

Making hyperpolarized gases in the liter quantities necessary to image lungs was a challenge taken up in the 1990s by Magnetic Imaging Technologies, Inc., in Durham, N.C. MITI has developed a machine the size of a desk to do the job and has an exclusive license from Princeton and the State University of New York at Stony Brook to commercialize hyperpolarized gases for

***HUMAN LUNGS** were visualized after inhalation of hyperpolarized helium 3, thereby enabling a computer to generate different views of the organs' surfaces. The space occupied by the heart is visible.*



JAMES R. BROOKEMAN *University of Virginia Health Sciences Center*



COURTESY OF G. ALLAN JOHNSON *Duke University Medical Center*

HEALTHY LUNGS visualized with hyperpolarized helium 3 (left) ***appear different from those ravaged by cystic fibrosis*** (right).

medical MRI. The company is collaborating with Nycomed Amersham near London, a large medical imaging concern that has international experience with licensing. Nycomed plans eventually to supply gases to imaging centers in their hyperpolarized state, says technology manager Tim Grey Morgan.

MITI's machine employs a laser to hyperpolarize rubidium atoms in a vapor—a relatively easy process. The rubidium atoms then transfer their spin to nuclei of helium or xenon mixed in with the vapor. Researchers at Johannes Gutenberg University in Mainz, Germany, use a direct, low-pressure technique that reaches higher levels of polarization than MITI's method can, but it works only for helium.

Most of the lung imaging done so far has used helium, which gives a stronger signal than xenon. In one study, 16 volunteers at the University of Virginia Health Sciences Center were scanned, and the technique showed the main divisions within the lungs as well as the spaces where major blood vessels run. The chronic obstructive pulmonary disease in three patients was plainly visible: the inhaled gas failed to reach large regions, which appeared on the scans as dark patches. Other scans also revealed some unrecognized lung defects and displayed a clear improvement in an emphysema patient who had parts of his lungs removed. "This is scary surgery," says Thomas M. Daniel, the surgeon who performed the so-called lung-shaving operation. "The trick is what part to take out." Daniel is confident the new technique will help him know what parts to extract in future operations.

Lungs are not the only organ that could benefit from better imaging. Daniel's physicist colleague James R. Brookeman has used helium 3 to visualize dogs' colons. Although the "helium enema" might be uncomfortable, Brookeman notes, it might be less so than the sigmoidoscopies that are now done routinely on humans to screen for colon cancer.

Progress toward optimizing image acquisition and other information from helium 3 MRI scans is rapid. At Johannes Gutenberg University, Hans-Ulrich Kauczor, Ernst W. Otten and their colleagues have developed special scanning techniques that can detect how quickly helium is diffusing in different parts of the lung, which could increase the ability to detect disease. And because oxygen makes hyperpolarized helium lose its spin faster, comparisons between scans made in rapid succession can reveal changes in regional oxygen concentration. That in turn should reveal the local blood flow, valuable information for doctors to know. Geneviève Tastevin of the CNRS Kastler Brossel Laboratory in Paris and others are studying how to use helium 3 to obtain high-quality images with machines using smaller magnets, which should bring down the cost and may offer technical advantages. G. Allan Johnson of Duke University has used highly hyperpolarized helium to visualize in animal lungs what he believes are acini, clusters of air-exchanging sacks only a few hundred microns across. "I am quite staggered at the speed with which the technology is developing," says Grey Morgan of Nycomed.

Helium 3 is not without problems, however. Governments extract the gas from expired tritium drained out of hydrogen bombs. Most helium 3 now comes from Russia, but the supply is limited, and the gas is expensive—several hundred dollars per liter. (It is abundant on the moon, deposited by the solar wind, but nobody is currently planning to go there to get it.) Xenon 129, in contrast, is abundant and cheap, and because it diffuses less rapidly it should ultimately yield sharper images, Johnson says. Moreover, it dissolves in blood, unlike helium, and despite its classification as an inert gas it interacts with biological chemicals, notes James R. MacFall of Duke.

When xenon 129 binds to chemicals in the body, its resonances are changed, points out physicist Ronald Walsworth of Harvard-Smithsonian Center for Astrophysics. That means researchers can tweak an MRI machine to visualize, or even depolarize, xenon in specific chemical environments, so that its movements and chemical associations can be tracked. Although hyperpolarized xenon is stable for only tens of seconds in the blood, that is enough time to image its transport to the brain and to distinguish white and gray matter there; xenon passes across the blood-brain barrier (producing anesthesia and euphoria). Even though xenon is harder to hyperpolarize and store than helium, Grey Morgan says Nycomed intends to bring xenon imaging up to the same level of sophistication as helium imaging. The result could be a remarkable new capability for medical science.

Since May of last year, most human work on hyperpolarized gases has been at a temporary halt. A court prompted the U.S. Food and Drug Administration to decide to regulate imaging agents as drugs rather than as devices. That means MITI has had to stop work on patients while it sponsors animal tests: several dozen beagles are now somewhere barking at a peculiarly high pitch as a result of being dosed with hyperpolarized helium 3. Bastiaan Driehuys, MITI's president, notes that divers breathe normal helium in large amounts and appear to suffer no ill effects—presumably because the gas does not dissolve in blood—but says the FDA is taking no chances with gases to be administered to patients with respiratory disease. One plausible concern is that rubidium could contaminate the product, so assays and materials have to be standardized.

Dreihuys says the FDA is expediting the process. He expects phase II clinical trials to start this year and is aiming for approval of helium 3 as a contrast agent in 2001. Better images will soon be in the air.

—Tim Beardsley in Charlottesville, Va.

DEFENSE POLICY

THE REAL STAR WARS

Politicians haggle over giving the Pentagon the ability to destroy commercial satellites in the name of "space control"

Although Democrats and Republicans have moved closer than ever to an agreement on the need for a missile defense system, the real "Star Wars" battle between the parties actually seems to be shaping up in space. At issue is whether the U.S. should develop weapons that can disable objects in orbit, such as communications or imaging satellites that adversaries could use to thwart U.S. military operations.

Politicians agree the Pentagon should protect U.S. satellites from attack and have the ability to destroy orbiting satellites. But they disagree about when to deploy offensive space-control technologies. Many Democrats, as well as the Clinton administration, are convinced that costly antisatellite (ASAT) weapons are not yet justified; besides, the administration argues, jamming satellite transmissions, attacking ground stations and using other methods are better options. Republicans think the threat is ever present and growing. More commercial imaging satellites are put up every year, and more access to sophisticated imagery of any spot on the globe is now available. Had Saddam Hussein enjoyed access to satellite images or communications relays during the Persian Gulf War, space-control proponents say, he might have fought more effectively against allied forces.

In 1997 the two sides were so far apart that President Bill Clinton used his briefly held line-item-veto power to kill three military space projects, two of which were related to space control and a third, the kinetic-energy ASAT missile program, representing the closest thing to an antisatellite weapon in the military's arsenal. Although the money was later restored after the Supreme Court declared the line-item veto unconstitutional, space-control advocates were relentless in their criticism of Clinton.

Last year, though, the two sides began to show greater willingness to cooperate. Republican lawmakers, led by Senator Bob Smith of New Hampshire, agreed to fund a generic space-control program instead of the kinetic-energy ASAT missile. In exchange, the Pentagon said it would devote additional money to space control: $10 million a year over six years, with more likely to come.

For space-control backers, it was progress. John Luddy, an aide to Smith, points to another indicator of movement on the administration's part: March testimony delivered by Deputy Defense Secretary John Hamre to Smith's Senate subcommittee. "Space system negation to counter ground- or space-based elements of an adversary's space system or its data linkages could be accomplished by various methods," Hamre testified. "Physical destruction is not the preferred approach, but we must preserve the option for irreversible denial"—Pentagonspeak for destroying satellites.

John Pike, a space policy analyst for the Federation of American Scientists, sees an ulterior motive in the administration's decision to fund space-control development. He notes that internal documents describing the new program state that earlier Pentagon reluctance to back space control drove lawmakers to "ignore" the Defense Department and "turn to outside special-interest groups for ideas." The Pentagon added funds to "reinject the department into the congressional dialogue on space control."

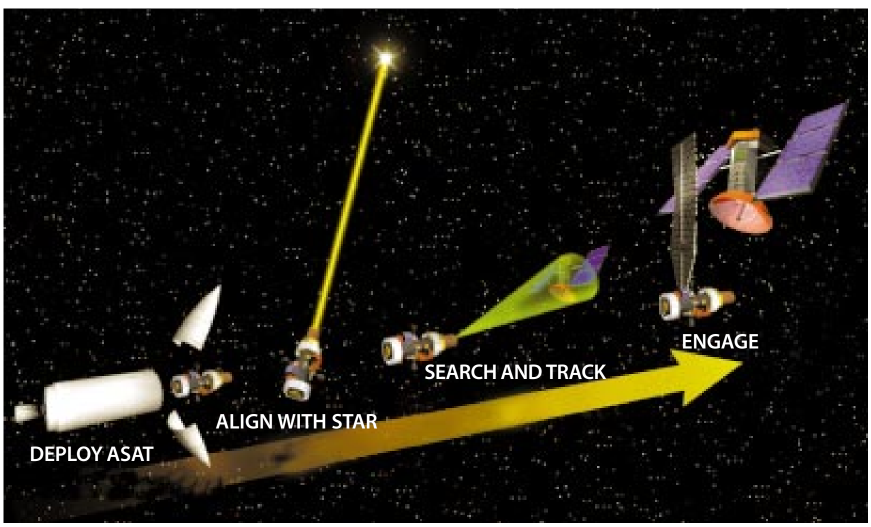
This, Pike declares, smacks of congressional appeasement. "It's totally divorced from any discussion of what the country actually needs," he says. And it won't work: Congress is as likely as ever to add funds for ASAT weapons, starting with the kinetic-energy ASAT program, regardless of what the Pentagon sets aside.

In reality, "ASATs are still weapons looking for a mission," argues ASAT congressional critic Senator Tom Harkin of Iowa, who opposed a test of an army laser in 1997 on the grounds that it could be construed as an ASAT test. "I have to question why the Pentagon would spend millions of dollars to build a weapon to attack a threat that does not exist."

For Harkin, it comes down to this: while the number of commercial satellites deployed every year grows, giving more access to unprecedented amounts of information, the control over those satellites is still held by the governments or companies of very few countries. Any satellite used by a potential enemy would almost certainly be one the U.S. or its allies has a piece of, Harkin believes. "It is absurd to spend millions of dollars to develop an ASAT weapon to be used against a satellite owned by the French or another of our allies," he says.

But for Luddy and Smith, now a U.S. presidential candidate for 2000, the need for space-control weapons is greater than ever, thanks to easy commercial satellite access. And the kinetic-energy ASAT program, Luddy says, could be deployed in a few years if Congress continues funding. "If our forces were engaged in mortal combat, and we had no other choice, we should have the option to destroy a commercial satellite," Luddy maintains. "While we would hope to never have to use it, we need to hold a fist behind our back." —*Daniel G. Dupont*

DANIEL G. DUPONT, based in Washington, D.C., described missile defense in the June 1998 issue and edits the newsletter Inside the Pentagon.



***KINETIC-ENERGY ANTISATELLITE WEAPON** would orient itself against a star and deploy a shroud to wrap and disable a satellite.*

Your 0.002 Cent's Worth

"Energy too cheap to meter" was the great canard of the atomic age. It's beginning to look as if "information for micropennies a page" will be the Internet-era equivalent. As the World Wide Web gained popularity, dozens of entrepreneurial groups rushed to meet the need for small on-line payments so that people could buy articles from their favorite newspaper, reports on new products, beautiful images for their computer screens. Giants such as Visa International and Carnegie Mellon University hawked their digital-payment wares right alongside the tiny start-ups with a patent and a dream.

Today, even as a Web standardization committee is putting the finishing touches on a format for encoding microtransactions in Web-page text, all that's left of most of the would-be five-and-dime tycoons is the Internet equivalent of an empty storefront: "404 Not Found" or "The server does not have a DNS entry." First Virtual, which billed itself as the first Internet bank, has abandoned the business altogether; DigiCash [see "Achieving Electronic Privacy," by David Chaum; Scientific American, August 1992] is in Chapter 11 reorganization, and its only telephone number leads to a message from the company's "interim president" saying he no longer listens to messages left there. Ostensible market leader CyberCash has stopped offering "cybercoin" transactions in its U.S. software. In the U.S., at least, all the banks that once supported micropayments have taken their resources elsewhere.

Once they got out of the pilot phase, micropayment schemes suffered from the dark side of the law of increasing returns: consumers didn't want to download unproved e-commerce software without an attractive range of things they could buy. But most Web firms weren't willing to invest in digital-cash servers and parcel up their sites into easily salable chunks without a guaranteed audience of willing buyers.

In addition, at least within the U.S., widely accepted Web security standards have made credit-card payments a de facto Internet standard. You can surf almost anywhere and buy with plastic, as long as the price tag is large enough—about $5 or $10—to cover transaction-processing fees and still allow a profit. In Europe and Asia, where credit-card transactions are not so ubiquitous, digital cash is making more headway, just as "smart cards" have in previous years.

U.S. consumers who might have been interested in data by the pennyworth (had they been for sale) have generally not been willing to buy information by the sawbuck. Web-based publications such as Microsoft's *Slate*—before the company gave up on paid subscriptions—found themselves with only a small fraction of the subscribers they needed to break even (or to match their print competitors).

As a result, instead of micropayments (or macropayments) from consumers, the Web has grown to its current multimillion-site sprawl in large part with micropayments from advertisers. Traffic statistics suggest that half of all pages sent over the Web every day contain an ad. Every time you click on a page with an advertising banner, the site owner gets anywhere from a few tenths of a cent to a dime from companies who believe a 60-by-460-pixel animated display might make you want to buy their products. Site managers settle accounts with an ad broker, rather than with thousands or millions of individual viewers. About 1 percent of sites generate enough traffic to attract advertisers; the best, such as Netscape.com or Yahoo.com, earn revenues in the millions.

DAVID SUTER

Advertisers measure the effectiveness of their banners by "click-through," the percentage of surfers who follow the banner link to a company's Web site. That number started above 10 percent in the earliest commercial days of the Web, sank to 2 percent by 1996 and dropped to 0.7 percent in 1998. As advertisers find themselves spending more money for fewer responses, many have begun to insist on "action-based" pricing, which rewards sites based on the number of users who click through. They may offer a percentage of the take or payments of $10 or more when sites refer someone who actually makes a purchase.

The next step for Web sites being paid according to click-through is to share some of that revenue with Web surfers. Cybergold, for example, offers on-line payments of several dollars per click to people who sign up with the site and make purchases at the dozen or so participating merchants. Users can withdraw the balance in their account for a fee or buy a small range of digital products from the Web site. AllAdvantage.com offers users 50 cents for every hour (up to $20 a month) they spend on-line with the company's software displaying ads across the bottom of their screens.

Russ Jones of Compaq Computer suggests that the opportunity to "earn" as well as spend small sums may eventually create a real market for digital cash and micropayments not tied to a single company or Web site. Jones is business manager for the company's MilliCent project (named for the size of the transactions its software was designed to handle without excessive overhead), which will see commercial application this summer in a collaboration of KDD, Japan's second-largest telecommunications provider, and 18 of the nation's leading magazines and newspapers. In trials last year, 10,000 users spent an average of a little more than a dollar each on items priced as low as 0.2 cent. They included such fare as dictionary searches, high-quality pictures of museum artifacts and articles from special-interest magazines, offered by 45 vendors.

It's unlikely anyone will get rich from micropayments, Jones says—for a small Web site, the income could cover Internet access fees and a holiday bonus. Depending on your opinion of the multibillion-dollar market valuations of Internet start-ups, that prediction could be a harbinger either of failure or of eventual success for digital small change. In either case, after making a few broad assumptions, expect this article to have cost you no more than four cents. *—Paul Wallich*

Using techniques drawn from the analysis of music, astronomers have been studying how galaxies form into progressively larger groupings

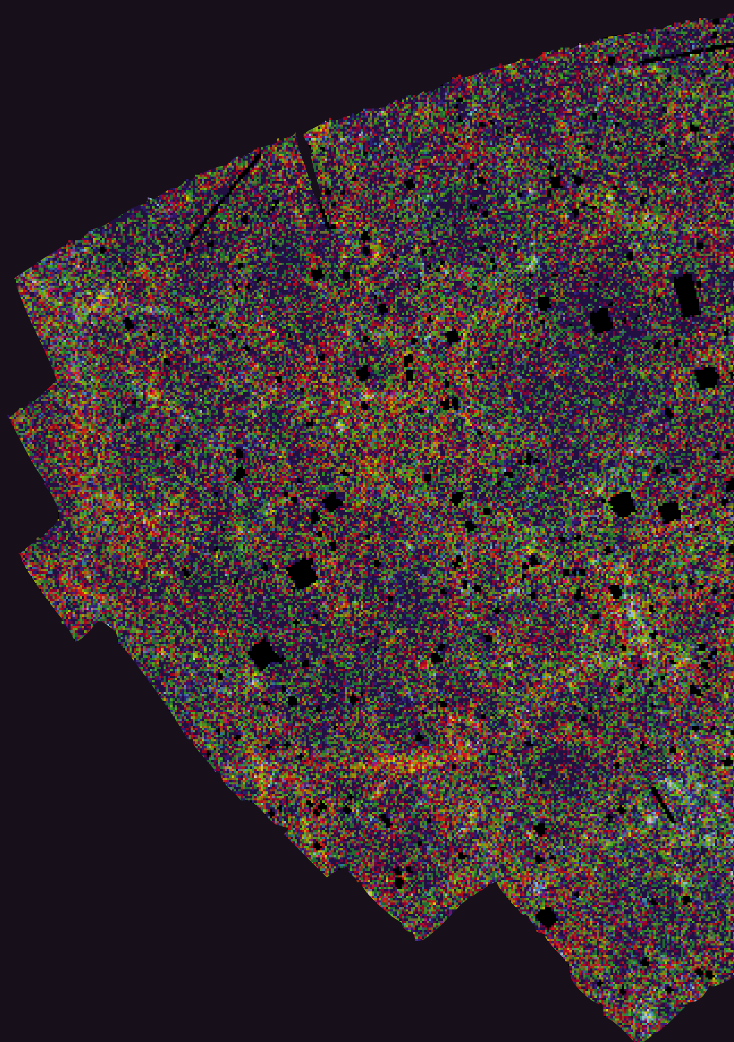
Mapping the Universe

by Stephen D. Landy

Even for most astronomers, a galaxy is a sizable thing—a throng of hundreds of billions of stars, threaded with gargantuan clouds of gas and dust, in a region hundreds of thousands of light-years across. But for cosmologists, those who study nature on its very largest scales, a galaxy is merely the basic unit of matter. Billions of them fill the observable universe. They congregate into clusters three million or more light-years across, which in turn constitute progressively larger assemblages. On all scales observed thus far by astronomers, galaxies appear to cluster and form intricate structures—presumably through physical processes that were dominant during the early expansion of the universe and later through gravitational interactions.

Yet there is a paradox. The clumpiness of galaxies runs contrary to one of the essential tenets of modern cosmology: the cosmological principle, the concept that the universe overall is homogeneous and isotropic, that it has no preferred place or orientation. Whenever cosmologists discuss the global properties of the universe, such as its mean density, expansion rate and shape, they do so under the auspices of this principle. On some large scale, such as that of the whole observable cosmos with a radius of 15 billion light-years, the distribution of these galactic motes should approach uniformity. But how can the evenness of matter on the ultimate scale be reconciled with the unevenness of matter on smaller scales?

Over the past several years, technological advances have enabled astronomers and cosmologists to probe the arrangement of galaxies at great distances. The naive notion that at some scale the cosmos becomes uniform has been replaced by an appreciation that the large-scale structure of the universe must be understood in terms of random processes. Although the universe is still considered to be homogeneous and isotropic, this is true only in a subtle, statistical sense. These insights are helping untangle some of the thorniest issues in cosmology:

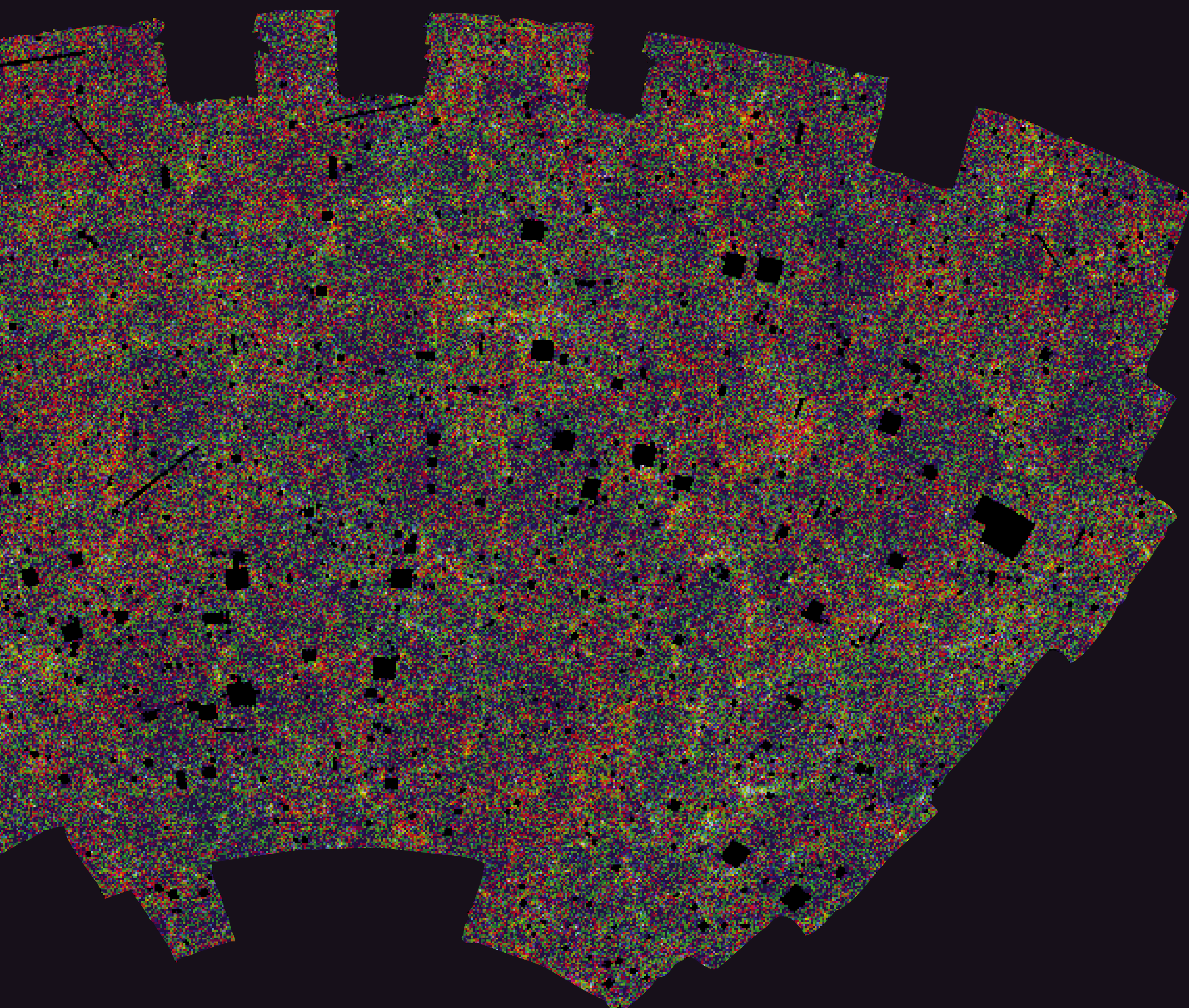


What did the universe look like at the dawn of time? How did it grow and develop into what we live in today? What forms of matter, both mundane and exotic, does it contain?

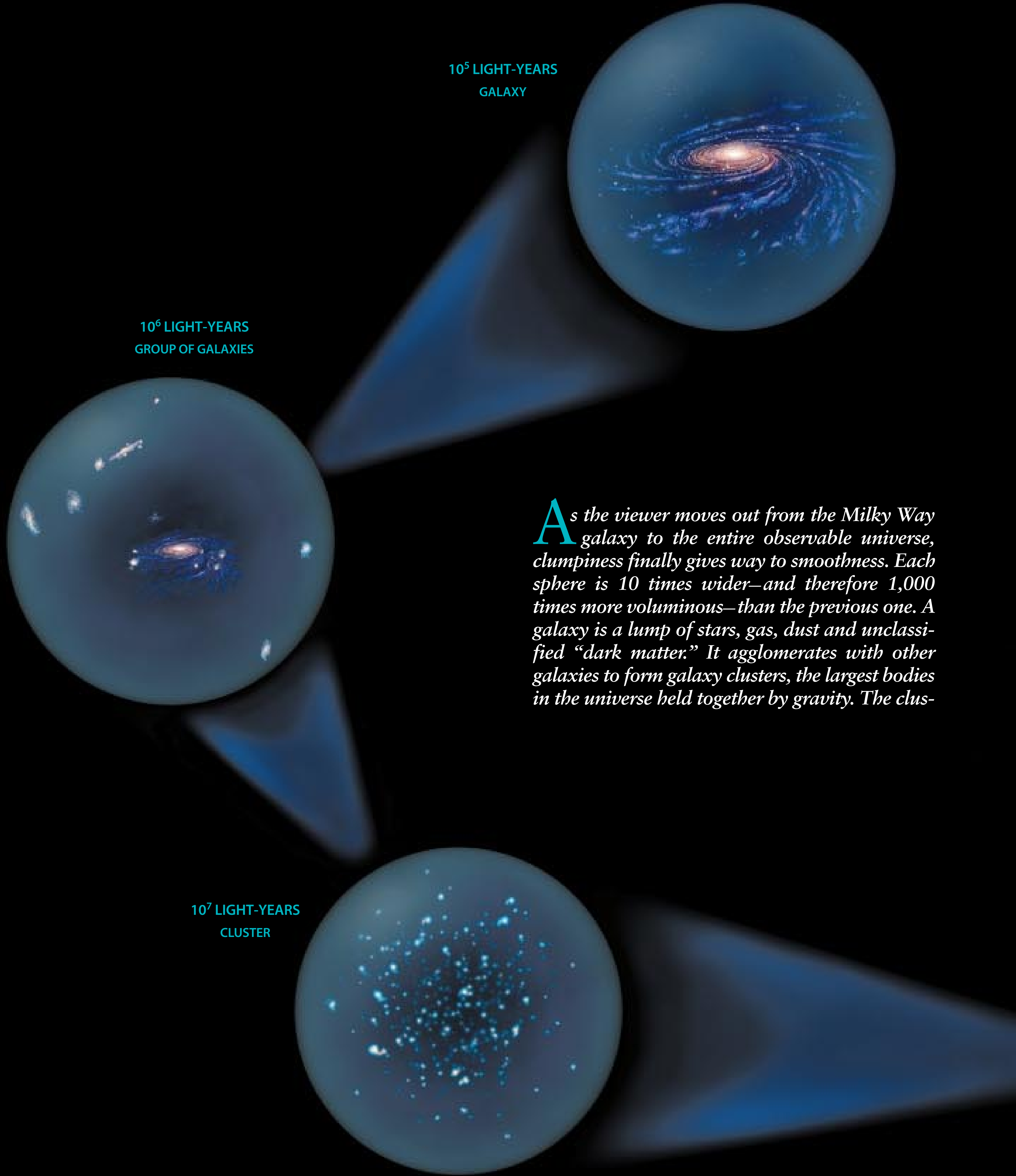
The recent work has followed two decades of exciting discoveries. In the late 1970s and early 1980s, cosmologists began to map galaxies in a systematic way [see "Superclusters and Voids in the Distribution of Galaxies," by Stephen A. Gregory and Laird A. Thompson; Scientific American, March 1982]. In so doing, they sought to measure the distribution of all matter, including the intergalactic "dark matter" that, unlike galaxies, does not give off light. (The assumption that luminous galaxies trace the total mass is no more than an approximation, albeit a constructive one; other research has attempted to quantify the bias that results.)

Cosmo-cartographers discovered that on scales of up to 100 million light-years, galaxies are distributed as a fractal with a dimension of between one and two. The fractal arrangement of matter would be a severe prob-

THREE MILLION GALAXIES, each one containing billions of stars, appear on the map of 15 percent of the sky centered on the constellation Sculptor. Although galaxies fill the sky, making it look roughly the same in every direction, they tend to fall into clusters, clumps and chains. This map, in which the brightness of each dot is proportional to the number of galaxies it represents, was pieced together by the Automated Plate Measuring Galaxy Survey from black-and-white photographs from the U.K. Schmidt Telescope. On this color-enhanced version, blue, green and red dots depict bright, medium and faint galaxies, respectively. The black patches are areas around bright stars that the survey was unable to probe.



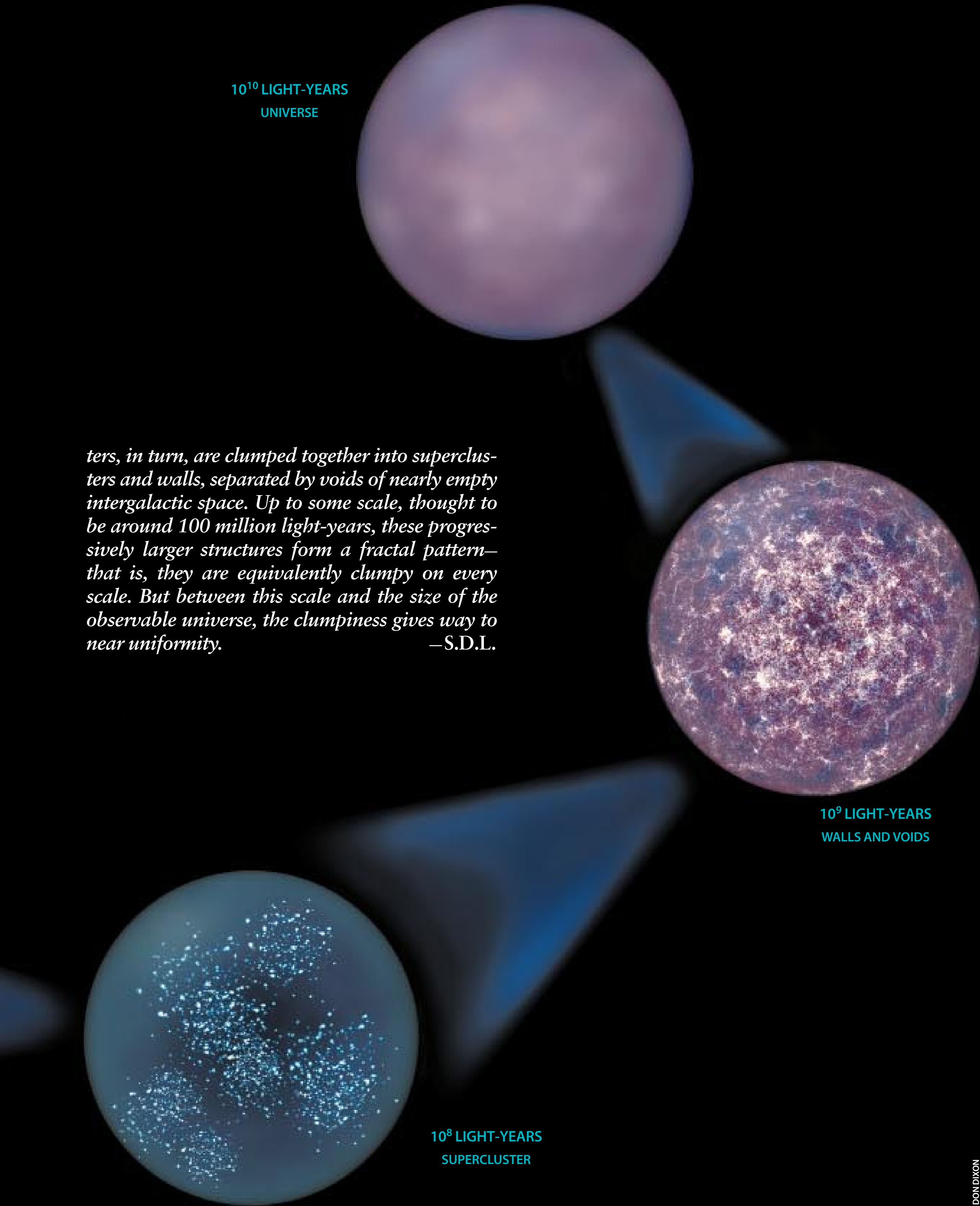
COURTESY OF STEVE MADDOX *University of Cambridge*



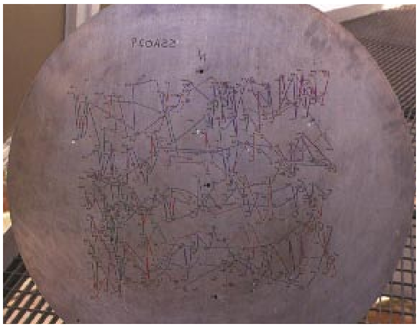
Large-Scale Structures in the Universe

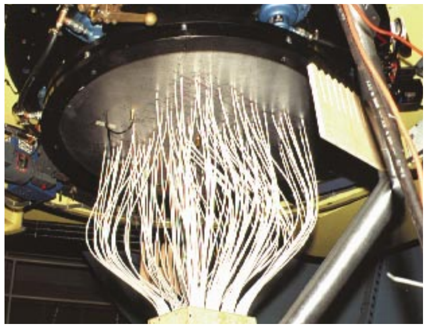
As the viewer moves out from the Milky Way galaxy to the entire observable universe, clumpiness finally gives way to smoothness. Each sphere is 10 times wider—and therefore 1,000 times more voluminous—than the previous one. A galaxy is a lump of stars, gas, dust and unclassified "dark matter." It agglomerates with other galaxies to form galaxy clusters, the largest bodies in the universe held together by gravity. The clus-

ters, in turn, are clumped together into superclusters and walls, separated by voids of nearly empty intergalactic space. Up to some scale, thought to be around 100 million light-years, these progressively larger structures form a fractal pattern—that is, they are equivalently clumpy on every scale. But between this scale and the size of the observable universe, the clumpiness gives way to near uniformity. —S.D.L.



DON DIXON





CARNEGIE OBSERVATORIES

TO SPEED UP THE SURVEY of more than 26,000 galaxies, Stephen A. Shectman designed an instrument capable of measuring 112 galaxies simultaneously. In a metal plate (*far left*), he drilled holes that corresponded to the positions of the galaxies in the sky. Fiber-optic cables (*near left*) carried the light from each galaxy down to a separate channel on a spectrograph at the 2.5-meter du Pont telescope at the Carnegie Observatories on Cerro Las Campanas in Chile.

lem for the cosmological principle if it extended to larger scales, because a fractal distribution is never homogeneous and isotropic. Unlike, say, a crowd of people, a fractal does not approach homogeneity when viewed from a distance; like a coastline, it looks uneven on every scale. In a fractal universe of dimension two, the expected mass within a spherical volume centered on a random galaxy would increase as the square of the radius instead of the cube. In such a universe, the mean density would be a function of scale, and other universal parameters such as the cosmic expansion rate would lose their meaning. In short, the fractal findings seemed to pull the rug out from under modern cosmology.

Subsequent surveys, however, indicated that on scales of hundreds of millions of light-years, the fractal nature broke down. The broader distribution of galaxies could be described in terms of a simple statistical process with a well-defined mean and variance—a noise process. The cosmological principle was saved. But in the late 1980s new problems rose to threaten it [see "Very Large Structures in the Universe," by Jack O. Burns; SCIENTIFIC AMERICAN, July 1986]. A high-resolution survey detected a "Great Wall" of galaxies 750 million light-years long, more than 250 million light-years wide and 20 million light-years thick. A noise process could not readily explain such a colossal, coherent structure. These discoveries motivated still larger mapping projects, including the Las Campanas Redshift Survey that my colleagues and I conducted from 1988 to 1994.

Slicing through the Universe

Because the Las Campanas survey sought to measure the distribution of galaxies on a scale several times that of previous studies, it encountered a number of observational challenges. The most distant galaxies were faint, so photographing them would require a lengthy exposure time. The large survey volume increased the number of objects that had to be observed. In sum, we had to observe more objects with a longer exposure but with only limited telescope time. For these reasons, we decided to construct a survey that would be very deep (out to two billion light-years) and wide (85 degrees across the sky) but thin (1.5 degrees)—effectively sampling the galaxy distribution in only two dimensions. Though thinness compromised the signal, it allowed a first glimpse of the organization of the cosmos on scales of several billion light-years.

The survey made six separate maps and recorded the positions of more than 26,000 galaxies. The data were collected at the Carnegie Observatories on Cerro Las Campanas in the Atacama Desert of Chile. This information was analyzed by Stephen A. Shectman of the Carnegie Observatories, Robert P. Kirshner and Huan Lin of the Harvard-Smithsonian Center for Astrophysics, Augustus Oemler and Douglas L. Tucker of Yale University, Paul L. Schechter of the Massachusetts Institute of Technology and me.

The survey involved several steps. First, we made photometric observations—basically, highly sensitive photographs of the sky—with a charge-coupled device (CCD) camera mounted on the one-meter Swope telescope at Las Campanas. For maximum efficiency, we used a specialized technique known as drift-scan photometry, in which we pointed the telescope at the beginning of a survey field and then turned off its automated drive. The telescope stood still as the sky drifted past. Computers read information from the CCD detector at exactly the same rate as the rotation of the earth, producing one long, continuous image at a constant celestial latitude. Completing the photometry took a total of 450 hours.

Second, we analyzed the strips to determine which objects were likely to be galaxies and suitable for inclusion into the survey. Candidates were chosen based on their brightness and galaxylike fuzziness. Finally, we observed these objects with a spectrograph at the 2.5-meter du Pont telescope at Las Campanas. The spectrograph broke the light down into a spectrum of colors, from which we calculated each galaxy's redshift, a measure of its distance.

Because gathering enough light to measure the spectrum of a galaxy in this survey took about two hours, if we had observed only one galaxy at a time, a survey of this size would have been impossible. But Shectman designed a multiple fiber-optic system to measure the spectra of 112 galaxies simultaneously. This system worked as follows: Once we had chosen the prospective galaxies, we drilled holes in a metal plate to be mounted at the focus of the telescope. These holes corresponded to the positions of the galaxies in the sky. Into these holes we plugged fiber-optic cables that carried the light from each galaxy down to a separate channel on the spectrograph. Even with this parallel processing, it took us 600 hours of observing time over 100 nights to measure all the spectra.

Sounding Out the Universe

Looking at the maps produced by the survey, the eye is struck by the sense that the galaxies are not randomly distributed but instead tend to bunch together [*see illustration on page 45*]. Yet one must be careful of visual impressions. Our brains often seek patterns where none exist. In this case, however, statistical techniques bear out the existence of clustering.

The simplest way to measure clustering is to use correlation functions, which represent the number of pairs of objects as a function of their separation. For example, the distribution of deer in a forest is highly clustered on small scales—say, a few tens of yards. In randomly picking out deer in the forest, you would notice that you are much more likely to find another deer a few yards away than a few hundred yards away. The correlation function would show a strong positive signal on the scale of a few tens of yards and a weak or negative signal on the scale of a few hundred yards. It mathematically describes the well-known fact that deer tend to travel in small groups.

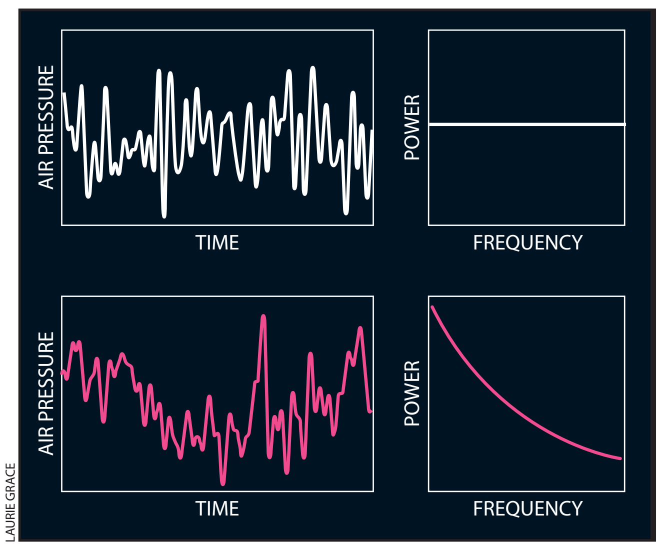
A similar analysis can be done on galaxies, and it works well on scales that are much smaller than the size of a survey. But on larger scales it is not very informative. The problem is that the number of galaxies—and therefore the number of galaxy pairs—is set. If there is an excess of pairs at small separations, there must be a deficit of pairs at larger separations, because the total number of pairs is fixed. This zero-sum game contaminates the clustering signal on larger scales.

Fortunately, a complementary technique can reliably measure clustering at large scales: harmonic analysis, also known as power spectrum analysis. Harmonic analysis, as its name suggests, is closely allied to the study of sound. In fact, the mathematical analysis of the distribution of galaxies and of random noise is identical. (The power spectrum is conceptually related to but physically distinct from the kind of spectrum that astronomers usually study, that of light.)

Many common phenomena, such as the waves on the surface of the sea and the air pressure fluctuations in a room, are most naturally described in terms of their power spectra. In fact, the human ear performs a similar analysis on pressure fluctuations—that is, sound. The fluctuations can be thought of as a collection of pure tones, each with a certain strength. The cochleas in our ears decompose the fluctuations into their constituent tones (or frequencies). The signal sent to the brain describes the strength (or amplitude) of each tone.

The power spectrum is a measure of the strength of the pressure fluctuations as a function of frequency. It is what the graphic equalizer of a stereo displays. Large musical instruments, such as a bass or a tuba, put out a large fraction of their power at long wavelengths, which correspond to low frequencies. The sound of breaking glass consists primarily of high frequencies.

Random noise is special because it can be completely described in terms of its power spectrum [see Mathematical Games, by Martin Gardner; SCIENTIFIC AMERICAN, April 1978]. Consider two people who go to visit the same waterfall several minutes apart. Each records several minutes of sound. Although their recordings will not be the same—the sound made by the waterfall is always changing—both will record the characteristic sound of the waterfall. If the observers take their recordings and perform a harmonic analysis, they will each find the same power spectrum. The statistical properties of their two recordings are identical.



WHITE AND PINK NOISE surround us. White noise, the grating sound of static on a badly tuned radio or television, is completely random. The sound fluctuates from instant to instant without any pattern (*top*). Pink noise, the sound of a waterfall or waves crashing on the beach, is fractal (*bottom*). This distinction is reflected in the power spectra (*graphs at right*): white noise has equal power at all frequencies, but pink noise has more power in the bass than in the treble, in inverse proportion to the frequency.

The Color of Sound

Noise with a flat power spectrum, corresponding to equal power at all frequencies, is called white noise. The term comes from an analogy with color. Each color has a different frequency; if you add all the colors together equally, you get white. In terms of sound, white noise is the static between radio stations. Its sound is perfectly random; at each instant the sound is unrelated to, or uncorrelated with, the sound that came before. Another special power spectrum is that of pink noise, in which each octave delivers the same power [*see illustration below*]. A waterfall produces pink noise.

Harmonic analysis can reconcile the cosmological principle with the clustering of matter. If the universe is homogeneous and isotropic, observers sitting on planets in separate galaxies should measure the same properties for the universe on its largest scales. Of course, they will see different galaxy distributions, just as any two slices in the Las Campanas survey are different. But given enough surveys, or a survey of sufficient size, the two observers should measure the same statistical fluctuations. These fluctuations, like those of the sound of a waterfall, can be described in terms of the power spectrum.

As the universe expands and evolves, various physical processes modify the power spectrum of its large-scale structure. Cosmologists generally believe that quantum-mechanical fluctuations imparted the initial power spectrum shortly after the start of the big bang. In the late 1960s English physicist Edward R. Harrison and Russian physicist Yakov B. Zel'dovich derived a shape for this primordial power spectrum—namely, a power law with the functional form of frequency to the negative third power, a pink-noise spectrum in three dimensions.

Harrison and Zel'dovich both reasoned that most natural forces, including gravity, have no intrinsic length scale; they are power laws. Therefore, the initial power spectrum should be some form of power law in frequency, so it does not single out any particular length scale. They also grasped the role of the horizon size in the evolution of the universe. The horizon size is simply the distance a beam of light could have traveled in the universe since the big bang up to any particular moment. Because the influence of gravity also travels at the speed of light, two points in the universe can interact gravitationally only if they are separated by a distance less than or equal to the horizon size. As the universe ages, the horizon size grows. Therefore, the horizon size defines a natural length scale over which gravity can operate.

What Harrison and Zel'dovich realized was that if the initial power-law spectrum was not precisely frequency to the negative third power, then one of two things would occur. If the power law were steeper—say, frequency to the negative fourth power—then fluctuations on very small scales would have been greater. In calculating the density fluctuations in the early history of the universe, when the horizon size was small, they found that many regions would have contained such a high density of matter that they would have quickly collapsed, filling the cosmos with black holes. Fortunately, this did not happen. Our very existence rules out such a power spectrum. On the other hand, if the power law were shallower, then at later times the density on large scales would fluctuate hugely. No such fluctuations exist.

Although this argument is quite persuasive to cosmologists, it does not explain how such a spectrum would have arisen. Cosmological inflation provides an explanation, which was an early success for the theory, as well as being one of its few testable consequences [see "The Inflationary Universe," by Alan H. Guth and Paul J. Steinhardt; Scientific American, May 1984].

A Great Number of Great Walls

The power spectrum of the universe today is very different from the primordial Harrison-Zel'dovich spectrum. Gravity has amplified the initial fluctuations and led to the growth of such structures as clusters of galaxies. At earlier times, the growth of fluctuations on specific scales was enhanced or retarded depending on whether the universe was dominated by matter or by radiation and whether elementary particles were light and fast-moving or heavy and slow-moving. One of the great challenges for modern cosmology is to determine how the initial power spectrum evolved into the spectrum observed today. Only in the past several years have observations, such as those of galaxy distribution and of the cosmic microwave background radiation, acquired enough data to put theories to the test.

So-called cold dark matter models are now the most popular explanations for the growth of structure. Their premise is that most of the mass in the universe resides in some unseen (hence, "dark"), relatively massive type of particle. It is "cold" because, being heavy, it travels slowly. The particle, which would interact with ordinary matter only through the force of gravity, could also account for the missing mass in galaxies and galaxy clusters [see "Dark Matter in the Universe," by Lawrence M. Krauss; Scientific American, December 1986].

One of the surprising results from our survey is its deviation from the cold dark matter model on scales of around 600 million light-years. At smaller scales the predictions of the model match our findings, but something strange singles out the large scales [*see illustration at right*]. Previous surveys had suggested such a discrepancy, and one of the principal results of Las Campanas has been to substantiate it. From the strength of the deviation and the size of the survey, we calculated the probability of seeing such a deviation purely by chance as one in several thousand.

What is very interesting about this deviation is that it can be traced back to the huge structures seen in the galaxy distribution [*see illustration on opposite page*]. These structures are defined by the sharp boundaries, filaments and voids in the galaxy maps. The largest are almost three billion light-years across, several times the size of the Great Wall. The association of these walls and voids with the deviation in the power spectrum is a crucial finding of the Las Campanas survey. It means that on this scale, the galaxy distribution cannot be fully characterized using the mathematics of random noise. Some other physical process must have acted to imprint this characteristic scale on the density fluctuations.

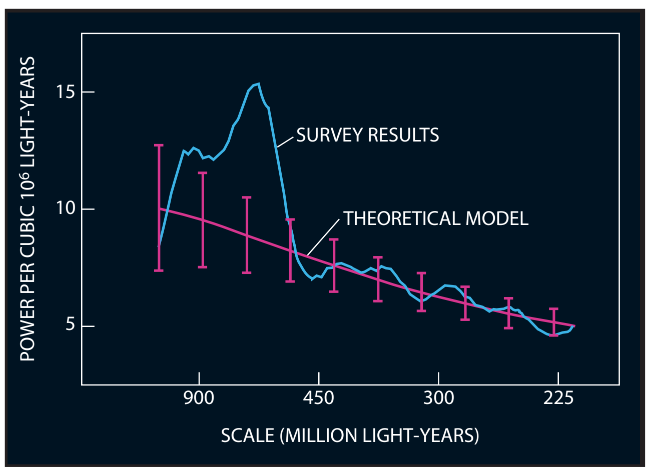
In fact, this inconsistency is what allows these walls and voids to properly be called structures. With a pure-noise process, walls and voids would occasionally appear by chance. But they would be much rarer, in keeping with the statistics of noise. They would be statistical fluctuations or chance superpositions, rather than true structures.

What could be responsible for the mammoth walls and voids? Gravity might be a good explanation except that it causes smaller-scale fluctuations to collapse more quickly, simply because it takes less time for gravity to pull matter together on small scales. If gravity were the culprit, galaxy clustering should have begun on small scales and then worked its way up to large scales. For the past two decades, such a bottom-up scenario, known as hierarchical clustering, has been the paradigm for explaining structure on scales smaller than about 150 million light-years. Yet the deviations in our survey begin to appear at much larger scales. Hierarchical clustering may still apply on the small scales, but it cannot explain the walls and voids on the larger scales.

The New Music of the Spheres

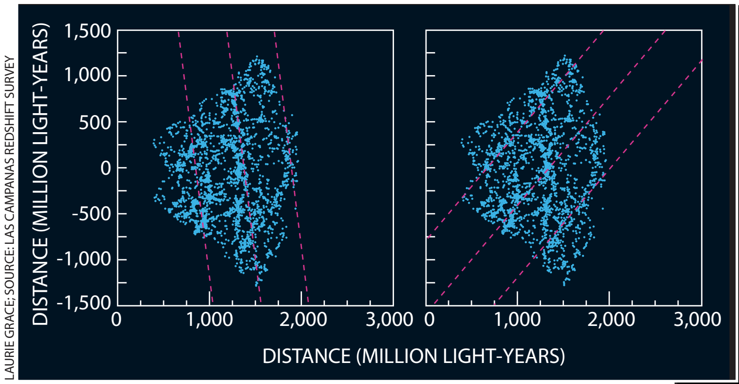
Several hypotheses have emerged, although none can yet be reconciled with all the data. The first is a hot dark matter scenario wherein the universe is dominated by light, fast-moving particles such as neutrinos. The result would be a top-down progression in structure formation starting on large scales. Unfortunately, this theory has the side effect of washing out structure on small scales, so it fails to account for the small-scale galaxy clustering.

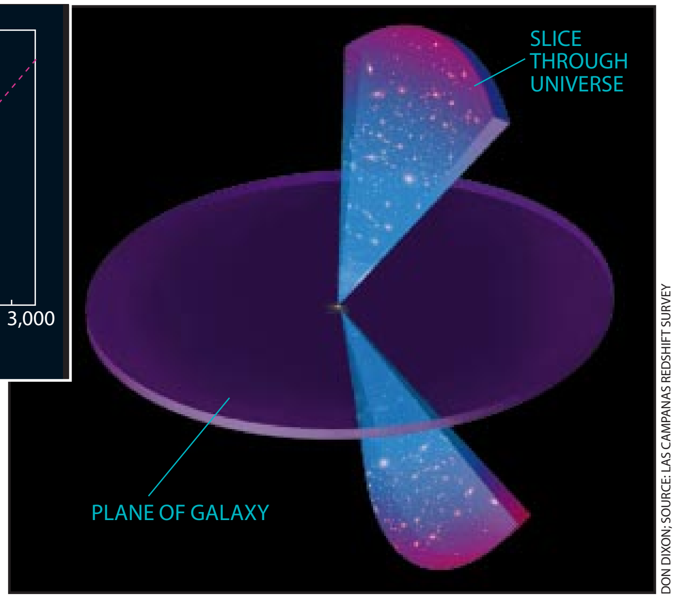
A second hypothesis posits that the universe is less dense than cosmologists suppose. Most of this decrease in density comes at the expense of exotic dark matter. Ordinary particles such as protons and electrons thus have a proportionately greater influence. They would have constituted a viscous fluid in the



LAURIE GRACE; SOURCE: LAS CAMPANAS REDSHIFT SURVEY

POWER SPECTRUM of the cosmos, as measured by the Las Campanas survey (*blue line*), generally follows the prediction of the cold dark matter model (*pink*). But the power increases dramatically on scales of 600 million to 900 million light-years. This discrepancy means that the universe is much clumpier on those scales than current theories can explain.





TWO SLICES of the universe (*right*), observed during the Las Campanas survey, graphically reveal the clumpiness of the universe on large scales. The dots, which represent the several thousand galaxies each slice contains, are not uniformly spread out; they bunch into walls (*dotted lines in inset*), which are separated by approximately 600 million light-years.

early universe. Before the universe was cool enough for the protons and electrons to combine and form atoms, sound waves reverberated through this fluid. When the protons and electrons recombined, the acoustic waves gave a boost to the gravitational collapse on certain scales. Intriguingly, an underdense universe would also resolve other cosmological conundrums [see "Inflation in a Low-Density Universe," by Martin A. Bucher and David N. Spergel; SCIENTIFIC AMERICAN, January].

A third hypothesis points out that 600 million light-years is roughly the horizon distance at the time when the average density of matter in the universe overtook that of radiation. Such a profound change would presumably have affected the power spectrum somehow. Whatever the final explanation, it may be that astronomers are detecting the largest unique length scale associated with any physical process in nature.

Even a survey the size of Las Campanas contains only about 50 independent measurements of the power spectrum at these large scales. Larger surveys are needed, and several are now either in the development stages or under way. An Anglo-Australian consortium called the 2DF Survey is mapping more than a quarter-million galaxies. Soon the American-Japanese Sloan Digital Sky Survey will begin to measure the distances to almost one million galaxies over half of the sky, sampling a volume 20 times greater than that of the Las Campanas survey.

These studies are not the first use of harmonic analysis in the history of astronomy. It was originally Pythagoras in the sixth century B.C. who applied musical analysis to the motion of the sun, moon, stars and planets. He believed that the celestial bodies were holes in a set of crystal spheres through which shone the celestial light. The motions of these spheres, he reasoned, must produce sounds. Their distances and their speeds must be in the same ratios as musical harmonies. This was the first "music of the spheres."

In the 17th century Johannes Kepler, before formulating his famous laws of celestial motion, believed that the orbits of the planets could be described in terms of heavenly spheres inscribed between the five perfect Pythagorean solids. He reasoned that the harmonious ratios of music might be derived from these solids, and thus he argued for a fundamental relation between the orbits of the planets and these harmonies. This was the second music of the spheres.

Today our notion of harmonic analysis is quite different. It is based on analyzing the harmonic components of random distributions, and the sound is more like the gush of a waterfall than that of divine instruments. Although this modern endeavor may seem neither as pleasing nor as spiritual as those of the past, the concept of an isotropic universe wedded with an understanding of random fields now allows us once again to hear the music of the spheres. SA

The Author

STEPHEN D. LANDY first became interested in cosmology when he was lost in the woods one night and had nothing to do but stare up at the stars. After receiving his Ph.D. in physics from Johns Hopkins University in 1994, he did postdoctoral research work at the Carnegie Observatories in Pasadena, Calif., and at the University of California, Berkeley. Currently he is a visiting scientist at the College of William and Mary.

Further Reading

PRINCIPLES OF PHYSICAL COSMOLOGY. P.J.E. Peebles. Princeton University Press, 1993.

THE TWO-DIMENSIONAL POWER SPECTRUM OF THE LAS CAMPANAS REDSHIFT SURVEY: DETECTION OF EXCESS POWER ON 100 H^{-1} MPC SCALES. Stephen D. Landy et al. in *Astrophysical Journal Letters,* Vol. 456, pages L1–L4; January 1, 1996. Preprint available at xxx.lanl.gov/abs/astro-ph/9510146 on the World Wide Web.

THE LAS CAMPANAS REDSHIFT SURVEY. Stephen A. Shectman et al. in *Astrophysical Journal,* Vol. 470, pages 172–188; October 10, 1996. Preprint available at xxx.lanl.gov/abs/astro-ph/9604167 on the World Wide Web.

THE LARGE-SCALE SMOOTHNESS OF THE UNIVERSE. Kelvin K. S. Wu, Ofer Lahav and Martin J. Rees in *Nature,* Vol. 397, pages 225–230; January 21, 1999.

The Las Campanas Redshift Survey site is available at manaslu.astro.utoronto.ca/~lin/lcrs.html on the World Wide Web.

The Sloan Digital Sky Survey site is available at www.sdss.org on the World Wide Web.

How the Body Te

The precise orientation of our internal organs—
is controlled in part by proteins that are

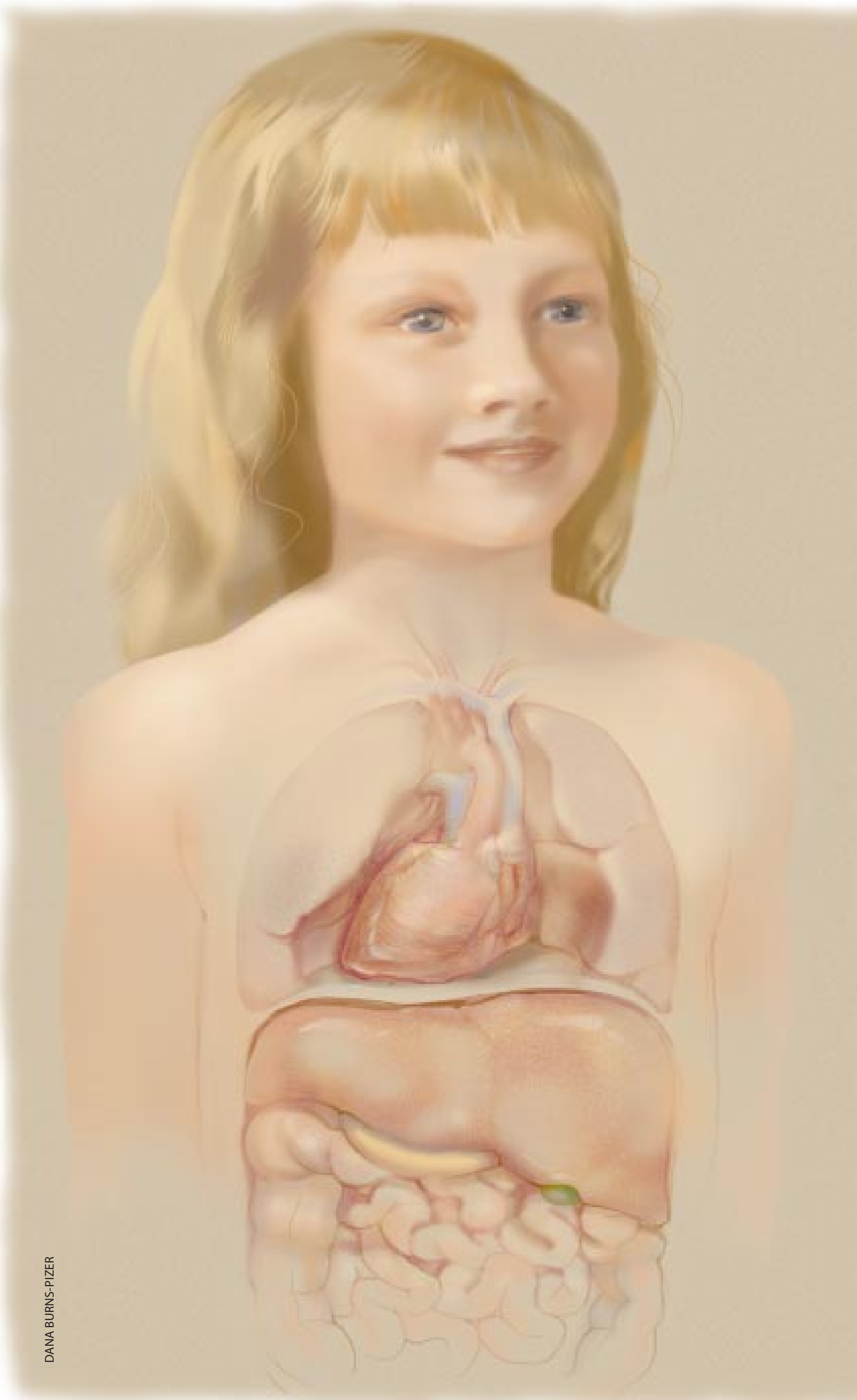
by Juan Carlos Izpisúa Belmonte

Look in the mirror and draw an imaginary line from the top of your head, along the bridge of your nose, and so on down your chest and your abdomen. You will notice that every external anatomical structure on one side of the line has a counterpart on the other side. Yet you have only one heart, one liver, one stomach, one pancreas and one spleen, and your colon coils from your right to your left. Even those organs that come in pairs show some asymmetry: the right lung has more lobes than the left, for instance, and some cerebral structures occur on only one side, or hemisphere, of the brain.

Why do our internal organs defy the symmetry of our overall body plan? And how do they get that way? Attempting to answer these questions, scientists have now identified several of the molecules that dictate organ placement, structure and orientation. We are finding that when these factors are absent or are produced in the wrong place, various human disorders can result. By understanding exactly how the factors function, we may learn how to treat or prevent such diseases.

A Place for Everything . . .

Asymmetric organ structure and placement seem to have evolved because they offer advantages for survival. The very complex digestive system of higher vertebrates—organisms with a backbone—can be more efficiently packed in the body cavity, for example, if the system follows an asymmetric pattern of loops and turns. Similarly, an asymmetric heart is bet-

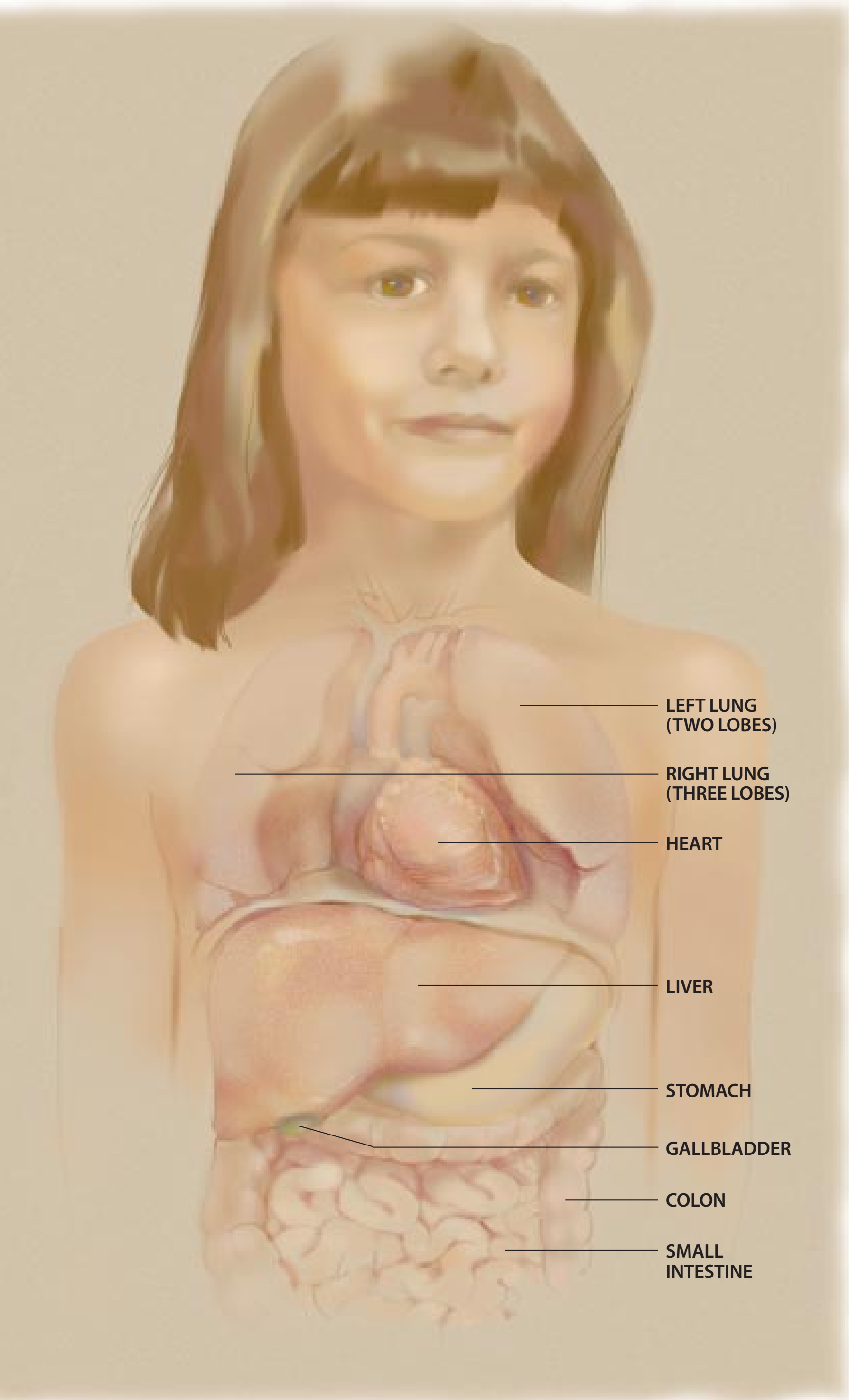


DANA BURNS-PIZER

CHILD WITH SITUS INVERSUS is born with all her internal organs in a mirror image of their normal position. The abnormality usually is benign. Serious problems can arise, however, when someone is born with two left sides or two right sides, so that normally asymmetric organs such as the heart are symmetric and do not function properly.

lls Left from Right

*and those of all other animals with a backbone—
produced on only one side of an embryo*



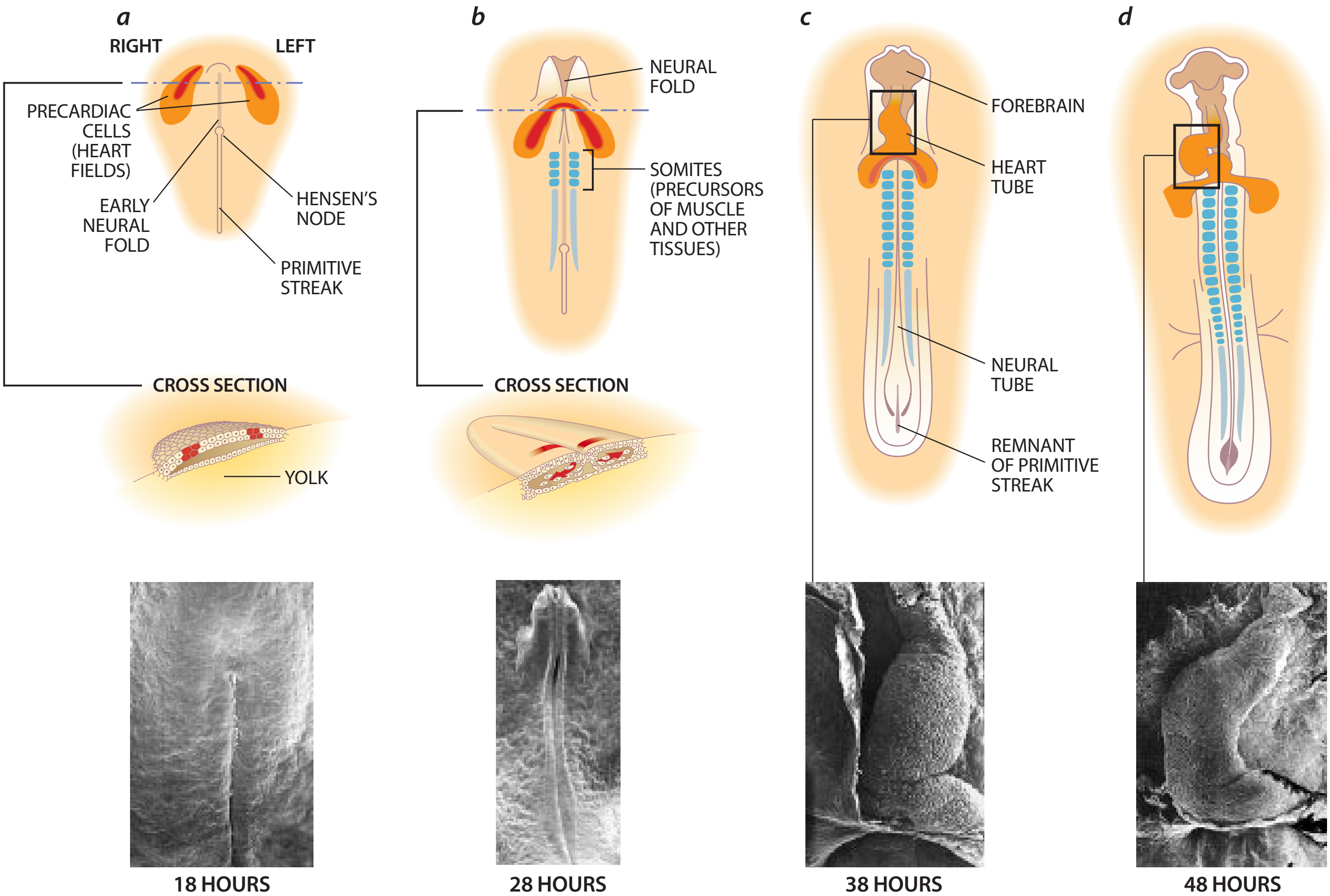
ter able to pump and distribute blood. Such cardiac asymmetry allows for two separate pumping systems: one for directing blood to the lungs, where it can take up oxygen and discharge carbon dioxide, and a second for delivering the reoxygenated blood to the body.

Interestingly, internal organs can develop in a mirror-image fashion to the usual arrangement and still work properly. Approximately one in every 8,000 to 25,000 people is born with a condition known as situs inversus, in which the positions of all the internal organs are reversed relative to the normal situation (situs solitus): the person's heart and stomach lie to the right, their liver to the left, and so on. (The organs are also mirror images of their normal structures.) These people are usually healthy, suggesting that as long as all a person's organs turn and loop with a specific pattern or internal logic, the actual direction of turning and looping is not important.

. . . And Everything in Its Place

People who are born with abnormally placed organs that are not a mirror image of the usual pattern are not so fortunate. Such individuals, who are said to have situs ambiguus, often die at an early age from lung or heart complications. Others who are born with a condition known as isomerism essentially have two left sides or two right sides to their bodies, so that they either have two spleens or no spleen, for instance. And internally, their hearts are exactly symmetric. The spectrum of disorders experienced by people with isomerism is complex, but for reasons that are still unclear those with left isomerism fare better than those with right isomerism. Many people with left

CHILD WITH NORMAL ORGAN PLACEMENT has her heart on her left, her liver on her right, a lung consisting of three lobes at the right and one having two lobes at the left. Her colon also coils from her right to her left. Researchers are now identifying genes that dictate the proper asymmetric structure and placement of internal organs.



CHRISTOPH BLUMRICH (*illustrations*); GARY SCHOENWOLF *University of Utah (two left photographs)*; JUAN M. HURLE *University of Cantabria (two right photographs)*

EARLY CHICK EMBRYO, like those of all vertebrates (animals with a backbone) normally develops with the precursor of the heart, called the heart tube, looping to the right side of the organism. The tube arises from two symmetric populations of cells (*a, red* and *orange*) that migrate from the surface of the embryo into a fold above a region called Hensen's node. After they fuse (*b*), they form a tube that is initially symmetric but that soon begins to loop asymmetrically toward the right (*c* and *d*). Scanning electron microscope images of the corresponding stages of development are shown beneath each diagram.

isomerism have no symptoms at all, whereas those with right isomerism rarely survive beyond one year.

Researchers have elucidated some of the mechanisms that control left-right asymmetry by studying the early stages of heart development in embryos. They concentrate on the heart because it is the organ most sensitive to abnormalities in the biological machinery controlling the body plan.

All asymmetric organisms begin as symmetric embryos. As far as anyone can tell, all vertebrate embryos are perfectly bilaterally symmetric at the earliest stages of development, with the left side an apparently perfect mirror image of the right side. But at some point early on, this evenness is broken. In vertebrates, the first obvious indication is a very specific event during the initial stages of forming the heart.

The heart arises from two symmetric groups of precardiac cells (the so-called heart fields) that fuse as development progresses [*see illustration above*], forming an initially symmetric heart tube. The first visible asymmetry is the bending of this tube to the right. This "looping" of the heart tube is one of the most crucial steps in heart formation because it determines the internal structure of the two pumping systems.

In 1995 Clifford J. Tabin of Harvard Medical School, Claudio D. Stern of Columbia University and their colleagues identified one of the biochemical factors that induces looping of the developing heart tube [see "How Limbs Develop," by Robert D. Riddle and Clifford J. Tabin; Scientific American, February]. Studying chick embryos, these researchers found that a protein playfully named Sonic hedgehog is required. (This protein got its name because when a version of it is lacking in fruit fly larvae, the maggots appear rounded and bristly, like frightened hedgehogs.) Specifically, they observed that right looping occurs only if Sonic hedgehog is secreted solely on the left side of a clump of embryonic cells known as Hensen's node. (Hensen's node is the location where cells in an early chick embryo sink below other cells to create a three-dimensional embryo; a similar node occurs in mammals.) If Sonic hedgehog appears on the right side of the node instead, the developing heart loops to the left.

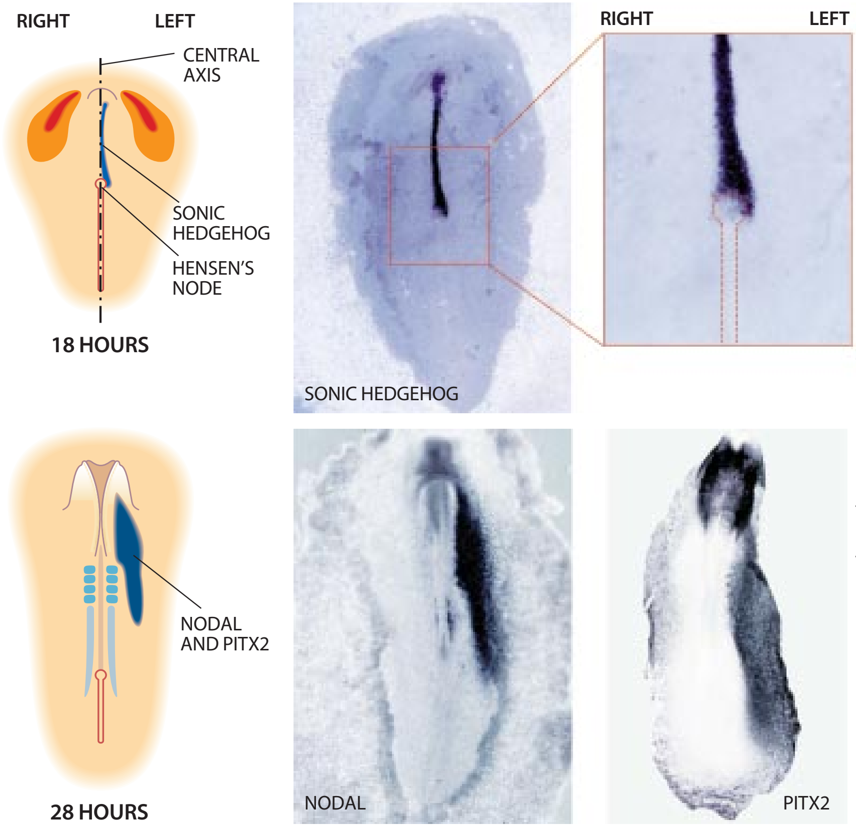
Sonic hedgehog is not the only player in determining the left-right asymmetry of the vertebrate heart. Other known proteins include Nodal and Lefty, which are secreted exclusively on the left side of an early embryo, and Activin βB, Snail and Fibroblast Growth Factor-8, which are only on the right side. When the proteins are made in their correct locations at the appropriate times during development, normal organ placement results; if the location or timing of production of any of these proteins is perturbed, abnormalities occur.

In chick embryos, for instance, the presence of Sonic hedgehog and Nodal on the left side of Hensen's node and Activin βB on the right leads to a normally asymmetric heart. Applying extra Sonic hedgehog or Nodal protein to the right side of an embryo (so that both sides of the node are now exposed to Sonic hedgehog or Nodal) can override the effects of Activin βB and confuse development: approximately half the embryos will have normal heart looping, but the heart tubes of the other half will loop in the opposite direction. The explanation for this random response seems to be that some additional factor or factors induce looping per se; in that case, Sonic hedgehog, Nodal and Activin βB influence the direction of looping. Production of Sonic hedgehog on both sides of the node leads to production of Nodal on both sides as well. Lacking clear signals as to which way to loop, each embryo "decides" on the direction of curvature randomly, resulting in 50 percent situs solitus and 50 percent situs inversus.

Interestingly, the result is the same when Sonic hedgehog or Nodal is absent from both sides. Thus, the complete absence of signals in the node or the presence of signals on both sides of the node results in random heart looping. These proteins, like all others, are made when the genes that specify their makeup are active, or switched on. It is not yet known whether people with situs inversus or isomerism have mutations in the genes for the human versions of the Sonic hedgehog and Nodal proteins, but researchers speculate that is the case.

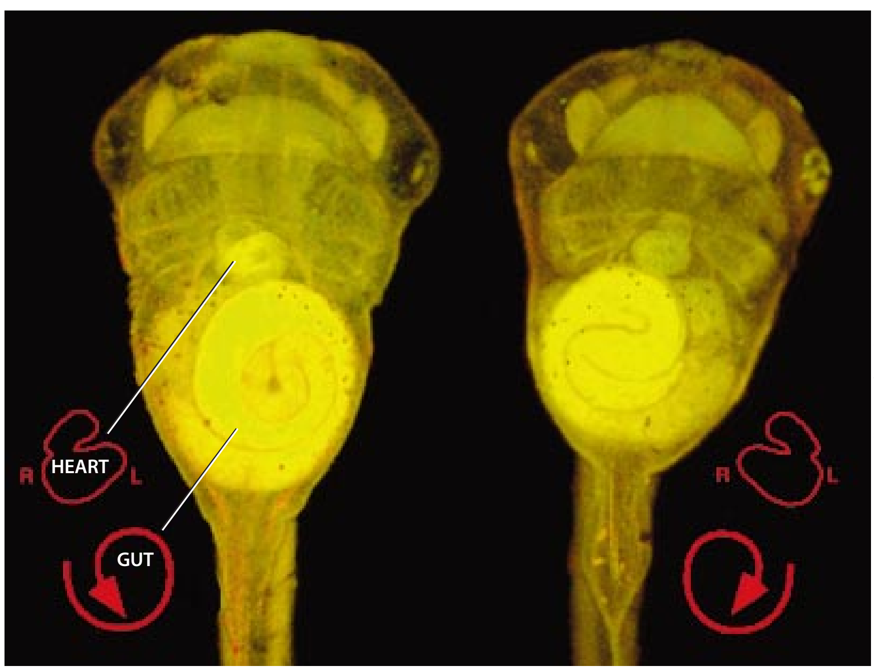
What controls the asymmetric placement and shape of other organs? A gene recently identified by six independent research groups, including mine, seems to be part of the answer. It codes for a protein named Pitx2. Like Sonic hedgehog and Nodal, Pitx2 appears on the left side of the nascent heart and influences the direction of looping. But unlike those substances, it continues to be produced asymmetrically late into embryonic development. Moreover, it is made throughout that period on the left side of organs that are asymmetric.

Manipulating the production of Pitx2 by inserting extra copies of its gene into an embryo results in isomerism or in reverse looping of the gut and other organs as well as the heart, probably depending on the levels of the protein being made. These studies, together with experiments in which the *Pitx2* gene is inactivated, indicate that Pitx2 is one of the first factors to establish "leftness" during embryonic development. But exactly how Pitx2 and other factors result in looping of the heart tube, the coiling of the gut or the asymmetric development of the brain is still unclear.



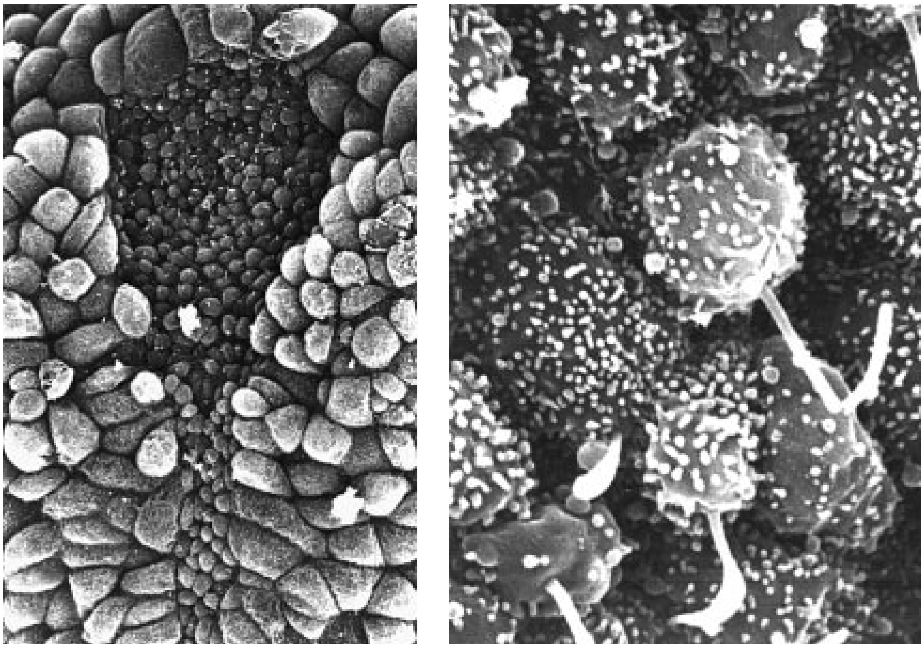
CHRISTOPH BLUMRICH (*illustrations*); CONCEPCIÓN RODRÍGUEZ-ESTEBAN *Salk Institute for Biological Studies*

GENES THAT ARE ACTIVE on only one side of a developing embryo, such as this early chick, establish the normal left-right asymmetry of internal organs. The gene directing the production of a protein named Sonic hedgehog (*dark blue in top images*) is one of the first to become active, on the left side of the embryo above Hensen's node. Ten hours later the *Sonic hedgehog* gene is no longer "on": its activity has been replaced by that of two other genes for the proteins Nodal and Pitx2 (*dark blue in bottom images*).



BRUCE BLUMBERG AND JAMIE SIMON *Salk Institute for Biological Studies*

NORMAL TADPOLE (*left*) has a heart that loops to the right and a gut that coils counterclockwise because of the *Pitx2* gene, which is usually active—and therefore directing the production of proteins—only on the left side of the animal. In contrast, the heart of a tadpole in which *Pitx2* is active only on the right side (*right*) loops to the left, and the gut coils clockwise. Exactly how Pitx2 proteins control such looping is still unclear.



KATHLEEN K. SULIK *University of North Carolina at Chapel Hill*

CELLS IN THE NODE of a mouse embryo (*far left*), a region akin to Hensen's node in chicks, appear as a clearly delineated patch on the embryo's surface in a scanning electron micrograph. Higher magnification (*left*) reveals that each cell in the node has a single hairlike structure called a cilium. Each cilium moves only in a counterclockwise direction, presumably to keep proteins that are important for establishing left-right asymmetry only on the left side of a developing embryo.

Another open question relates to how the initial asymmetry of the body is established. What prompts the production of Sonic hedgehog, Activin βB or Lefty in the first place? One possibility is vitamin A. Over the past few years, researchers have discovered that vitamin A affects the types of cells that arise in an embryo as well as an embryo's ability to tell left from right, head from tail and back from front. They have also made great progress in understanding how vitamin A exerts these effects.

My group and others have observed, for instance, that an excess of a form of vitamin A called retinoic acid can even out the normal asymmetry of the heart in rodents and birds. It seems to do so by perturbing the production of proteins such as Nodal, Pitx2 and Lefty. Thus, it appears that the establishment of left-right asymmetry requires the exquisite regulation of vitamin A production during the early stages of embryonic development.

Other factors are certainly involved as well. Accumulating evidence suggests that specialized cell structures called cilia play a pivotal part. Cilia are whiplike structures on the outer membrane of specialized cells, such as those that line the gut; they also allow sperm to swim. Scanning electron microscopy studies have shown that all cells in the nodes of mouse embryos display a single motile cilium, located in a central position on the cell surface. The ciliated cells face the ventral (belly) side of the embryo.

In the human condition known as Kartagener's syndrome, patients have defective cilia in several cell types, including sperm. These people are prone to developing respiratory infections (because they lack the cilia that normally sweep microbes out of the airways), and males are infertile. In addition, the patients tend to have situs inversus. Similarly, mice that carry a mutant form of a protein that is a component of cilia display randomized organ placement. The obvious conclusion is that the absence of functional cilia in the node causes organ positioning to be determined at random.

The Whip Factor

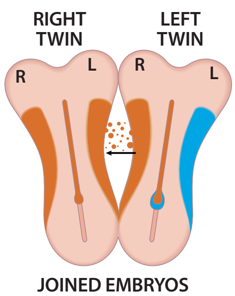
Astonishing findings are beginning to clarify how cilia in the node help to ensure normal organ placement. In 1998 Nobutaka Hirokawa of the University of Tokyo and his colleagues observed that mouse nodal cells, which extend their cilia into the fluid surrounding the embryo, rotate their cilia counterclockwise, in a unidirectional motion that has never been seen in other cilia. This motion, in turn, creates a flow of fluid that could sweep critical factors such as retinoic acid, Nodal and Lefty to the left side of the node. That accumulation of fluid and proteins on the left may then provide the bias required to break the initial embryonic symmetry. In other words, a feature of

JUAN M. HURLE *University of Cantabria*

DEVELOPING HEART (*red*) in young chick embryos shows the importance of vitamin A on the correct positioning of that organ. Exposure to normal concentrations of retinoic acid, a form of vitamin A, results in a heart that loops properly (*far left*). In the presence of too much retinoic acid, however, the heart loops in the opposite direction (*left*). Researchers hypothesize that retinoic acid helps to regulate activity of genes such as *Nodal* that dictate left-right asymmetry.

Siamese Twins

The findings discussed in the accompanying article have enabled Clifford J. Tabin and his colleagues at Harvard Medical School to propose an explanation for why certain Siamese, or conjoined, twins have a high probability of developing abnormally placed organs. Interestingly, that propensity is dependent on where the twins are physically linked to each other. When twins are joined side by side (dicephalus twins), like Abigail and Brittany Hensel (*right*), in half the sets one member of the pair (typically the one to the right of the other) ends up with the heart on the right instead of the left. Like all Siamese twins, the dicephalus types develop from a single fertilized egg that divides incompletely. In this case, the two embryos that arise lie essentially parallel to each other. That proximity presumably allows secreted factors expressed in the node of one twin to exert an influence on the other.



CHRISTOPH BLUMRICH

Studies in chick embryos show that Activin βB secreted on the right side of the left twin (*orange in illustration at left*) is able to repress the production of the human version of Sonic hedgehog on the left side of the right twin, which results in the heart of the second twin having an equal chance of developing on the right or left side. —*J.C.I.B.*

STEVE WEWERKA *Impact Visuals*

THE HENSEL TWINS, Abigail and Brittany, are joined side by side.

cellular architecture (the direction of rotation of cilia in the node) is translated into a left-right bias in embryonic development that effectively controls the way our internal organs develop.

No one understands just why the cilia rotate in a counterclockwise fashion. Presumably, though, that pattern arises because the molecules driving cilial motion are themselves asymmetric. Nevertheless, normal asymmetric organ placement occurs in half the individuals (people or mice) that have absolutely no cilia in their nodes. It follows that nodal cilia are not required for organ development. Rather they are needed to establish the molecular gradients that are required for the proper orientation and positioning of the organs.

When cilia are absent, the preferred flow of extraembryonic fluid fails to materialize; consequently, the left or right determinants carried by the fluid appear on both sides of the node. In such cases, organ position is established at random, presumably because of the random predominance of the appropriate chemical signals on one side of the node or the other.

The problem of left-right determination in the developing embryo has fascinated many biologists for decades, but until very recently progress was slow, in part because of the lack of molecular data. The recent discovery of genes that are active asymmetrically in the early embryo has uncovered many new clues. When some of the genes involved in a particular developmental process are known, researchers can turn them on or off in differing parts of an embryo in the laboratory to test hypotheses about the roles played by the proteins those genes encode. Although the exact nature of the initial event that establishes asymmetry in the embryo is still elusive, identification of proteins involved later on should facilitate discovery of proteins involved in other aspects of organ development. This knowledge may lead to the identification of formerly unknown mutations that predispose to specific organ malformations, which, in turn, will help in developing new systems of prenatal diagnosis. SA

The Author

JUAN CARLOS IZPISÚA BELMONTE received his Ph.D. from the University of Valencia and the Colegio de España in Bologna in 1987. He later moved to the European Molecular Biology Laboratory in Heidelberg, Germany, and, more recently, to the University of California, Los Angeles. He is currently an associate professor of developmental biology at the Salk Institute for Biological Studies and the University of California, San Diego. Belmonte has made many contributions to the study of the molecular basis of limb development and left-right asymmetry in vertebrates. Before becoming a scientist, Belmonte played professional soccer in Alicante, Spain. The author wishes to acknowledge the important contributions of his colleagues Concepción Rodríguez-Esteban and Javier Capdevila.

Further Reading

Left-Right Asymmetry in Animal Development. William B. Wood in *Annual Review of Cell and Developmental Biology,* Vol. 13, pages 53–82; 1997.

The Compulsion of Chirality: Toward an Understanding of Left-Right Asymmetry. Michael Levin and Mark Mercola in *Genes & Development,* Vol. 12, pages 763–769; March 15, 1998.

Molecular Mechanisms of Vertebrate Left-Right Development. Ann F. Ramsdell and H. Joseph Yost in *Trends in Genetics,* Vol. 14, No. 11, pages 459–465; November 1998.

Hypersearching the Web

With the volume of on-line information in cyberspace growing at a breakneck pace, more effective search tools are desperately needed. A new technique analyzes how Web pages are linked together

by Members of the *Clever* Project

Every day the World Wide Web grows by roughly a million electronic pages, adding to the hundreds of millions already on-line. This staggering volume of information is loosely held together by more than a billion annotated connections, called hyperlinks. For the first time in history, millions of people have virtually instant access from their homes and offices to the creative output of a significant—and growing—fraction of the planet's population.

But because of the Web's rapid, chaotic growth, the resulting network of information lacks organization and structure. In fact, the Web has evolved into a global mess of previously unimagined proportions. Web pages can be written in any language, dialect or style by individuals with any background, education, culture, interest and motivation. Each page might range from a few characters to a few hundred thousand, containing truth, falsehood, wisdom, propaganda or sheer nonsense. How, then, can one extract from this digital morass high-quality, relevant pages in response to a specific need for certain information?

In the past, people have relied on search engines that hunt for specific words or terms. But such text searches frequently retrieve tens of thousands of pages, many of them useless. How can people quickly locate only the information they need and trust that it is authentic and reliable?

We have developed a new kind of search engine that exploits one of the Web's most valuable resources—its myriad hyperlinks. By analyzing these interconnections, our system automatically locates two types of pages: authorities and hubs. The former are deemed to be the best sources of information on a particular topic; the latter are collections of links to those locations. Our methodology should enable users to locate much of the information they desire quickly and efficiently.

The Challenges of Search Engines

Computer disks have become increasingly inexpensive, enabling the storage of a large portion of the Web at a single site. At its most basic level, a search engine maintains a list, for every word, of all known Web pages containing that word. Such a collection of lists is known as an index. So if people are interested in learning about acupuncture, they can access the "acupuncture" list to find all Web pages containing that word.

Creating and maintaining this index is highly challenging [see "Searching the Internet," by Clifford Lynch; Scientific American, March 1997], and determining what information to return in response to user requests remains daunting. Consider the unambiguous query for information on "Nepal Airways," the airline company. Of the roughly 100 (at the time of this writing) Web pages containing the phrase, how does a search engine decide which 20 or so are the best? One difficulty is that there is no exact and mathematically precise measure of "best"; indeed, it lies in the eye of the beholder.

Search engines such as AltaVista, Infoseek, HotBot, Lycos and Excite use heuristics to determine the way in which to order—and thereby prioritize—pages. These rules of thumb are collectively known as a ranking function, which must apply not only to relatively specific and straightforward queries ("Nepal Airways") but also to much more general requests, such as for "aircraft," a word that appears in more than a million Web pages. How should a search engine choose just 20 from such a staggering number?

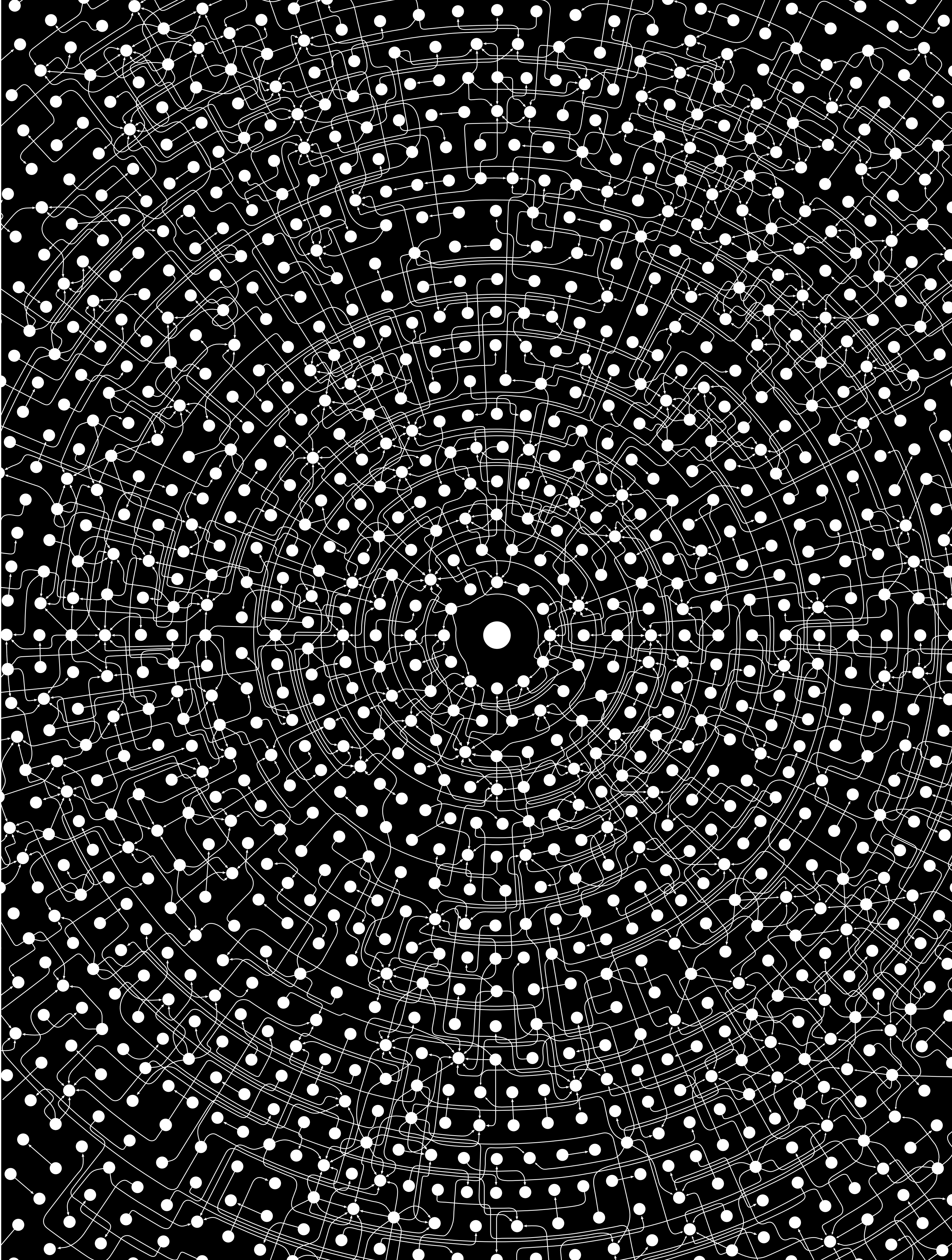
Simple heuristics might rank pages by the number of times they contain the query term, or they may favor instances in which that text appears earlier. But such approaches can sometimes fail spectacularly. Tom Wolfe's book *The Kandy-Kolored Tangerine-Flake Streamline Baby* would, if ranked by such heuristics, be deemed very relevant to the query "hernia," because it begins by repeating that word dozens of times. Numerous extensions to these rules of thumb abound, including approaches that give more weight to words that appear in titles, in section headings or in a larger font.

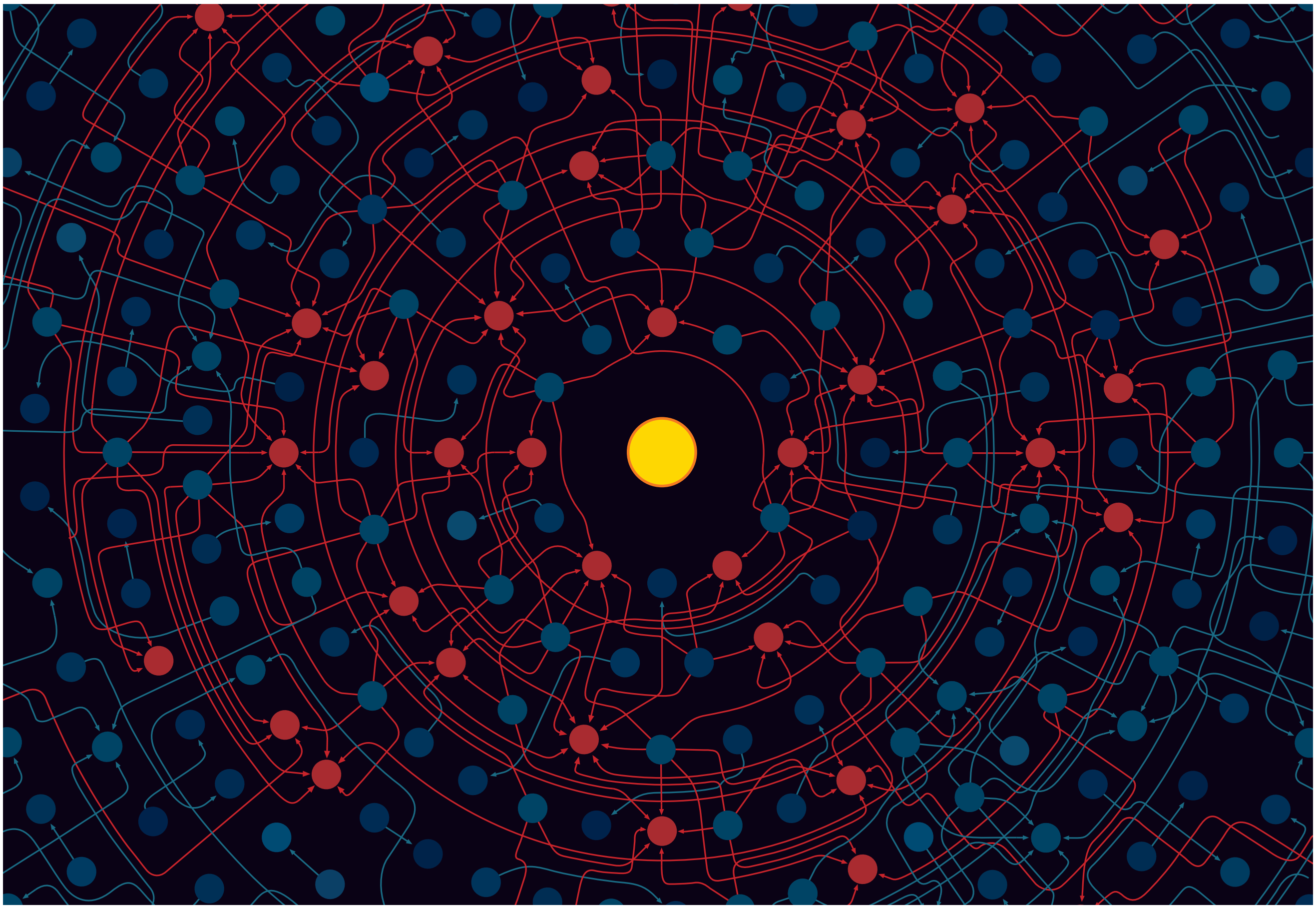
Such strategies are routinely thwarted by many commercial Web sites that design their pages in certain ways specifically to elicit favorable rankings. Thus, one encounters pages whose titles are "cheap airfares cheap airfares cheap airfares." Some sites write other carefully chosen phrases many times over in colors and fonts that are invisible to human viewers. This practice, called spamming, has become one of the main reasons why it is currently so difficult to maintain an effective search engine.

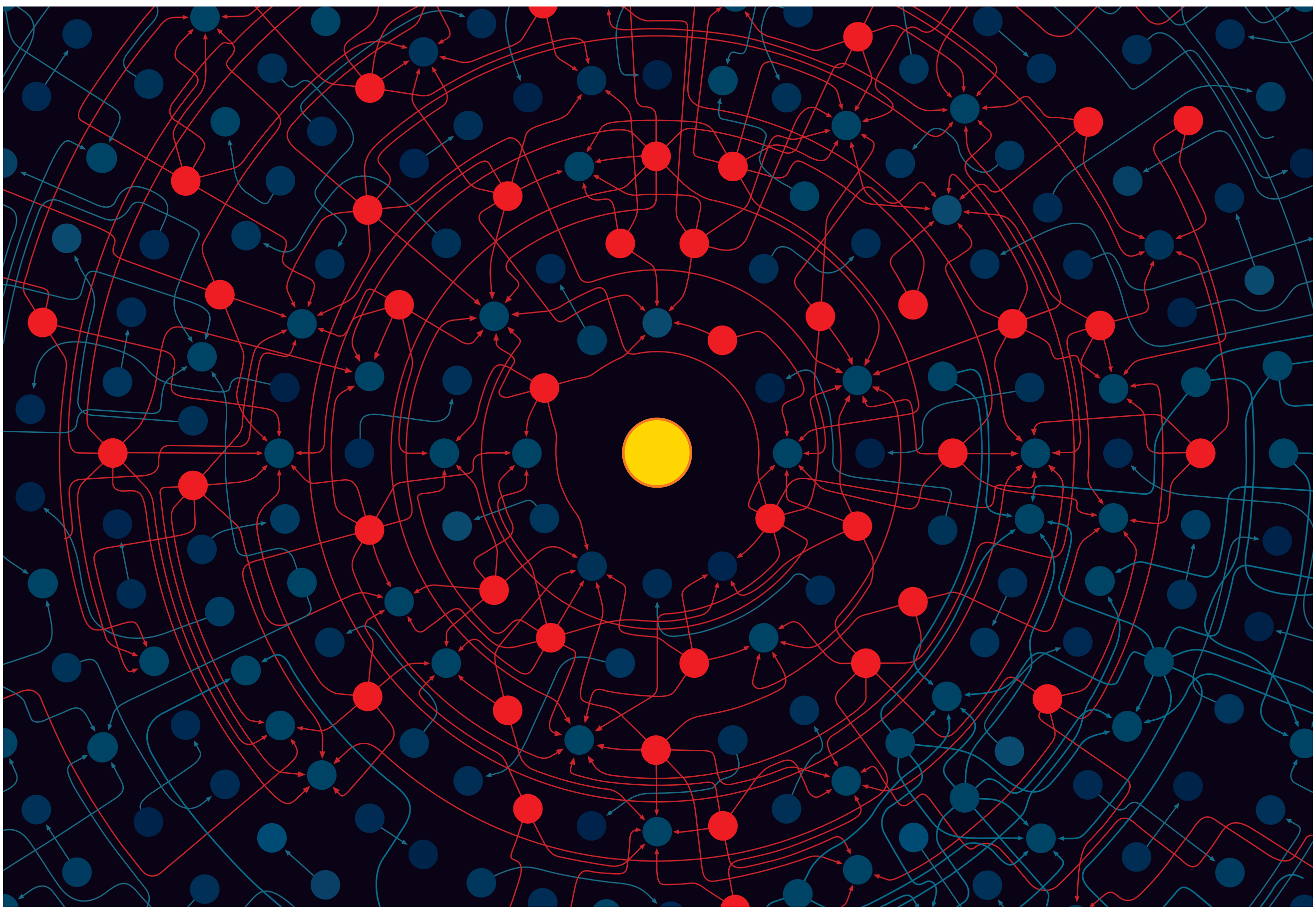
Spamming aside, even the basic assumptions of conventional text searches

ALL ILLUSTRATIONS BY BRYAN CHRISTIE

WEB PAGES (*white dots*) are scattered over the Internet with little structure, making it difficult for a person in the center of this electronic clutter to find only the information desired. Although this diagram shows just hundreds of pages, the World Wide Web currently contains more than 300 million of them. Nevertheless, an analysis of the way in which certain pages are linked to one another can reveal a hidden order.





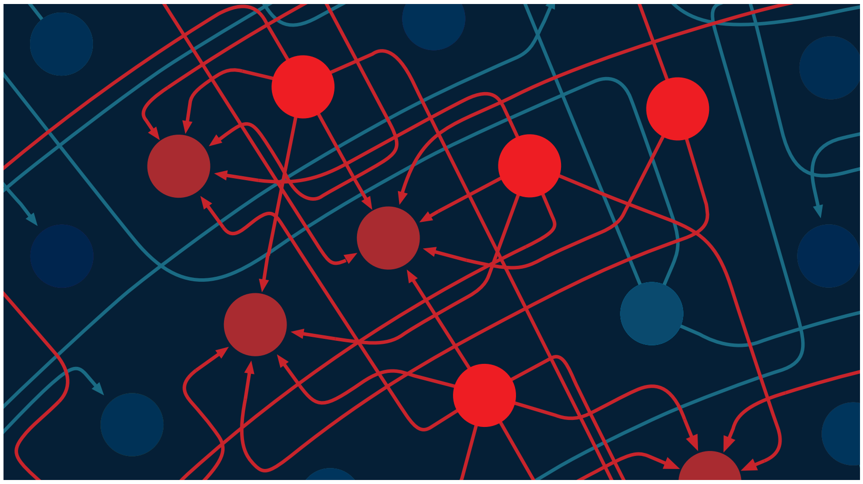


are suspect. To wit, pages that are highly relevant will not always contain the query term, and others that do may be worthless. A major cause of this problem is that human language, in all its richness, is awash in synonymy (different words having the same meaning) and polysemy (the same word having multiple meanings). Because of the former, a query for "automobile" will miss a deluge of pages that lack that word but instead contain "car." The latter manifests itself in a simple query for "jaguar," which will retrieve thousands of pages about the automobile, the jungle cat and the National Football League team, among other topics.

One corrective strategy is to augment search techniques with stored information about semantic relations between words. Such compilations, typically constructed by a team of linguists, are sometimes known as semantic networks, following the seminal work on the WordNet project by George A. Miller and his colleagues at Princeton University. An index-based engine with access to a semantic network could, on receiving the query for "automobile," first determine that "car" is equivalent and then retrieve all Web pages containing either word. But this process is a double-edged sword: it helps with synonymy but can aggravate polysemy.

Even as a cure for synonymy, the solution is problematic. Constructing and maintaining a semantic network that is exhaustive and cross-cultural (after all, the Web knows no geographical boundaries) are formidable tasks. The process is especially difficult on the Internet, where a whole new language is evolving—words such as "FAQs," "zines" and "bots" have emerged, whereas other words such as "surf" and "browse" have taken on additional meanings.

Our work on the Clever project at IBM originated amid this perplexing array of issues. Early on, we realized that the current scheme of indexing and retrieving a page based solely on the text it contained ignores more than a billion carefully placed hyperlinks that reveal the relations between pages. But how exactly should this information be used?



FINDING authorities and hubs can be tricky because of the circular way in which they are defined: an authority is a page that is pointed to by many hubs; a hub is a site that links to many authorities. The process, however, can be performed mathematically. Clever, a prototype search engine, assigns initial scores to candidate Web pages on a particular topic. Clever then revises those numbers in repeated series of calculations, with each iteration dependent on the values of the previous round. The computations continue until the scores eventually settle on their final values, which can then be used to determine the best authorities and hubs.

AUTHORITIES AND HUBS help to organize information on the Web, however informally and inadvertently. Authorities (●) are sites that other Web pages happen to link to frequently on a particular topic. For the subject of human rights, for instance, the home page of Amnesty International might be one such location. Hubs (●) are sites that tend to cite many of those authorities, perhaps in a resource list or in a "My Favorite Links" section on a personal home page.

When people perform a search for "Harvard," many of them want to learn more about the Ivy League school. But more than a million locations contain "Harvard," and the university's home page is not the one that uses it the most frequently, the earliest or in any other way deemed especially significant by traditional ranking functions. No entirely internal feature of that home page truly seems to reveal its importance.

Indeed, people design Web pages with all kinds of objectives in mind. For instance, large corporations want their sites to convey a certain feel and project a specific image—goals that might be very different from that of describing what the company does. Thus, IBM's home page does not contain the word "computer." For these types of situations, conventional search techniques are doomed from the start.

To address such concerns, human architects of search engines have been tempted to intervene. After all, they believe they know what the appropriate responses to certain queries should be, and developing a ranking function that will automatically produce those results has been a troublesome undertaking. So they could maintain a list of queries like "Harvard" for which they will override the judgment of the search engine with predetermined "right" answers.

This approach is being taken by a number of search engines. In fact, a service such as Yahoo! contains only human-selected pages. But there are countless possible queries. How, with a limited number of human experts, can one maintain all these lists of precomputed responses, keeping them reasonably complete and up-to-date, as the Web meanwhile grows by a million pages a day?

Searching with Hyperlinks

In our work, we have been attacking the problem in a different way. We have developed an automatic technique for finding the most central, authoritative sites on broad search topics by making use of hyperlinks, one of the Web's most precious resources. It is the hyperlinks, after all, that pull together the hundreds of millions of pages into a web of knowledge. It is through these connections that users browse, serendipitously discovering valuable information through the pointers and recommendations of people they have never met.

The underlying assumption of our approach views each link as an implicit endorsement of the location to which it points. Consider the Web site of a human-rights activist that directs people to the home page of Amnesty International. In this case, the reference clearly signifies approval.

Of course, a link may also exist purely for navigational purposes ("Click here to return to the main menu"), as a paid advertisement ("The vacation of your dreams is only a click away") or as a stamp of disapproval ("Surf to this site to see what this fool says"). We believe, however, that in aggregate—that is, when a large enough number is considered—Web links do confer authority.

In addition to expert sites that have garnered many recommendations, the Web is full of another type of page: hubs that link to those prestigious locations, tacitly radiating influence outward to them. Hubs appear in guises ranging from professionally assembled lists on commercial sites to inventories of "My Favorite Links" on personal home pages. So even if we find it difficult to define "authorities" and "hubs" in isolation, we can state this much: a respected authority is a page that is referred to by many good hubs; a useful hub is a location that points to many valuable authorities.

These definitions look hopelessly circular. How could they possibly lead to a computational method of identifying both authorities and hubs? Thinking of the problem intuitively, we devised the following algorithm. To start off, we look at a set of candidate pages about a particular topic, and for each one we make our best guess about how good a hub it is and how good an authority it is. We then use these initial estimates to jump-start a two-step iterative process.

First, we use the current guesses about the authorities to improve the estimates of hubs—we locate all the best authorities, see which pages point to them and call those locations good hubs. Second, we take the updated hub information to refine our guesses about the authorities—we determine where the best hubs point most heavily and call these the good authorities. Repeating these steps several times fine-tunes the results.

We have implemented this algorithm in Clever, a prototype search engine. For any query of a topic—say, acupuncture—Clever first obtains a list of 200 pages from a standard text index such as AltaVista. The system then augments these by adding all pages that link to and from that 200. In our experience, the resulting collection, called the root set, will typically contain between 1,000 and 5,000 pages.

For each of these, Clever assigns initial numerical hub and authority scores. The system then refines the values: the authority score of each page is updated to be the sum of the hub scores of other locations that point to it; a hub score is revised to be the sum of the authority scores of locations to which a page points. In other words, a page that has many high-scoring hubs pointing to it earns a higher authority score; a location that points to many high-scoring authorities garners a higher hub score. Clever repeats these calculations until the scores have more or less settled on their final values, from which the best authorities and hubs can be determined. (Note that the computations do not preclude a particular page from achieving a top rank in both categories, as sometimes occurs.)

The algorithm might best be understood in visual terms. Picture the Web as a vast network of innumerable sites, all interconnected in a seemingly random fashion. For a given set of pages containing a certain word or term, Clever zeroes in on the densest pattern of links between those pages.

As it turns out, the iterative summation of hub and authority scores can be analyzed with stringent mathematics. Using linear algebra, we can represent the process as the repeated multiplication of a vector (specifically, a row of numbers representing the hub or authority scores) by a matrix (a two-dimensional array of numbers representing the hyperlink structure of the root set). The final results of the process are hub and authority vectors that have equilibrated to certain numbers—values that reveal which pages are the best hubs and authorities, respectively. (In the world of linear algebra, such a stabilized row of numbers is called an eigenvector; it can be thought of as the solution to a system of equations defined by the matrix.)

With further linear algebraic analysis, we have shown that the iterative process will rapidly settle to a relatively steady set of hub and authority scores. For our purposes, a root set of 3,000 pages requires about five rounds of calculations. Furthermore, the results are generally independent of the initial estimates of scores used to start the process. The method will work even if the values are all initially set to be equal to 1. So the final hub and authority scores are intrinsic to the collection of pages in the root set.

A useful by-product of Clever's iterative processing is that the algorithm naturally separates Web sites into clusters. A search for information on abortion, for example, results in two types of locations, pro-life and pro-choice, because pages from one group are more likely to link to one another than to those from the other community.

From a larger perspective, Clever's algorithm reveals the underlying structure of the World Wide Web. Although the Internet has grown in a hectic, willy-nilly fashion, it does indeed have an inherent—albeit inchoate—order based on how pages are linked.

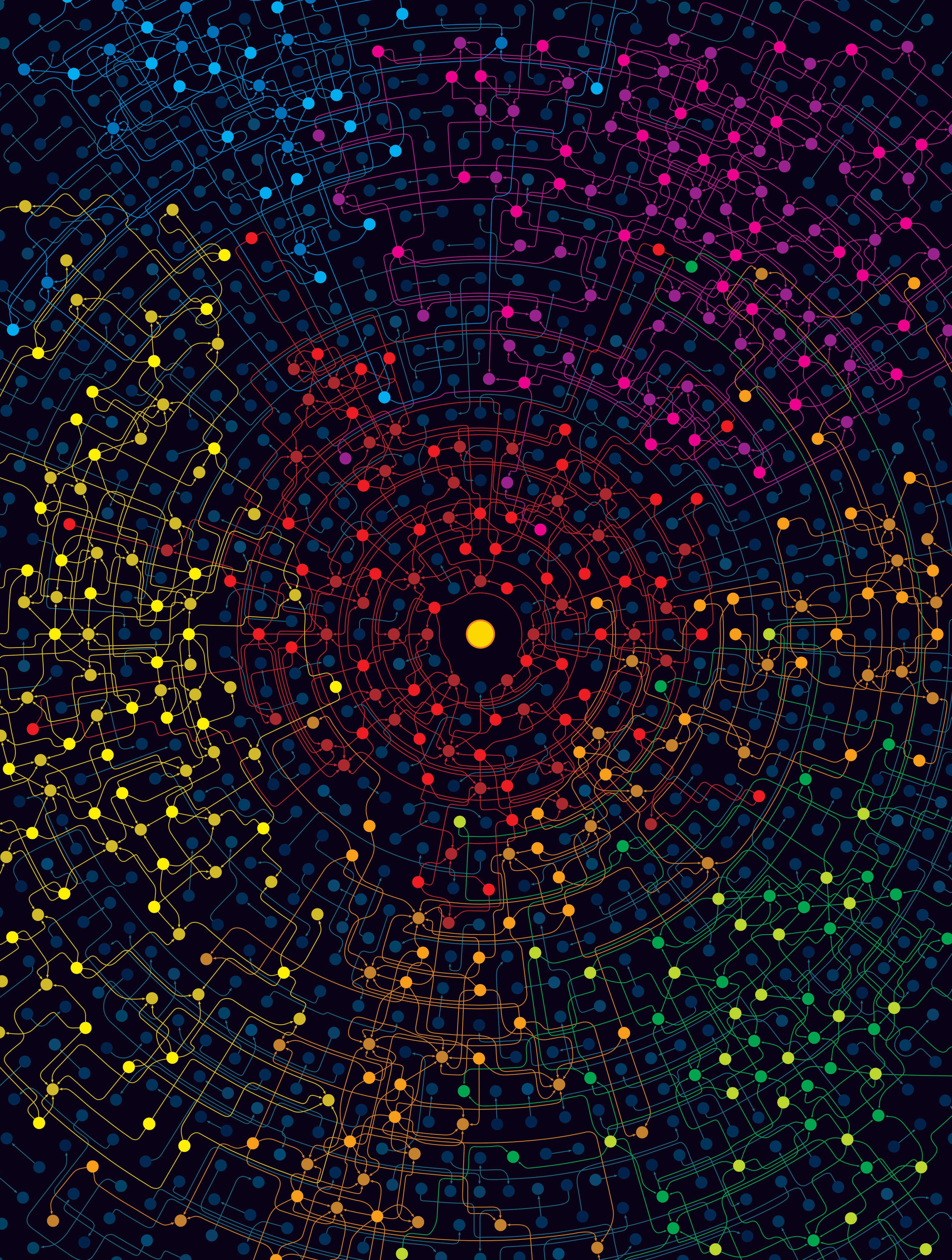
The Link to Citation Analysis

Methodologically, the Clever algorithm has close ties to citation analysis, the study of patterns of how scientific papers make reference to one another. Perhaps the field's best-known measure of a journal's importance is the "impact factor." Developed by Eugene Garfield, a noted information scientist and founder of *Science Citation Index,* the metric essentially judges a publication by the number of citations it receives.

On the Web, the impact factor would correspond to the ranking of a page simply by a tally of the number of links that point to it. But this approach is typically not appropriate, because it can favor universally popular locations, such as the home page of the *New York Times,* regardless of the specific query topic.

Even in the area of citation analysis, researchers have attempted to improve Garfield's measure, which counts each reference equally. Would not a better strategy give additional weight to citations from a journal deemed more important? Of course, the difficulty with this approach is that it leads to a circular definition of "importance," similar to the problem we encountered in specifying hubs and authorities. As early as

CYBERCOMMUNITIES (*shown in different colors*) populate the Web. An exploration of this phenomenon has uncovered various groups on topics as arcane as oil spills off the coast of Japan, fire brigades in Australia and resources for Turks living in the U.S. The Web is filled with hundreds of thousands of such finely focused communities.



1976 Gabriel Pinski and Francis Narin of CHI Research in Haddon Heights, N.J., overcame this hurdle by developing an iterated method for computing a stable set of adjusted scores, which they termed influence weights. In contrast to our work, Pinski and Narin did not invoke a distinction between authorities and hubs. Their method essentially passes weight directly from one good authority to another.

This difference raises a fundamental point about the Web versus traditional printed scientific literature. In cyberspace, competing authorities (for example, Netscape and Microsoft on the topic of browsers) frequently do not acknowledge one another's existence, so they can be connected only by an intermediate layer of hubs. Rival prominent scientific journals, on the other hand, typically do a fair amount of cross-citation, making the role of hubs much less crucial.

A number of groups are also investigating the power of hyperlinks for searching the Web. Sergey Brin and Lawrence Page of Stanford University, for instance, have developed a search engine dubbed Google that implements a link-based ranking measure related to the influence weights of Pinski and Narin. The Stanford scientists base their approach on a model of a Web surfer who follows links and makes occasional haphazard jumps, arriving at certain places more frequently than others. Thus, Google finds a single type of universally important page—intuitively, locations that are heavily visited in a random traversal of the Web's link structure. In practice, for each Web page Google basically sums the scores of other locations pointing to it. So, when presented with a specific query, Google can respond by quickly retrieving all pages containing the search text and listing them according to their preordained ranks.

Google and Clever have two main differences. First, the former assigns initial rankings and retains them independently of any queries, whereas the latter assembles a different root set for each search term and then prioritizes those pages in the context of that particular query. Consequently, Google's approach enables faster response. Second, Google's basic philosophy is to look only in the forward direction, from link to link. In contrast, Clever also looks backward from an authoritative page to see what locations are pointing there. In this sense, Clever takes advantage of the sociological phenomenon that humans are innately motivated to create hublike content expressing their expertise on specific topics.

The Search Continues

We are exploring a number of ways to enhance Clever. A fundamental direction in our overall approach is the integration of text and hyperlinks. One strategy is to view certain links as carrying more weight than others, based on the relevance of the text in the referring Web location. Specifically, we can analyze the contents of the pages in the root set for the occurrences and relative positions of the query topic and use this information to assign numerical weights to some of the connections between those pages. If the query text appeared frequently and close to a link, for instance, the corresponding weight would be increased.

Our preliminary experiments suggest that this refinement substantially increases the focus of the search results. (A shortcoming of Clever has been that for a narrow topic, such as Frank Lloyd Wright's house Fallingwater, the system sometimes broadens its search and retrieves information on a general subject, such as American architecture.) We are investigating other improvements, and given the many styles of authorship on the Web, the weighting of links might incorporate page content in a variety of ways.

We have also begun to construct lists of Web resources, similar to the guides put together manually by employees of companies such as Yahoo! and Infoseek. Our early results indicate that automatically compiled lists can be competitive with handcrafted ones. Furthermore, through this work we have found that the Web teems with tightly knit groups of people, many with offbeat common interests (such as weekend sumo enthusiasts who don bulky plastic outfits and wrestle each other for fun), and we are currently investigating efficient and automatic methods for uncovering these hidden communities.

The World Wide Web of today is dramatically different from that of just five years ago. Predicting what it will be like in another five years seems futile. Will even the basic act of indexing the Web soon become infeasible? And if so, will our notion of searching the Web undergo fundamental changes? For now, the one thing we feel certain in saying is that the Web's relentless growth will continue to generate computational challenges for wading through the ever increasing volume of on-line information. SA

The Authors

THE *CLEVER* PROJECT: Soumen Chakrabarti, Byron Dom, S. Ravi Kumar, Prabhakar Raghavan, Sridhar Rajagopalan and Andrew Tomkins are research staff members at the IBM Almaden Research Center in San Jose, Calif. Jon M. Kleinberg is an assistant professor in the computer science department at Cornell University. David Gibson is completing his Ph.D. at the computer science division at the University of California, Berkeley.

The authors began their quest for exploiting the hyperlink structure of the World Wide Web three years ago, when they first sought to develop improved techniques for finding information in the clutter of cyberspace. Their work originated with the following question: If computation were not a bottleneck, what would be the most effective search algorithm? In other words, could they build a better search engine if the processing didn't have to be instantaneous? The result was the algorithm described in this article. Recently the research team has been investigating the Web phenomenon of cybercommunities.

Further Reading

Search Engine Watch (www.searchenginewatch.com) contains information on the latest progress in search engines. The WordNet project is described in *WordNet: An Electronic Lexical Database* (MIT Press, 1998), edited by Christiane Fellbaum. The iterative method for determining hubs and authorities first appeared in Jon M. Kleinberg's paper "Authoritative Sources in a Hyperlinked Environment" in *Proceedings of the 9th ACM-SIAM Symposium on Discrete Algorithms,* edited by Howard Karloff (SIAM/ACM–SIGACT, 1998). Improvements to the algorithm are described at the Web site of the IBM Almaden Research Center (www.almaden.ibm.com/cs/k53/clever.html). *Introduction to Informetrics* (Elsevier Science Publishers, 1990), by Leo Egghe and Ronald Rousseau, provides a good overview of citation analysis. Information on the Google project at Stanford University can be obtained from www.google.com on the World Wide Web.

Image-Guided Surgery

Virtual-reality technology is giving surgeons the equivalent of x-ray vision, helping them to remove tumors more effectively, to minimize surgical wounds and to avoid damaging critical tissues

MICHAEL LEVENTON *Artificial Intelligence Laboratory, Massachusetts Institute of Technology*

by W. Eric L. Grimson, Ron Kikinis, Ferenc A. Jolesz and Peter McL. Black

The scene is an operating room. A young woman is about to undergo surgery to remove a brain tumor that is causing almost daily seizures. Elimination of this mass, which has become life-threatening, should be curative, but the operation is perilous. The tumor is pressing against the motor cortex, a strip of tissue that controls voluntary movements. The tumor and cortex look alike to the unaided eye. If some of the tumor is left behind, it will return. Yet if part of the motor cortex is mistakenly excised, the woman could be paralyzed.

The neurosurgeon has agreed to the operation only because he has access to extraordinary tools designed to greatly improve his chances of success. In a corner of the room, he is using one of those innovations now. He is looking at a monitor displaying a three-dimensional computer-generated replica of the patient's head—a model constructed earlier from pictures produced by noninvasive magnetic resonance imaging (MRI).

He rotates the model to obtain a view similar to the one he will see when the operation is under way. Then, with a few clicks of a computer mouse, he strips away skin, fat and bone to expose the brain. There the tumor and other significant features (such as blood vessels and the motor cortex) are highlighted in colors. Noting that the tumor is not only touching the motor cortex but is also close to key blood vessels, he makes a plan for reaching and removing the tumor in a way that will both eliminate all traces of the growth and minimize the risk of bleeding and paralysis.

His strategy set, he turns to the pa-

SAM OGDEN

BRAIN TUMOR (*green, at left*) in a woman about to undergo neurosurgery was made visible to a surgeon (from his vantage) by a display that merged live video footage with a three-dimensional computer-generated model of the patient's brain. When surgery is carried out in a special magnetic resonance imaging (MRI) device (*above*), such models, which are constructed before surgery, can be augmented by new scans that reveal whether tissues have shifted from their original positions. The 3-D models and real-time scans help physicians to pursue the safest routes to their surgical targets and, in the case of tumors, to remove growths more completely.

tient. She lies not on a standard operating table but on a platform incorporated into an advanced MRI system that will provide images of the woman's brain during surgery. A typical MRI machine consists of one large hollow cylinder, into which a patient is fully inserted for scanning. In this newer device, the cylinder—a magnet, really—has been cut in two, and the resulting doughnut-shaped sections have been moved apart. The operating table spans the "doughnut holes." This arrangement leaves room for the surgeon to stand in the gap between the magnets and to reach the patient.

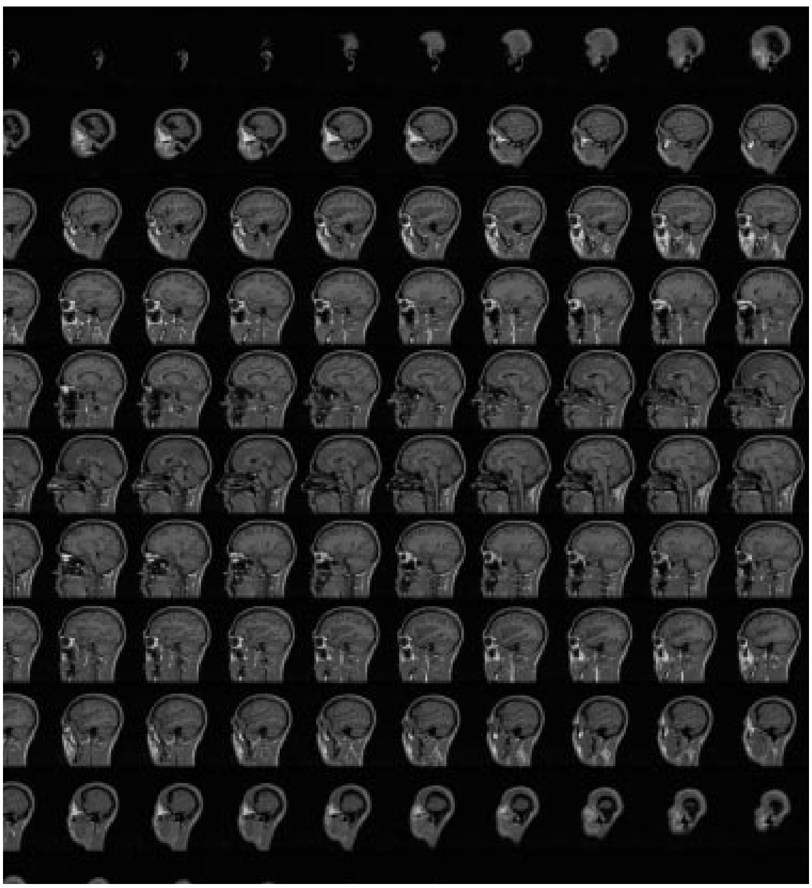
The surgeon steps into the gap and pulls down a screen displaying the same model he viewed earlier, but now it is fused with a live video image of the patient; the composite picture is in perfect register with the patient's head as seen from the surgeon's vantage. It is as if he has developed "x-ray vision," for he can locate internal structures before he ever picks up a scalpel. He takes a pen and, guided by the enhanced live video on the screen, marks on the patient's partly shaved scalp the positions of the tumor and other selected structures. He also sketches the shape of the small window he will form in the skull to gain access to the tumor. Then he looks directly at the patient and begins cutting.

As he works, he frequently checks his exact position and trajectory by gently inserting a traceable, sterile probe into the depth of the cut. A quick look at the monitor tells him the pointer's position relative to the otherwise invisible structures below the small area of exposed surface. The pointer, therefore, helps him to determine whether he is on course and likely to maintain a safe distance from the motor cortex and blood vessels he wants to avoid.

He also asks periodically for fresh MRI scans at the site of the probe. A few seconds later those images appear, superimposed on the presurgical model. They enable him to compare the preoperative and current positions of the tumor and other tissues of interest, so as to discover any displacements or deformations that must be taken into account. The images, moreover, help him to locate tumor remnants that might otherwise have been left behind.

Guided by such information, the surgeon clears out the full tumor without disrupting the motor cortex or blood vessels. Days later the patient walks out of the hospital, tired from surgery but ready to begin her life anew.

SERIAL MRI SCANS are the raw material from which three-dimensional models of a patient's internal anatomy are constructed. To create the models, a computer combines the individual slices into a cohesive whole.



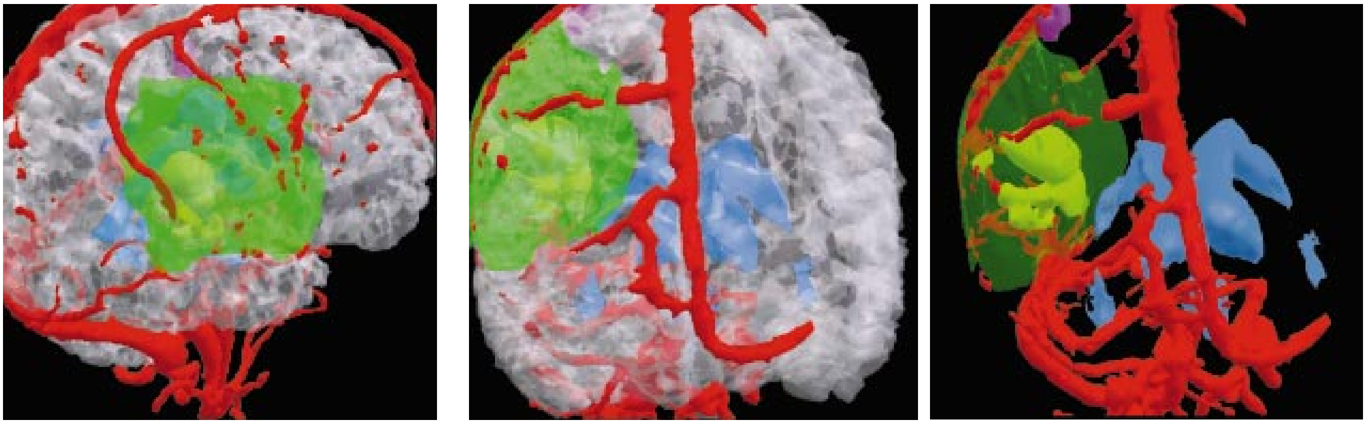
MICHAEL LEVENTON

Real Progress

Although this story may sound like science fiction, it is science fact. Patients can be treated in just this way today. Indeed, our surgical team at Brigham and Women's Hospital in Boston has performed such sophisticated image-guided neurosurgery in the "double-doughnut," or open-magnet MRI machine, on roughly 300 individuals over the past three years.

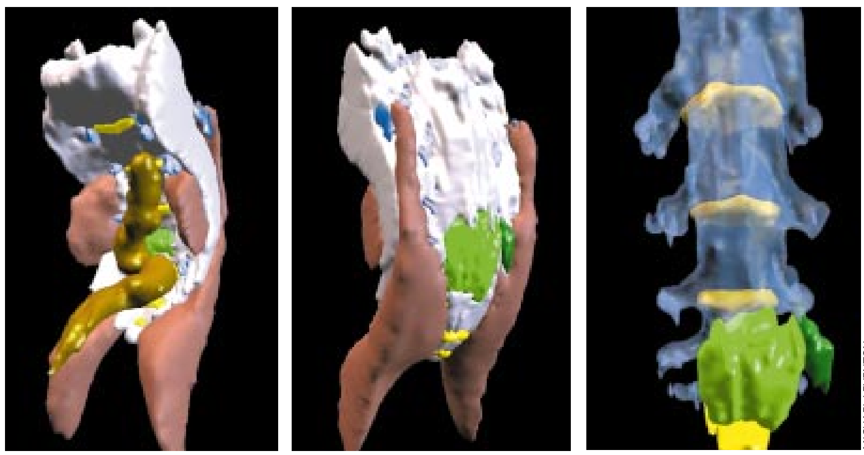
The system in service at Brigham and Women's grew out of extensive collaboration. The Image-Guided Therapy Program at the hospital and General Electric Medical Systems developed the open magnet, and both groups cooperated with the Artificial Intelligence Laboratory at the Massachusetts Institute of Technology to devise the advanced image-guidance system. Michael Leventon and David Gering of M.I.T. integrated the modeling and imaging techniques. Advanced image-guidance systems developed by others are also in use at several centers in the U.S. and Europe and are aiding surgery for a range of problems. Together the various approaches are effecting a revolution in surgery.

By enhancing the surgeon's view, image-guided surgery is enabling doctors to treat many patients more effectively. When tumors are the focus, the imagery facilitates identification of tumor boundaries and of the safest, least damaging paths to the growths (processes known as localization and targeting). Most important, it improves the physician's ability to remove curable tumors completely and to excise more of cancers that are too diffuse or invasive to be eliminated fully (so as to ease symptoms longer or better). The technology helps the surgeon to spare functionally critical tissue during other kinds of operations. Moreover, it can make surgical procedures shorter (which minimizes anesthesia and loss of blood) and, in some cases, permits operations that would



MICHAEL LEVENTON

3-D RECONSTRUCTIONS of one man's brain (*above*) and of the base of another patient's spinal column (*below*) have been segmented: selected structures have been highlighted in different colors. As is shown, such models can be rotated. In addition, components can be faded back or removed. Among the features delineated in the brain are blood vessels (*red*), ventricles (*blue*), a tumor (*green*) and a cyst in the tumor (*yellowish*). The views of the spinal column highlight bone (*white*), muscles (*pink*), the rectum (*brown*), spaces between vertebrae (*yellow*), the sac around neural tissue (*blue*), a tumor (*green*) and areas suspected of belonging to the tumor (*dark green*).



MICHAEL LEVENTON

have been considered too risky just a few years ago.

Image-guided surgery can simplify difficult procedures, but the technology behind it is complex—and fascinating. To demonstrate just how the images are prepared and presented, we will now step behind the scenes to reveal the central techniques involved. The methods applied in neurosurgery at Brigham and Women's will provide our main example.

The first essential step is constructing a 3-D representation of the surface and internal anatomy of the body part, or volume, being treated. This model, which will enable the surgeon to see internal structures that would otherwise be hidden, must be made of course without dissecting the patient.

Building an Anatomical Model

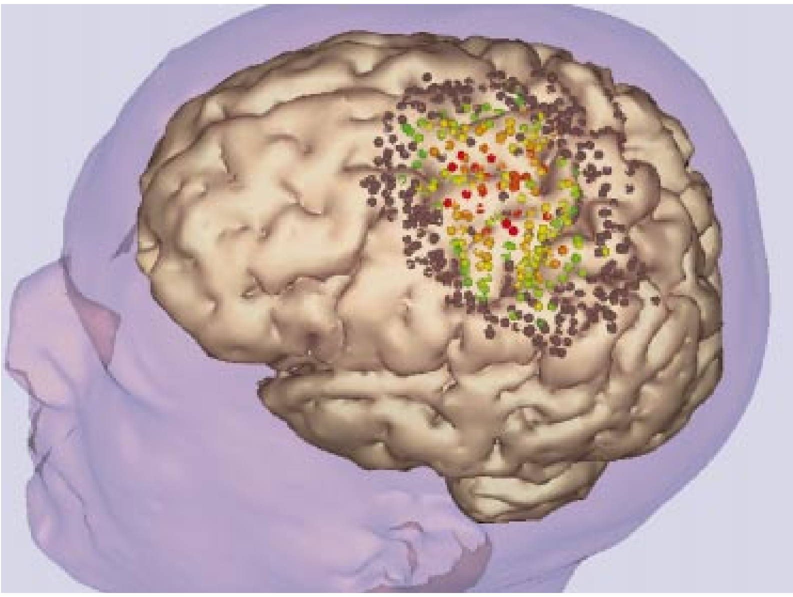
Noninvasive imaging holds the key to such modeling. Most readers have seen x-ray images of their own body. When the rays pass through bones and organs, they are absorbed to some extent. As a result, some areas show up darker than others on the detecting film. Unfortunately, the resulting picture is a flat, two-dimensional projection of a 3-D structure and provides little information about tissue other than bone.

Computed tomography (CT) and MRI, in contrast, can produce a stack of virtual slices, as if the body part of interest has been cut into hundreds of thin sections, each of which has been imaged individually in series. Both techniques also store the scans in a computer and can combine the slices into a three-dimensional model, in which every point is defined by its horizontal and vertical coordinates on a slice and by the number of the slice. Of the two, we favor magnetic resonance imaging, mainly because it demonstrates anatomy better and is more sensitive to diseased tissue. It also spares patients from exposure to ionizing radiation, relying instead on measurements of the body's responses to magnetic fields.

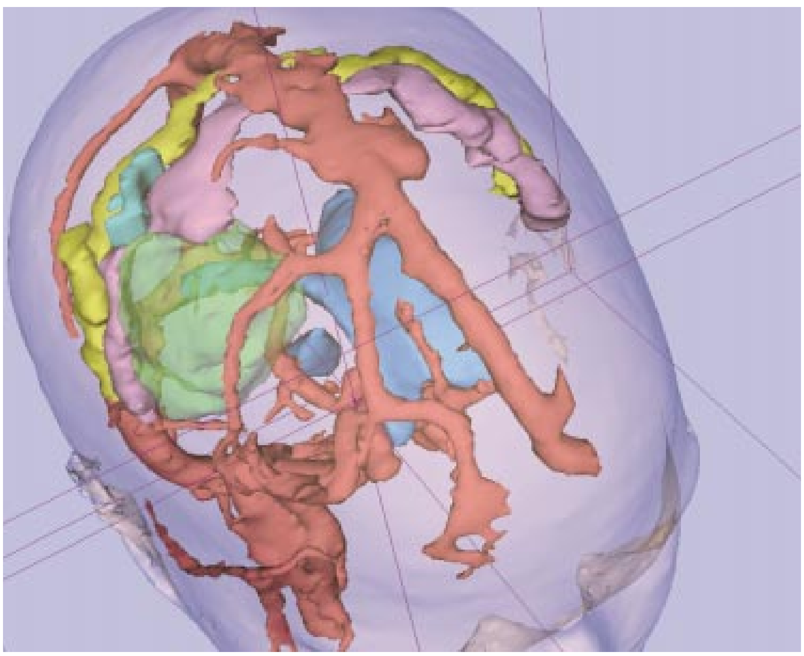
As the patient lies in the bore of the cylindrical magnet, the MRI machine produces a constant magnetic field. In essence, this field causes certain protons (positively charged subatomic particles) to spin like tops. If a second field is applied briefly (as a pulse), the tops will tilt in a new position as they spin. When the pulse is gone, the tops will pop back to their original orientation, giving up a detectable amount of energy as they go. Different tissues emit different amounts of energy in response to the pulse. More energy is recorded as more brightness, or intensity, in the MRI scan.

After the two-dimensional slices are combined, the full-dimensional product must be "segmented"—each small voxel (or volume element, the three-dimensional equivalent of a pixel) must be labeled by tissue type and combined with like voxels into identifiable structures. In neurosurgical cases, normal tissue might be labeled as fat, bone, blood vessel, skin, ventricle (fluid-filled cavity), cerebrospinal fluid, gray matter or white matter. In theory, a computer can be programmed to assign the labels by rote—according to each voxel's brightness. Indeed, certain structures, such as the skull or the ventricles, are often obvious, both to the computer and to naive observers, and can have their labels locked in immediately by the computer.

Tissue boundaries that are not terribly distinct may, however, be difficult to distinguish on the basis of simple readings. The computer may have trouble, say, separating gray matter in the cere-



MICHAEL LEVENTON



ARYA NABAVI AND ALEXANDRA V. CHABRERIE *Brigham and Women's Hospital;* DAVID GERING *M.I.T.*

"FUNCTIONAL" MAPPING reveals areas of the cortex that control specific muscles. In one approach, a device sends harmless impulses into single spots of the brain, and electrodes placed around the body indicate which muscles respond. At the top, dots distinguish among strong (*red*), medium (*orange* and *yellow*), weak (*green*) and no (*black*) responses by muscles of the right hand. Functional maps can be merged into structural models. In the bottom image, depicting the brain of a cancer patient, the motor cortex (identified through a second technique) is magenta and turquoise; the tumor (*green*) has displaced some of that cortex.

bral cortex from the underlying white matter or resolving the edges of a tumor and the normal tissue around it. To cope with that challenge, our group and others have invented new algorithms for interpreting ambiguous signals.

One begins with a manual step. For each kind of tissue, a technician selects a few voxels that clearly belong to that tissue and records their intensities. In this way, every tissue type is assigned a range of intensities. Then the computer examines the brightness of all other voxels and groups them with the ranges they approach most closely.

To ensure that the assignments are correct, another algorithm is applied. This one, developed by William M. (Sandy) Wells of our team, attempts to correct for variations in the pulsed magnetic fields emitted by the magnet. If the pulses were fully predictable and uniform over the entire imaging area, the readings for specific tissues would always be predictable as well. Unfortunately, that aspect of MRI technology is not perfect. Hence, one part of the scanned area might receive a different amount of energy than another part. In consequence, some voxels might be misleadingly bright or dark and might be classified incorrectly.

Wells's program starts by generating a list indicating the intensities that would represent each tissue type if the MRI pulse were uniform everywhere. Then it compares the intensity of every voxel to this list and, wherever possible, assigns a tissue label. If the intensity falls outside the range predicted for any tissues but close to one particular range, the voxel is tentatively assigned to the corresponding tissue type. Next, the program estimates the error in the magnetic field by calculating the difference between the actual and the predicted intensities. It then adjusts the intensities and begins the assignment and correction processes again. These steps are repeated until each voxel is assigned a single, definitive label.

At times, tissues cannot be distinguished by intensity alone. For instance, white matter in the brain and muscles in the neck might have a similar molecular composition and thus yield the same range of values in MRI scans. In that case, confusion can often be resolved by an automatic program created by Tina Kapur and Simon Warfield of our group. This software predicts the general positions of different structures based on a computerized atlas of anatomy. It could note, for example, that although the intensities of a span of tissue in the brain match those for both white matter and muscle, the brain does not contain muscle in the region of interest; therefore, the tissue must be white matter. Finally, technicians often review segmented scans on a monitor to be sure that the final tissue assignments make anatomical sense.

Once each voxel has been labeled with its tissue type, other programs delineate individual tissues with distinct markings, usually colors. Starting with a single point, the computer will paint with one color all bordering voxels having the same tissue assignment, then repeat the process until all connected voxels are gathered together. The program will then perform the same procedure for other tissues, assigning a specific color to each type. As an example, we typically depict blood vessels in red, ventricles in blue and tumors in green.

Supplying Extra Detail

The segmented model is very useful for displaying features that would go unseen by the surgeon's unaided eye, such as the location and shape of a tumor. Standard MRI and segmentation technology cannot, however, provide certain other anatomical and physiological information that might be needed. A second bag of algorithmic tricks incorporates that extra data.

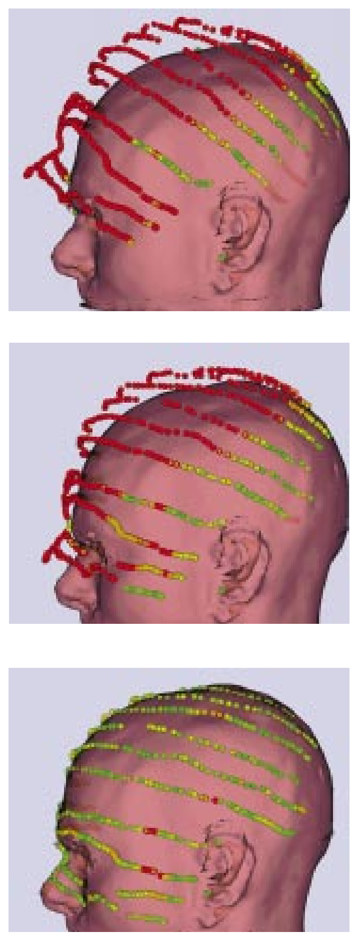
In one frequent problem, the MRI scans that form the basis for building the virtual model of a patient's head do not delineate blood vessels crisply. To achieve greater clarity, the surgical team might produce images known as MR angiograms. These angiograms are made by scanning the patient once again, but this time adjusting the MRI fields to highlight flowing blood.

The MR angiograms that result must then be aligned with the original set of MRI scans and merged into the model. Our automated registration process accomplishes this merger by overlaying the two data sets and then searching for the best way to translate and rotate one set relative to the other. It finds the optimal arrangement by exploiting a mathematical concept known as mutual information. Essentially, the computer aligns regions according to the amount of information they display: areas with much information (such as those exhibiting a lot of texture) are matched with similarly information-rich regions, and areas with little information (such as those of uniform intensity) are matched with information-poor regions.

As we noted earlier, the surgeon also needs to monitor the locations of regions that have critical functions—often the motor cortex. Imaging alone is insufficient, because the tissue properties of the motor cortex are indistinguishable from those in other kinds of cortex, which means that the signal intensities on MRI scans are alike. Likewise, the motor cortex looks no different from cortex serving other functions, so it cannot be distinguished by direct viewing.

We have two noninvasive ways to address this problem. When the body uses a muscle, blood flow increases in the cortical region controlling that movement. "Functional" magnetic resonance imaging can detect those increases and thereby pinpoint the cortical areas responsible for each muscle. In addition, a device called a transcranial magnetic stimulator can be used. A pair of electromagnets induces small electric currents in focused areas of brain cortex. This stimulation is painless and harmless. By attaching electrical pickups to the patient's skin, we can identify which

"MASK" OF LASER LIGHT (*red lines*) traces the contours of a patient's face as she lies on the operating table (*left*). To precisely register a computer model of an individual's brain with the true brain, a computer rotates and translates the model (*right images*) until the contours of the virtual face and of the laser mask snap into perfect alignment.



MICHAEL LEVENTON

muscles are affected by stimulation to specific spots in the cortex. We can also record functional information in the virtual model of our patient's head, keying any markings to the muscles that are affected.

Aligning Models with Patient

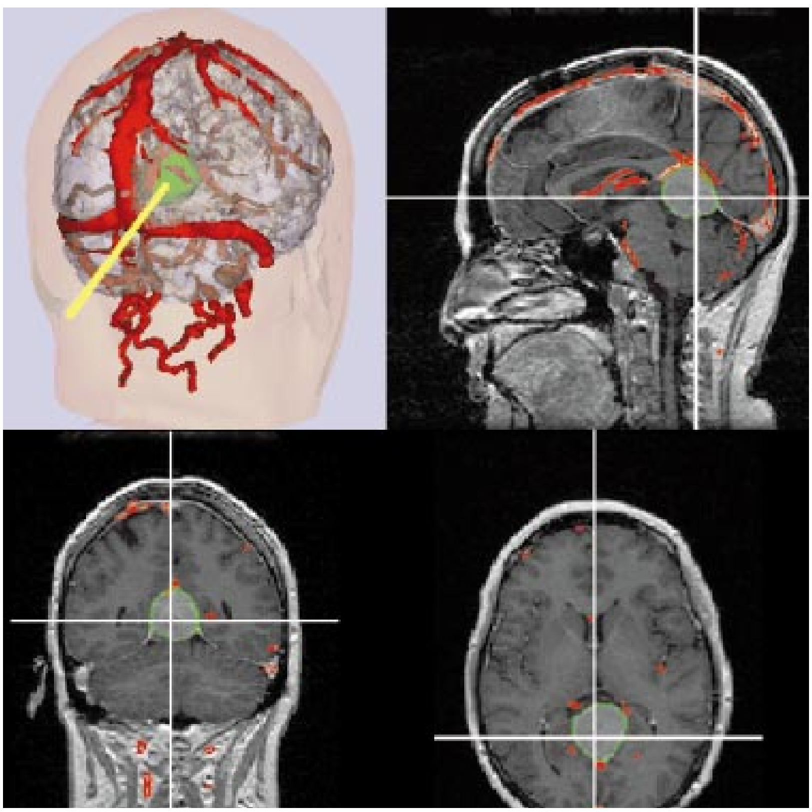
See-through models are a major asset for planning surgical procedures. But they are most useful when aligned with the patient on the table. That way, the internal anatomy can be "seen" from the surgeon's point of view during the operation. This alignment spares the physician from having to transform the models mentally, perhaps incorrectly.

The classical tool for registering presurgical imagery with the actual patient is the stereotactic frame—a boxlike structure that is screwed into the patient's skull. If the frame is worn by the patient during preoperative testing as well as surgery, landmarks on the frame can enable the physician to correlate preoperative images with the brain itself during the operation. The frames, however, are painful and cumbersome for the patient and a hindrance to the surgeon. We therefore sought a gentler, more elegant alternative, which Steven White of our group provided.

White's system involves shining laser light on the scalp and face of the patient, whose head is clamped in a fixed position throughout the registration procedure and the surgery that follows. Light from the laser generator passes through a lens, causing the beam to spread into a line. If the line of light were hitting the surface of the operating table instead of the patient, it would remain flat and straight. When it falls across the patient's face, it deforms in a way that matches the contours of the face, much as would occur if a piece of string were dropped across the face at that point. A camera captures the line, and a linked computer (the same one storing the segmented model of the patient's head) records the deformations from the flat line. Then the line is moved farther up on the face in set increments, with each line captured and recorded. In the end, the series of lines describes the surface topology of the patient's head in its exact position.

With this laser "cast" of the face stored in the computer, we invoke another algorithm devised at M.I.T. to rotate the virtual head until the face exactly matches the contours of the laser lines. But we still have another problem. The image displayed on the screen during the operation has to show the patient from the doctor's vantage, not from that of the camera used to photograph the lasers. A second registration maneuver (involving calculating the doctor's position relative to the position of the laser system) makes this adjustment fairly easily. Having completed the alignment step and ensured that all internal structures have moved in synchrony with the surface of the face, we can finally insert the virtual head into a live video of the patient, yielding our "x-ray vision" visualization.

DURING SURGERY a trackable probe can reveal the trajectory and exact position of the scalpel. Often the computer will display the three-dimensional model as well as two-dimensional cross sections showing views from the side, top and front of the brain. The yellow arrowhead in the 3-D model and the crosshairs in the other images denote the tip of the probe. The tumor is green; the blood vessels, red.



MICHAEL LEVENTON

Enhancing Navigation

Though extraordinary, this presentation is still rather passive. Beyond localization and targeting, a central goal of image-guided surgery is enabling surgeons to monitor the coordinates of the scalpel at all times. We accomplish this aim by providing a probe topped with infrared light-emitting diodes.

As the surgeon touches the sterile tip of the probe against a bit of tissue, three cameras, set at known distances from one another, track the light, which emerges from the diodes at a fixed distance from the tissue-contacting end of the probe. By standard triangulation procedures, much like those used in surveying, computers linked to the cameras can calculate the exact position of the probe in the body and display it on the anatomical model. In our case, the monitor augments this three-dimensional display with images indicating the probe's position in three separate cross-sectional views.

Of course, the models we build reflect the anatomy of the patient before the operation begins. Once the surgeon moves or removes tissue, the original representations promptly become old news. We depend on the open magnet to help us meet this final challenge: providing up-to-date images as surgery progresses. Because surgery occurs within the bore of the magnet, new scans of a patient can be taken at any time and registered to previously acquired imagery and to the surgeon's point of view. Updating is particularly important when the anatomy is flexible and can alter position from moment to moment.

The interactive and updating capabilities of our system have proved highly beneficial. They allow for frequent checks of the surgeon's progress. And they easily answer such questions as, "Where are the tumor margins?" "How close am I to the motor cortex?" "In which direction should I move now?" "Have I really extracted as much of the tumor as possible, or is there more to remove?"

For now, the new images we produce during surgery are two-dimensional and are shown either next to the preoperative model or superimposed on it, depending on the surgeon's preference. The goal, however, is to segment, colorize and combine the new images and to do so rapidly, so that the three-dimensional model, with all its helpful, easy-to-see information, can be updated directly throughout surgery. Such prompt updating is entirely feasible. In fact, we are currently perfecting our methods and expect to add that capability to our system within a year or so.

NAJLAH FEANNY *SABA*

LYNDA TOLVE, now 32, had a seizure-inducing brain tumor removed in 1996, thanks to a preliminary version of image-guided surgery introduced at Brigham and Women's Hospital in Boston. Physicians elsewhere had turned her away, on the grounds that they could not excise the tumor fully without great risk of cutting into the adjacent motor cortex and paralyzing her. The next year Tolve married her fiancé, Daniel McCafferty (*right*). She remains seizure-free.

Just around the Corner . . .

Already, however, the technologies we have described—and procedures much like ours—are increasingly being used for neurosurgery and beyond, including to support complex operations on bones, the nasal sinuses, the kidneys, the liver, the spine and other tissues. But their potential applications are not limited to surgery.

For cancer care in particular, the new techniques are finding many roles. In radiation therapy, model-building methods and real-time imaging are being applied to ensure that beams of radiation converge at the desired anatomical site, delivering high doses in tumors but low doses in surrounding tissues. To assess better the effectiveness of radiation and drug therapies, physicians review three-dimensional displays that highlight such features as the size and positioning of tumors before and after treatment. The imaging capabilities might even have value for detecting nascent tumors. Our group is evaluating the ability of three-dimensional representations built from MRI scans to discern cancerous changes in a breast before they can be identified clearly in mammograms.

With respect to future surgical applications of computer-assisted visualizations, technical challenges remain. Most notably, investigators still have difficulty making useful representations of highly flexible tissues. Models made of abdominal organs, in particular, can quickly become inaccurate when the patient breathes or contracts certain muscles. Algorithms able to predict tissue deformations are being developed to help resolve that problem.

Despite its current limitations, image-guided surgery is having a powerful influence on medicine today. With the computer as a valuable assistant to the physician, surgeries of the future are likely to be less invasive, shorter, less risky and more successful.

The Authors

W. ERIC L. GRIMSON, RON KIKINIS, FERENC A. JOLESZ and PETER McL. BLACK bring a range of expertise to image-guided surgery. Grimson is Bernard Gordon Professor of Medical Engineering, professor of computer science and engineering, and associate director of the Artificial Intelligence Laboratory at the Massachusetts Institute of Technology. Kikinis is director of the Surgical Planning Laboratory at Brigham and Women's Hospital and associate professor of radiology at Harvard Medical School. Jolesz is B. Leonard Holman Professor of Radiology at Harvard Medical School and director of the Magnetic Resonance Imaging Division and of the Image-Guided Therapy Program at Brigham and Women's. Black is Franc D. Ingraham Professor of Neurosurgery at Harvard Medical School and neurosurgeon in chief at Brigham and Women's and Children's hospitals.

Further Reading

ADAPTIVE SEGMENTATION OF MRI DATA. W. M. Wells III, W.E.L. Grimson, R. Kikinis and F. A. Jolesz in *IEEE Transactions on Medical Imaging,* Vol. 15, No. 4, pages 429–442; August 1996.

DEVELOPMENT AND IMPLEMENTATION OF INTRAOPERATIVE MAGNETIC RESONANCE IMAGING AND ITS NEUROSURGICAL APPLICATIONS. P. M. Black et al. in *Neurosurgery,* Vol. 41, No. 4, pages 831–842; October 1997.

IMAGE-GUIDED PROCEDURES AND THE OPERATING ROOM OF THE FUTURE. Ferenc A. Jolesz in *Radiology,* Vol. 204, No. 3, pages 601–612; 1997.

Additional information is available on the World Wide Web:
http://www.ai.mit.edu/projects/medical-vision/
http://splweb.bwh.harvard.edu:8000/
http://cisstweb.cs.jhu.edu/

Biological Warfare against Crops

Intentionally unleashing organisms that kill an enemy's food crops is a potentially devastating weapon of warfare and terrorism

by Paul Rogers, Simon Whitby and Malcolm Dando

On November 25, 1969, President Richard Nixon announced that the U.S. would unilaterally "renounce the use of lethal biological agents and weapons, and all other methods of biological warfare." The official reason for the renunciation was that biological weapons were of limited military significance. Testifying before the U.S. Senate in 1989, Harvard University's Matthew S. Meselson, a molecular biologist and expert on biological weaponry, outlined the true reasons: "First, these weapons could be as great a threat as nuclear weapons; second, they could be simpler and less expensive to develop and produce than nuclear weapons; and crucially, the U.S. offensive biological weapons program could be easily duplicated.... This stark analysis led to the conclusion that our biological weapons program was a substantial threat to our own security."

Biological weapons date back at least to the Roman Empire, when a common practice was to throw dead animals into enemy water supplies to poison them. The U.S. government defined biological warfare as "the intentional cultivation or production of pathogenic bacteria, fungi, viruses ... and their toxic products, as well as certain chemical compounds, for the purpose of producing disease or death."

The horror of biological weapons is usually portrayed in terms of the intentional exposure of a human population to deadly diseases, such as anthrax or plague. Nefarious individuals have already attempted to procure disease-causing agents in the hopes of using them for terrorist purposes; these efforts have been well publicized, making the general public aware of the danger of intentionally inflicted human disease. But a less obvious type of biological weapon has great destructive capability and gets little attention. The "other methods of biological warfare" mentioned by Nixon include those that kill crops rather than people.

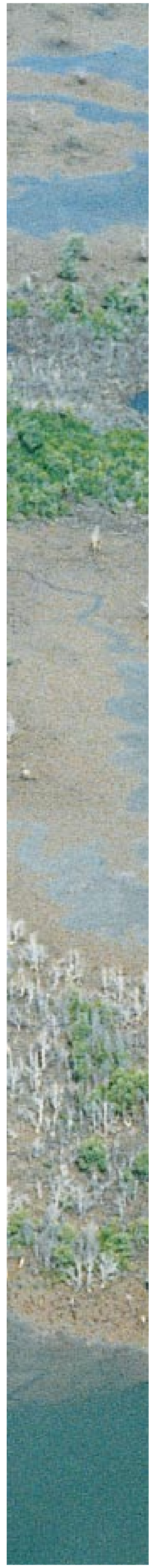
Plant disease expert J. E. Van Der Plank of the Plant Protection Research Institute in Pretoria, South Africa, saw the significance of anticrop measures in the early 1960s. "We often call an epidemic explosive," he wrote. "In time of peace the adjective is neatly descriptive. In time of war it could be grimly real in the military sense. An enemy has few explosives to surpass a pathogen that increases at a rate of 40 percent per day ... and continues to increase for several months.... Many types of spores disperse as easily as smoke.... They have only to be dispersed in the proper places at the proper times. Nature sees to the explosion."

Potential of Anticrop Warfare

The unilateral U.S. decision helped to pave the way for the 1972 Biological and Toxin Weapons Convention, which required signatories to stop biological weapons work and destroy their existing stockpiles of such weapons. Despite 141 state parties agreeing to these terms, concerns over the risks of biological warfare have risen substantially in the past decade. The specter of terrorism is one reason for the increased anxiety. Another is the revelation that Iraq had an active biological weapons program prior to the Gulf War, a venture that included anticrop weaponry.

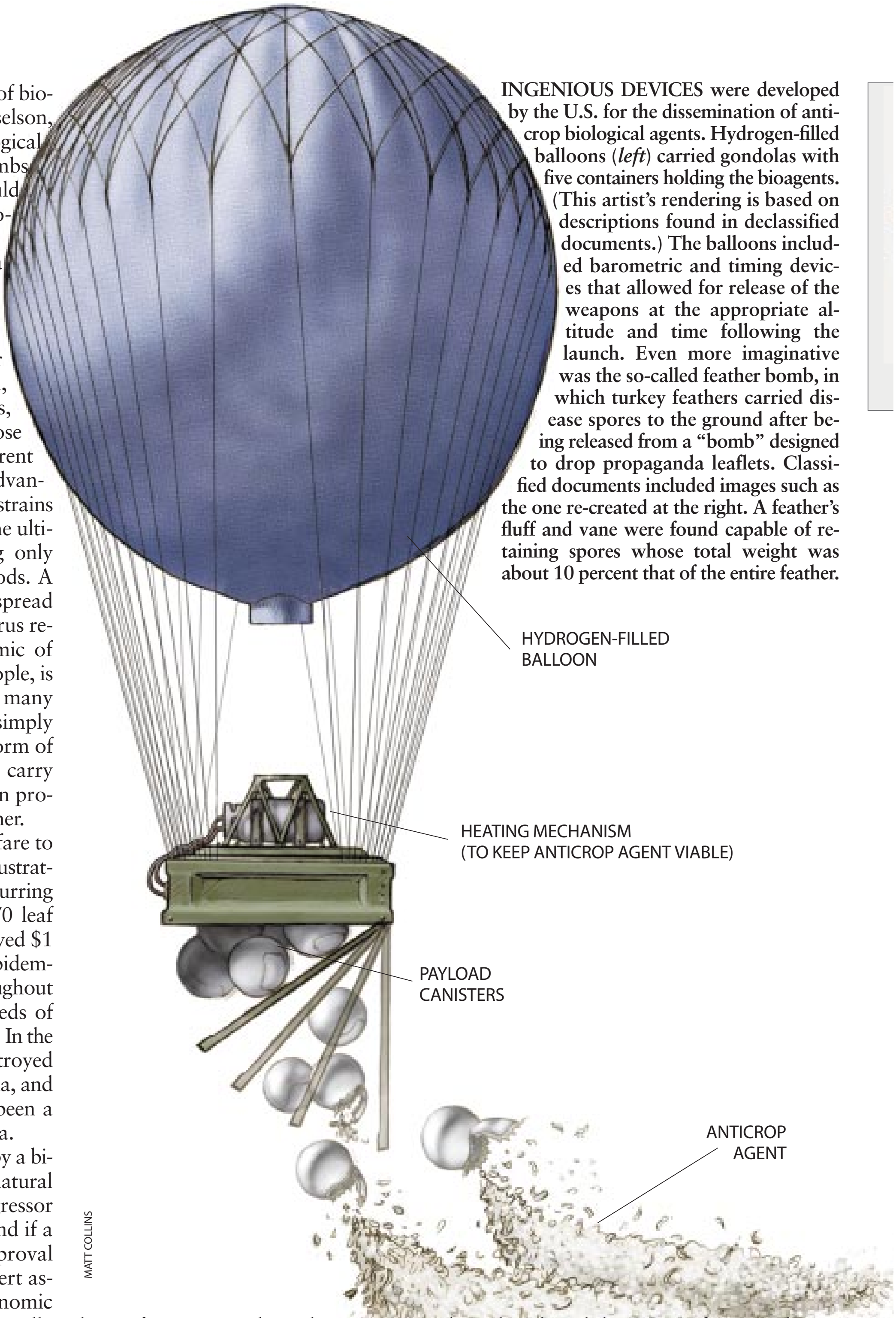
Iraqi bioweapons work originated in the 1970s and peaked from 1985 to 1991; it dealt with human pathogens, such as anthrax, and toxins, such as botulism and aflatoxin. The anticrop effort concentrated on wheat smut, a disease caused by fungus species of the genus *Tilletia*. Wheat smut fungus replaces the flowering part of the wheat plant with masses of black spores, which can then spread to other plants. Wheat smuts are endemic in many parts of the world and in a heavy infestation can cause massive reductions in crop yields. The likely target of the Iraqi efforts was Iran, where wheat is the most important cereal crop. (Wheat smut has an additional and unusual quality useful for waging war: the pathogen produces flammable trimethylamine gas, which can blow up harvesters that have collected infected grain.)

The Iraqi anticrop program demonstrates the need



CHEMICAL DEFOLIANTS, such as those used in the war in Vietnam (*above*), came out of the same programs, dating back to World War II, that led to the development of biological weapons aimed against food crops.

DICK SWANSON



INGENIOUS DEVICES were developed by the U.S. for the dissemination of anticrop biological agents. Hydrogen-filled balloons (*left*) carried gondolas with five containers holding the bioagents. (This artist's rendering is based on descriptions found in declassified documents.) The balloons included barometric and timing devices that allowed for release of the weapons at the appropriate altitude and time following the launch. Even more imaginative was the so-called feather bomb, in which turkey feathers carried disease spores to the ground after being released from a "bomb" designed to drop propaganda leaflets. Classified documents included images such as the one re-created at the right. A feather's fluff and vane were found capable of retaining spores whose total weight was about 10 percent that of the entire feather.

for serious attention to this form of biological warfare. As noted by Meselson, a country lacking the technological expertise to produce atomic bombs can still make weapons that could set off devastating famines or economic losses.

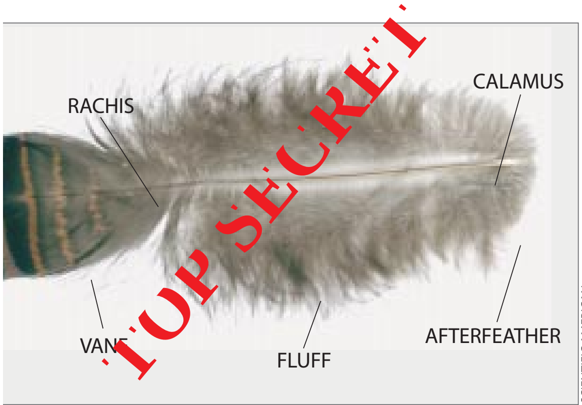
All major food crops come in a number of varieties, each usually suited to specific climate and soil conditions. These varieties have varying sensitivities to particular diseases. Crop pathogens, in turn, exist in different strains or races, which will infect and damage those individual crop varieties to different degrees. An aggressor can take advantage of these properties to isolate strains of pathogens that would act as the ultimate "smart" bombs, attacking only the enemy's sources of staple foods. A human disease agent that can spread through the air, such as the flu virus responsible for the global pandemic of 1918, which killed 20 million people, is especially threatening. Similarly, many of the worst crop pathogens simply float from plant to plant in the form of fungal spores. The wind may carry them, or a splashing raindrop can propel a spore from one leaf to another.

The potential for anticrop warfare to inflict economic damage can be illustrated by looking at naturally occurring losses caused by disease. In 1970 leaf blight in the southern U.S. destroyed $1 billion worth of corn. Periodic epidemics of cereal rusts and smuts throughout the world often consume hundreds of millions of dollars' worth of crops. In the 19th century, coffee leaf rust destroyed coffee plantations in southeast Asia, and for the past two decades it has been a pressing problem in Latin America.

A food crop epidemic initiated by a biological attack might look like a natural outbreak, freeing the covert aggressor from blame and repercussion. And if a government requires public approval for maintaining hostilities, an overt assault against plants, like an economic sanction, may be more psychologically acceptable than attacks on people. For example, an anthrax attack against an unprotected population of a city has the potential to kill many hundreds of thousands, all dying rapidly from an extremely unpleasant and painful illness. In contrast, destroying crops seems almost benign, with no immediate effects against communities.

In reality, though, the results could be appalling. A poor country in which millions of citizens are dependent on a staple crop such as rice and in which that rice crop is seriously damaged by a deliberate anticrop attack could well experience famine that would be at least as costly, in human terms, as an anthrax attack on a city. Malnutrition and starvation would ensue, with the poorest segment of the population being hardest hit. In addition to the direct effects of starvation, immune resistance to a wide range of common illnesses would be reduced, and the extent of pain and suffering could be every bit as bad as that resulting from an anthrax attack.

Either way, the warfare would be directed primarily against civilian populations, with no pretense that "military" targets were being hit. Over the past 100 years, vigorous attempts have been made to develop international legal control of warfare, the recent ban on antipersonnel land mines being an example. Much of the emphasis has been on



SCIENTIFIC AMERICAN

trying to minimize attacks on unprotected civilians, but anticrop warfare would have its greatest effects precisely against such people. An apparently anodyne form of warfare, with no explosions, bullets, mines or shrapnel, could, in reality, be terrifyingly effective in causing mass casualties.

History shows that crop diseases can rival a military invasion in devastation of a civilian population. Late blight of potatoes helped to bring about the Irish famine of 1845–46, which killed one million and drove another million from the country. Brown spot disease of rice was partially responsible for the Bengal famine in India in 1942–43, in which more than two million people starved.

In theory, then, anticrop agents can be an effective part of a country's armamentarium—a possibility that has attracted widespread interest over much of this century.

Allied and Axis Endeavors

France's biological weapons program started in 1921, and by the end of the 1930s it included work on two potato killers, late blight and the Colorado beetle. During World War II, the British focused their biological warfare efforts on anthrax. (The tests included anthrax releases on Gruinard Island, off the coast of Scotland, that rendered that landmass uninhabitable for almost 50 years. Concerns about the proximity of the mainland moved the trials in 1943 to the Suffield Experimental Station, amid open prairie in Alberta, Canada.) The British also invested in anticrop warfare, concentrating on various herbicides. In the 1950s some of those chemical plant killers found roles in battles with communist insurgents in Malaya and set the stage for the extensive use of chemical defoliants in the 1960s and 1970s by the U.S. in Vietnam.

Germany likewise worked with biological weapons during World War II, studying both antihuman and anticrop agents. A postwar U.S. assessment of the German program reported: "There were probably more plans and ideas considered by the workers in the plant section than in any of the other[s].... There is repeated emphasis on the possible use of different agents for attack against England, and in one case America is specifically mentioned."

Germany investigated numerous crop diseases, including late blight of potatoes and leaf-infecting yellow and black wheat rusts, as well as insect pests, such as the Colorado beetle, the rapeseed beetle and the corn beetle. By 1943 a large-scale program to breed the Colorado beetle was in its early stages. Records indicate that the beetle may have even been ready for deployment by June 1944, but by then it was too late to damage that year's British potato crop. With the German surrender the next year, the Colorado beetle field trial was left untested.

Japan's World War II biological weapons program was dominated by the notorious Unit 731. In addition to performing vivisections on prisoners, members of Unit 731 developed biological agents designed for use against humans. Details of the Japanese anticrop program remain sketchy, but up to 100 workers were involved in research on numerous plant pathogens and chemical herbicides. Much of the emphasis was on diseases that could infect Soviet and American crops, particularly those growing in the Pacific Northwest. Smut disease and nematode infestations of wheat seem to have been the weapons that the Japanese considered most promising. They also established a facility able to produce more than 90 kilograms (about 200 pounds) of cereal rust spores annually. Dispersing on the winds like dust, spores in that quantity could have wiped out vast tracts of America's amber waves of grain.

American Efforts

The U.S. maintained a substantial biological warfare program, including extensive studies of anticrop weapons, from the 1940s through the Nixon announcement in 1969. In fact, according to Julian Perry Robinson of the University of Sussex, work with anticrop agents was encouraging enough to keep the entire U.S. biological weapons program afloat when it faced extinction at times prior to 1969.

Many of the details of American biological weapons capability are now declassified and available under freedom of information legislation. In his work elucidating the threat of chemical weapons, Robinson first noted some of the previously concealed intelligence concerning anticrop warfare. One of us (Whitby) then discovered further data on anticrop weapons within more general biological weapons material that had been uncovered by various researchers.

The U.S. anticrop program dealt with many diseases, such as late blight of potatoes and sclerotium rot, which attacks crops such as soybeans, sugar beets, sweet potatoes and cotton. The main targets of the U.S. program, however, were wheat in the western Soviet Union, especially Ukraine, and rice in Asia, chiefly China.

Between 1951 and 1969 the U.S. stockpiled more than 30,000 kilograms of spores of *Puccinia graminis tritici,* the fungus that causes stem rust of wheat; that quantity is probably enough to infect every wheat plant on the planet. *P. graminis* has excellent weapons potential because it retains its viability in cool storage for more than two years, and it spreads rapidly after being released—a single infected wheat kernel can contain 12 million spores, each of which can then potentially infect another plant. The U.S. chose blast disease, caused by *Piricularia oryzae,* as its main antirice agent, and had a cache of nearly a ton of dust mote–size spores by 1966.

The U.S. also developed a number of weapons systems, some of which can only be described as ingenious, designed to deliver anticrop agents. One of the early weapons was a 500-pound bomb originally designed to release propaganda leaflets. Instead this extraordinary weapon was packed with bird feathers, which carried the fine dust of fungal spores. Perhaps not since pre-Revolutionary America, when the British distributed smallpox-ridden blankets to Indians, have such benign objects served such deadly ends. The U.S. performed field tests of the "feather bomb" at Camp Detrick in Maryland and in the U.S. Virgin Islands. When let loose from their container, the feathers floated to the ground over a wide area. As they landed on crops, some of the disease-causing spores moved from feather

HOLT STUDIOS INTERNATIONAL *Photo Researchers, Inc. (left)*; NIGEL CATTLIN/HOLT STUDIOS INTERNATIONAL *Photo Researchers, Inc (right)*

RANDALL C. ROWE *Ohio State University*

POTATO FIELDS can be destroyed by late blight, as is clearly visible in these photographs comparing healthy potato plants (*top left*) and diseased plants (*top right*). Potatoes even mildly damaged by late blight (*bottom right*) are unpalatable. The disease, which caused the Irish Famine that started in 1845, would make a potent biological weapon.

to leaf. According to a declassified Camp Detrick report, "feathers dusted with 10 percent by weight of cereal rust spores and released from a modified M16A1 cluster adaptor at 1,300 to 1,800 feet [400 to 550 meters] above ground level will carry sufficient number of spores to initiate a cereal rust epidemic."

Other U.S. delivery techniques developed in the 1950s relied on spraying pathogens from F-100, F-105 and F-4C strike aircraft, a system that eventually was used for showering chemical herbicides over Vietnam. Another strategy depended on unmanned, free-floating balloons to carry dispensers designed to disseminate anticrop agents.

U.S. anticrop warfare work ceased with the decision to forsake unilaterally its entire biological weapons program. Information acquired from defectors suggests that the former Soviet Union maintained an active anticrop program until its dissolution in 1991, but a dearth of intelligence surfaced on any other such efforts until revelations by the United Nations Special Commission on Iraq in 1995.

A Growing Threat?

In the 21st century, countries in both the developing and the developed world will still have much to fear from enemies—be they nations, political factions or terrorists—who may choose to engage in anticrop warfare. Most plant diseases that spread rapidly within a growing season have a short incubation period and visibly affect leaves. The strong agricultural extension service in the U.S., for example, can likely be counted on to identify a disease outbreak early, and it can prescribe costly pesticides to stop the flare-up. Such detection and control measures, however, require the kinds of resources that poorer countries often lack.

On the other hand, the developed nations of North America and western Europe have their own unique hazards because of the prevalent practice of growing only one or two varieties of major food crops. The lack of diversity in such monocultures renders the entire crop susceptible to organisms that are pathogenic to those varieties. An enemy could deliver the disease agents when weather conditions and the growth stage of the crop would best ensure a regionwide pandemic. Even if the victim nation successfully stopped the outbreak before widespread crop destruction occurred, it could suffer considerable economic losses.

The ongoing revolution in biotechnology and genetic engineering can extend the technical capabilities of anyone interested in developing biological weaponry, thereby increasing the threat. Basic studies are deciphering botanical genomes and the interactions of plants and their pathogens. Although this work should boost agricultural productivity, it could also unwittingly serve those interested in designing more effective anticrop weapons. Researchers could produce strains of hardier disease-causing organisms, which might be resistant to conventional pesticides or might survive over wider ranges of temperature or humidity.

A United Nations working paper has cited 10 international crop diseases as having weapons potential. Most of the world's key food crops are susceptible to these conditions, some of the most damaging being wheat rust, sugarcane smut and rice blast. Other crops at risk include corn, potatoes, numerous beans, various fruits and coffee. Pine trees, important economically for lumber, could also be targeted.

In the post–cold war era, political pressure and economic sanctions can be as significant as direct military confrontation; the mere power to drive economic resources toward stemming incipient epidemics gives anticrop warfare considerable clout. The prohibition of anticrop weapons should thus be a critical part of the current efforts to strengthen the Biological and Toxin Weapons Convention.

Meetings in Geneva have been under way since shortly after the 1991 Gulf War with such an aim. An important means to achieve that goal would be an effective verification protocol. Such a plan would establish an organization that would evaluate declarations of the most relevant facilities capable of developing biological weapons. The organization would have the power to check such declarations through, for example, site visits. Provisions would also exist for "challenge" inspections of facilities—described in the arms-control community as "anytime, anywhere, with no right of refusal"—in the event of alleged treaty violations. Field investigations of any alleged uses of biological weapons would also be permitted.

The U.S., the European Union and various other states strongly support a verification protocol, which could help drive an agreement before 2001 (when the fifth Five-Year Review Conference of the original treaty is scheduled), but that consensus is not certain. In addition to the considerable technical difficulties posed by verification plans, obvious political problems remain to be resolved. A significant division exists between industrial nations and developing states over the degree of scientific and technical assistance to be built into any protocol. The protocol itself should not be a tool by which unregulated advanced technology that could be used to create weapons of war is transferred from have to have-not states, but neither should it be used to prevent the legitimate transfer of technology for peaceful purposes. Large biotechnology companies also have concerns over possible losses of commercial proprietary information during visits and inspections. And, of course, some countries may wish to retain the option of developing biological weapons.

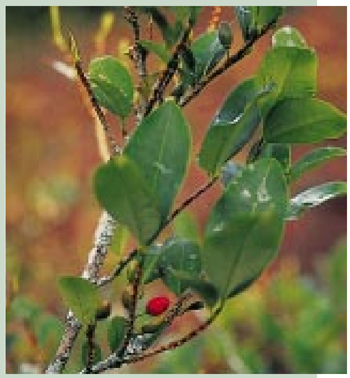
Should current efforts to strengthen the Biological and Toxin Weapons Convention fail, the world faces the prospect of lack of control over a major group of weapons of mass destruction during a period of accelerating scientific and technological advancement. The consequence over the next few decades could be the creation of a devastating range of new weaponry, some of which is certain to be aimed at the food crops that feed billions of the world's citizens.

Silver Bullet or Poison Chalice: The Biowar against Drugs

Last year the U.S. Congress approved a $23-million antidrug program that includes research on plant pathogens. Among the target plants are those that produce narcotics such as cocaine, heroin and marijuana. Advocates of the program hail it as a potential breakthrough. Representative Bill McCollum of Florida, one of the co-sponsors of the legislation, said, "All of the indications are that this has the potential for making a big difference in the drug war.... This could be the silver bullet."

Article I of the 1972 Biological and Toxin Weapons Convention (BTWC) bans the development, production and stockpiling of biological agents intended "for hostile purposes or in armed conflict." Also outlawed are biological weapons "that have *no* justification for prophylactic, protective or other peaceful purposes." Proponents of the use of plant pathogens against drug crops therefore point out that they would be used in cooperative programs with states in which the drugs are produced.

Opponents of the plans have three concerns. One is that induced epidemics might, in some circumstances, spread to other plants. Another is that plant pathogens could be used in drug-producing regions without the consent of the state in question. Whereas such use might be popular with antidrug agencies, it would almost certainly breach the BTWC and also set a dangerous precedent. The greatest concern, however, is that the development of a capability to destroy drug crops with plant pathogens will inevitably provide a wealth of knowledge and practical experience that could readily be applied in much more aggressive, offensive biological warfare targeting food crops. *—P.R., S.W. and M.D.*



STEVEN R. KING *Peter Arnold, Inc.*

Coca plant

The Authors

PAUL ROGERS, SIMON WHITBY and MALCOLM DANDO are members of the department of peace studies at the University of Bradford in England. Rogers, who heads the department, earned a doctorate in plant pathology and lectured at Imperial College, London. He has worked for the past 20 years on issues of resource conflict and other aspects of international security. Whitby, a research assistant in the peace studies department, is currently completing a doctorate on the history of anticrop biological warfare programs. Dando has a doctorate in neurophysiology from the University of St. Andrews in Scotland and is a professor of international security at Bradford. He also heads Bradford's program on strengthening the Biological and Toxin Weapons Convention.

Further Reading

Anti-Crop Biological Warfare—Implications of the Iraqi and U.S. Programs. Simon Whitby and Paul Rogers in *Defense Analysis,* Vol. 13, No. 3, pages 303–318; 1997.

Plant Pathology. Fourth edition. George N. Agrios. Academic Press, 1997.

Biotechnology, Weapons and Humanity. Malcolm Dando. British Medical Association, Harwood Academic Publishers, 1999.

The Bradford Program on Strengthening the Biological and Toxin Weapons Convention site is available at www.brad.ac.uk/acad/sbtwc on the World Wide Web.

The Chemical and Biological Warfare Conventions Bulletin of the Harvard-Sussex Program on CBW Armament and Arms Limitation site is available at fas-www.harvard.edu/~hsp/ on the World Wide Web.

Gödel and the Limits of Logic

Mathematical genius Kurt Gödel was devoted to rationality in his work but struggled with it in his personal life

by John W. Dawson, Jr.

The man in the photograph seen at the right looks formal, reserved and somewhat undernourished. His face and his writings are unfamiliar to most, except for a few philosophers and mathematical logicians. He was Kurt Gödel, celebrated for his incompleteness theorems, the implications of which are far-reaching for the foundations of mathematics and computer science. The story of his life and work is that of a persistent quest for rationality in all things, pursued against a background of recurrent mental instability.

Gödel proved that the mathematical methods in place since the time of Euclid were inadequate for discovering all that is true about the natural numbers. His discovery undercut the foundations on which mathematics had been built up to the 20th century, stimulated thinkers to seek alternatives and generated a lively philosophical debate about the nature of truth. Gödel's innovative techniques, which could readily be applied to algorithms for computations, also laid the foundation for modern computer science.

Born on April 28, 1906, in Brno, Moravia, Gödel was the second of two children of Rudolf and Marianne Gödel, expatriate Germans whose families were associated with the city's textile industry. There were no scholars among Gödel's forebears, and his father received only a trade school education. But being ambitious and hardworking, Rudolf Gödel rose through the ranks to become manager and then part-owner of one of Brno's large textile factories. Along the way he acquired wealth enough to purchase a villa in a fashionable neighborhood and to send his children to private, German-language schools, where both sons did very well in their studies.

Indeed, only once during his primary and secondary school career did young Kurt ever receive less than the highest mark in any subject (mathematics!). Yet he gave no early intimation of genius. He was a highly inquisitive child, so much so that he was nicknamed *der Herr Warum* ("Mr. Why"). But he was also introverted, sensitive and somewhat sickly. At about the age of eight he contracted rheumatic fever, and although it seems not to have caused lasting physical damage, it kept him out of school for some time and may have fostered the exaggerated concern for his health and diet that was to become increasingly prominent over the years.

The Introvert

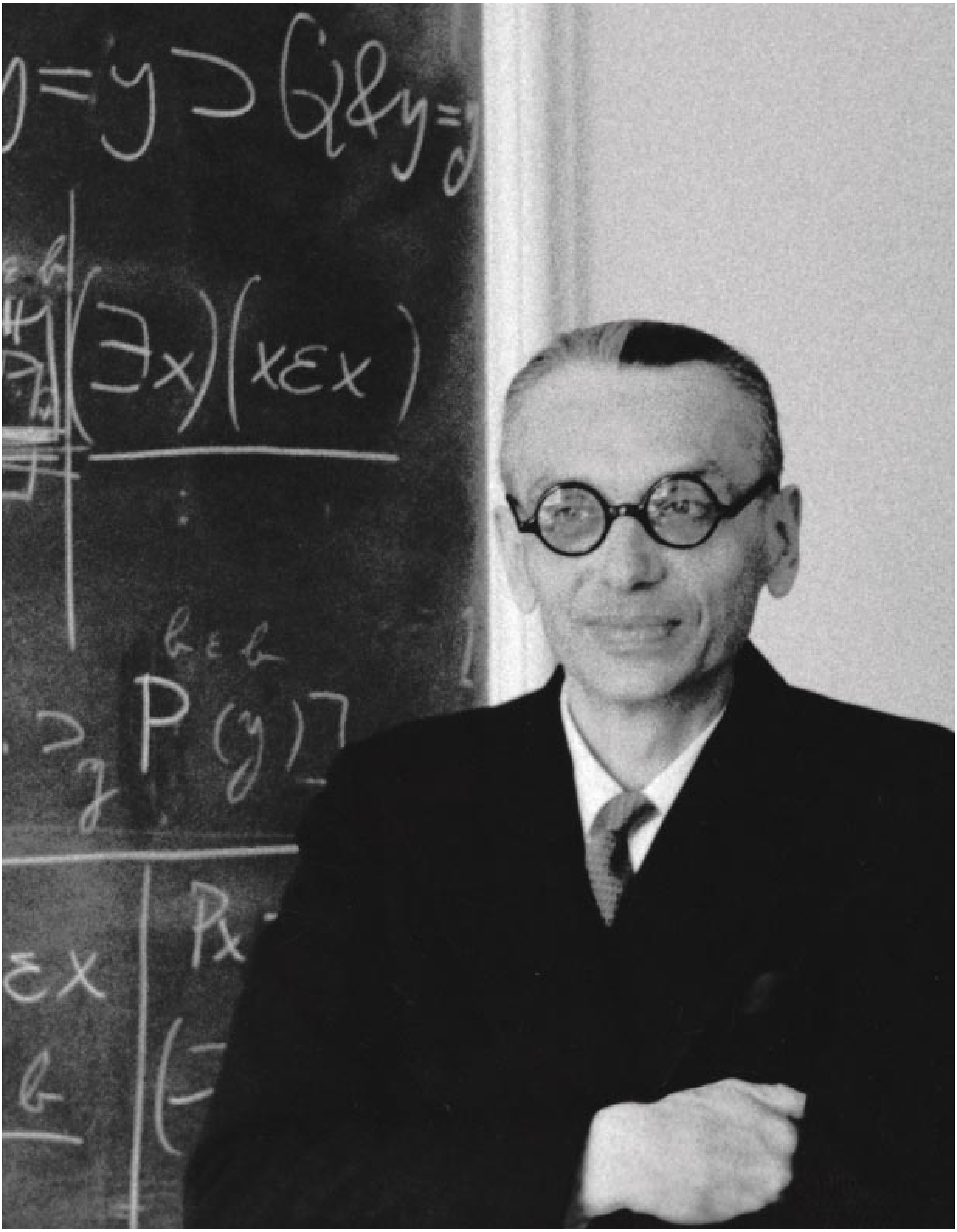
In 1924, after his graduation from the *Realgymnasium,* or technical high school, in Brno, Gödel left his homeland to enroll at the University of Vienna, where his brother had gone four years earlier to pursue medical studies. Vienna's economy was then in ruins. The university, however, retained much of its former eminence. So despite the material privations, during the years between the two world wars Vienna was home to a dramatic flowering of creativity in science, the arts and philosophy.

At the time of his enrollment Gödel intended to seek a degree in physics. But after a short while, impressed by the lectures of professors Philipp Furtwängler and Hans Hahn, he switched to mathematics. His remarkable talents soon attracted attention—so much so that just two years after his matriculation he was invited to attend sessions of a discussion group that Hahn and philosopher Moritz Schlick had founded two years earlier. The group, which was later to become famous as the Vienna Circle, was inspired by the writings of Ernst Mach, a champion of rationalism who believed that all things could be explained by logic and empirical observation, without recourse to metaphysical agencies.

The Circle brought Gödel into contact with scholars such as philosopher of science Rudolf Carnap and mathematician Karl Menger and helped to acquaint him with the literature of mathematical logic and philosophy. In particular, the Circle was immersed in the writings of Ludwig Wittgenstein, whose concern about the extent to which language can speak about language may have prompted Gödel to probe analogous questions about mathematics. Some of the Circle's members, including Carnap, Hahn and physicist Hans Thirring, were active in the investigation of parapsychological phenomena—matters in which Gödel, too, exhibited a keen interest. (Years later he remarked to his close friend, economist Oskar Morgenstern, that in the future it would be deemed a great oddity that 20th-century scientists had discovered the elementary physical particles but had failed even to consider the possibility of elementary psychic factors.)

Gödel did not, however, share the positivistic philosophical outlook of the Circle, which extended Mach's ideas. Instead he was a Platonist: he believed that in addition to objects, there exists a world of concepts to which humans have access by intuition. Thus, for him a statement would have a definite "truth value"—be true or not—whether or not it had been proved or was amenable to being empirically confirmed or refuted. In his own view, that philosophy was an aid to his remarkable mathematical insights.

Although Gödel was an attentive observer and clearly brilliant, he rarely contributed to the Circle's discussions, unless they were about mathematics. Shy and reclusive, he had few close friends. (He did, however, like the company of women and was apparently quite attractive to them.) After 1928 he seldom



COURTESY OF THE ARCHIVES OF THE INSTITUTE FOR ADVANCED STUDY

KURT GÖDEL proved that mathematical systems are essentially incomplete: not everything that is true can be proved to be so. In later life he turned his attention to a variety of other problems, including relativity. This photograph was taken in May 1958 in Gödel's office at the Institute for Advanced Study in Princeton, N.J., by Finnish logician Veli Valpola.

COURTESY OF JOHN W. DAWSON, JR.

TWO BROTHERS, Kurt (*right*) and Rudolf, were close when they were young but as adults drifted apart. This studio shot is from around 1908.

attended the group's meetings but became active instead in a mathematical colloquium organized by Menger. Its proceedings were published as an annual journal, which Gödel helped to edit and to which he later contributed more than a dozen articles.

A Reticent Genius

During this period, Gödel suddenly acquired international stature in mathematical logic. Two papers in particular thrust him into prominence. One was his doctoral dissertation, submitted to the University of Vienna in 1929 and published the next year. The other was his treatise "On Formally Undecidable Propositions of *Principia Mathematica* and Related Systems," published in German in 1931 and submitted as his *Habilitationsschrift* (qualifying dissertation for entrance into the teaching profession) in 1932.

The dissertation, entitled "The Completeness of the Axioms of the First-Order Functional Calculus," solved an open problem that David Hilbert and Wilhelm Ackermann had posed in their 1928 textbook *Grundzüge der theoretischen Logik* ("Foundations of Theoretical Logic"). The question was whether the accepted rules, stated in the book, for manipulating expressions involving logical connectives ("and," "or" and so on) and quantifiers ("for all" and "there exists," applied to variables that ranged over numbers or sets) would, when adjoined to the axioms of a mathematical theory, enable the deduction of all and only those statements that held true in every structure that satisfied the axioms. In plain words, could one actually prove everything that was true under all interpretations of the symbols?

The expected answer was yes, and Gödel confirmed that it was. His dissertation established that the principles of logic developed up to that time were adequate for their intended purpose, which was to prove everything that was true on the basis of a given set of axioms. It did not show, however, that every true statement concerning the natural numbers could be proved on the basis of the accepted axioms of number theory.

Those axioms, proposed by Italian mathematician Giuseppe Peano in 1889, include the principle of induction. It asserts that any property that is true of zero, and true of a natural number $n + 1$ whenever true of n, must be true of all natural numbers. Sometimes called the domino principle—because if you knock one over, the rest will topple—the axiom might seem self-evident. Yet mathematicians found it problematic because it refers not just to numbers themselves but to properties of numbers. Such a "second-order" statement was thought too vague and ill defined to serve as a basis for the theory of natural numbers.

As a result, the induction axiom was recast as an infinite schema of similar axioms that refer to specific formulas rather than to general properties of numbers. Unfortunately, those axioms no longer uniquely characterize the natural numbers, as Norwegian logician Thoralf Skolem demonstrated a few years before Gödel's work: other structures satisfy them as well.

Gödel's completeness theorem states that one can prove all those statements that follow from the axioms. There is a caveat, however: if some statement is true of the natural numbers but is not true of another system of entities that also satisfies the axioms, then it cannot be proved. That did not seem to be a serious problem, because mathematicians hoped that entities that masqueraded as numbers but were essentially different from them did not exist. So Gödel's next theorem came as a shock.

In his 1931 paper Gödel showed that some statement that is true of the natural numbers must fail to be provable. (That is, objects that obey the axioms of number theory but fail to behave like the natural numbers in some other respects do exist.) One could escape this "incompleteness theorem" if all true statements were taken to be axioms. In that case, however, deciding whether some statements are true or not becomes a priori problematic. Gödel showed that whenever the axioms can be characterized by a set of mechanical rules, it does not matter which statements are taken to be axioms: if they are true of the natural numbers, some other true statements about those numbers will remain unprovable.

In particular, if the axioms do not contradict one another, then that fact itself, suitably encoded as a numerical statement, will be "formally undecidable"—neither provable nor refutable—on the basis of those axioms. Any proof of consistency must therefore appeal to stronger principles than the axioms themselves. (For an elucidation of the arguments, see "Gödel's Proof," by Ernest Nagel and James R. Newman; SCIENTIFIC AMERICAN, June 1956.)

The latter result greatly dismayed David Hilbert, who had envisioned a program for securing the foundations of mathematics through a "bootstrapping" process, by which the consistency of complex mathematical theories could be derived from that of simpler, more evident theories. Gödel, on the other hand, saw his incompleteness theorems not as demonstrating the inadequacy of the axiomatic method but as showing that the derivation of theorems cannot be completely mechanized. He believed they justified the role of intuition in mathematical research.

The concepts and methods Gödel introduced in his incompleteness paper are central to the discipline of recursion theory, which underlies all of modern computer science. Extensions of his ideas have allowed the derivation of several other results about the limits of computational procedures. One is the unsolvability of the "halting problem"—that of deciding, for an arbitrary computer with an arbitrary input, whether the computer will eventually halt and produce an output rather than becoming stuck in an infinite loop. Another is the demonstration that no program that does not alter a computer's operating system can detect all programs that do (viruses).

Shelter in America

Gödel spent the 1933–34 academic year in Princeton, N.J., at the newly founded Institute for Advanced Study, where he lectured on his incompleteness results. He was invited to come there the next year as well but suffered a mental breakdown shortly after his return to Vienna. He recovered in time to return to Princeton in the fall of 1935, but a month after his arrival he experienced a relapse and did not return to lecturing until the spring of 1937 in Vienna.

Without access to Gödel's confidential medical records (he was counseled by a psychiatrist in Princeton), his actual diagnosis must remain unknown. His problems seem to have started with hypochondria: he was obsessive about his diet and bowel habits and kept a daily record for two decades or more of his body temperature and milk of magnesia consumption. He had a fear of accidental and, in later years, deliberate poisoning. This phobia led him to avoid eating food, so that he became malnourished. At the same time, though, he ingested a variety of pills for an imaginary heart problem.

Except in times of crisis, Gödel's mental problems hampered his work surprisingly little. The person who kept him going was Adele Porkert, whom he had met at a Viennese nightclub during his student years. Porkert was a Catholic divorcée six years older than Gödel, who worked as a dancer and whose face was disfigured by a port-wine-stain birthmark. His parents regarded her as a scandalous person. But the two were devoted to each other, and more than once, by serving as his food taster, she helped to allay Gödel's growing fears that someone was trying to poison him. After a long courtship the two were married in September 1938, just before Gödel returned once more to America, where he lectured at the Institute for Advanced Study and at the University of Notre Dame on exciting new results he had obtained in set theory.

That achievement involved the resolution of some controversial aspects of the theory of collections of objects. In the late 19th century, German mathematician Georg Cantor had introduced a notion of size for infinite sets. According to that concept, a set A is smaller than a set B if, no matter how the ele-

COURTESY OF THE ARCHIVES OF THE INSTITUTE FOR ADVANCED STUDY

ADELE PORKERT and Gödel were an unlikely but devoted couple. This photograph, taken at an outdoor Viennese cafe, is from the period of their long courtship. Porkert shielded Gödel from the worst of his irrational fears and was often the only person who could persuade him to eat. More than anyone else, she was responsible for keeping him alive and productive.

ments of A are correlated in a one-to-one fashion with elements of B, some elements of B are always left over. Using this concept, Cantor proved that the set of natural numbers is smaller than the set of all decimal numbers. He further conjectured that no set has a size intermediate between those two—an assertion that came to be known as the continuum hypothesis.

In 1908 Cantor's compatriot, Ernst Zermelo, formulated a list of axioms for set theory. Among them was the axiom of choice, which states (in one version) that given any infinite collection of nonoverlapping sets, each of which contains at least one element, there is a set that contains exactly one element from each set in the collection. Though seemingly unobjectionable—why shouldn't one be able to select one element from each set?—the axiom of choice has a multitude of highly counterintuitive consequences. It implies, for example, that a sphere may be decomposed into a finite number of pieces that can be separated and reassembled, using only rigid motions, to form a new sphere having twice the volume of the first.

As a result, the axiom became highly controversial. Mathematicians suspected—correctly, as it turned out—that neither the axiom of choice nor the continuum hypothesis could be deduced from the other axioms of set theory. They feared that the use of those theorems in proofs might lead to contradictions. Gödel, however, proved that both principles are consistent with the other axioms.

Gödel's set-theoretic results answered a question that Hilbert had posed in 1900 in an address to the International Congress of Mathematicians. As such, they were a major achievement, but they were still not enough to earn him a permanent academic position. During his year at the Institute for Advanced Study and Notre Dame, his authorization to teach at Austrian universities lapsed. When he returned to Vienna to be reunited with his wife in the summer of 1939, he was summoned for a military physical and declared fit for service in the Nazi armed forces.

Deepening Fears

Until then, Gödel appears to have been aloof to the frightening developments in Europe. He was interested in politics and kept abreast of events but remained oddly unmoved by them. His lack of emotional engagement with people may have kept him from appreciating the significance of what was happening. He seemed oblivious to the fates befalling his colleagues and professors, many of whom were Jewish, and stayed immersed in his work while the world around him fell apart. Finally, he realized it was taking him down as well.

In that desperate situation, unemployed and subject to imminent induction, he enlisted the support of the Institute for Advanced Study to help secure exit visas for himself and his wife. His efforts were successful, and in January 1940 the two of them began a long journey eastward via the trans-Siberian railway. From Yokohama they continued by ship to San Francisco and from there by train to Princeton, where they arrived around the middle of March.

Gödel never again left the U.S. After a series of annual appointments he was made a permanent member of the institute faculty in 1946. Two years later he acquired American citizenship. (On that occasion, the judge who swore him in made the unfortunate error of asking his opinion of the U.S. Constitution and unleashed a pent-up lecture on its inconsistencies.) But Gödel was not promoted to professor until 1953—the same year he was elected to membership in the National Academy of Sciences—in part because his expressed fear that poison gases were escaping from his refrigerator aroused continuing concern about his mental stability. During those years, his friend Albert Einstein took it on himself to look after Gödel as best he could, taking a walk with him every

Undecidable Propositions

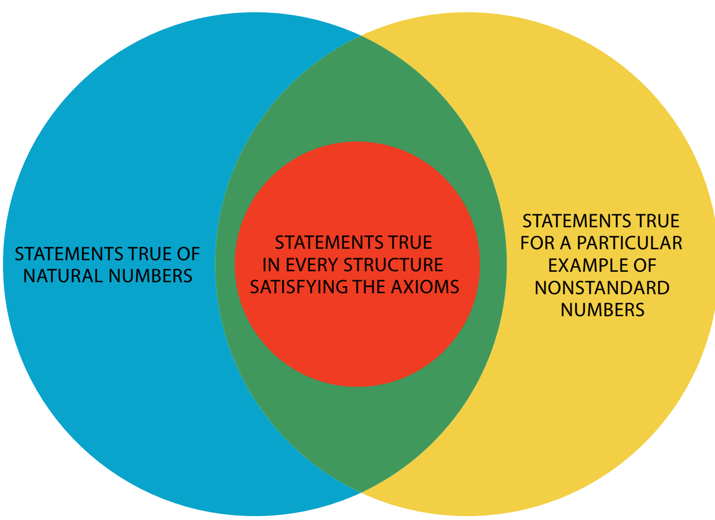
Gödel's most famous contribution was the proof that some statements about natural numbers are true but unprovable. Unfortunately, a long history of attempts to find statements that are undecidable—that is, neither provable nor disprovable—has led to few simple examples. One is the following sentence:

This statement is unprovable.

The above can be coded as a numerical equation according to a formula devised by Gödel. The equation is not provable and therefore affirms the meaning of the English-language proposition. That means, however, that the statement is true.

A less trivial example involves polynomial equations. One can state, for example, that a certain polynomial equation has no roots (that is, solutions) that are whole numbers. Such statements can turn out to be undecidable.

Gödel's proof demonstrated that the axioms of number theory are incomplete. That is, there are true statements about the natural numbers that cannot be proved by those axioms. His argument implies that "nonstandard numbers"—entities that obey the said axioms but have some properties that are different from those of natural numbers—exist. Because everything proved from axioms (*red*) must apply to all entities that obey the axioms, some true statements about natural numbers (*blue, green* and *red*) must be unprovable (*blue* and *green*). —*J.W.D.*



BRYAN CHRISTIE

day. Their conversations seem to have had a calming effect on Gödel.

After his emigration Gödel gave up work in set theory and turned to philosophy and relativity theory. In 1949 he demonstrated that universes in which time travel into the past is possible were compatible with Einstein's equations. In 1950 he spoke about those results at the International Congress of Mathematicians, and the next year he delivered the prestigious Gibbs Lecture to the annual meeting of the American Mathematical Society. But in the interval between those addresses he nearly succumbed to a bleeding ulcer, neglected until an extremely advanced stage because of his distrust of doctors.

Gödel's last published paper appeared in 1958. After that he withdrew more and more into himself, becoming increasingly emaciated, paranoid and hypochondriacal. He last appeared in public in 1972, when the Rockefeller University granted him an honorary doctorate. Three years later he was awarded the National Medal of Science but declined to attend the awards ceremony on grounds of ill health.

On July 1, 1976, having reached the mandatory retirement age of 70, Gödel became professor emeritus at the institute. His responsibilities did not lessen, though, because his wife, who for so many years had nurtured and protected him, had suffered an incapacitating stroke a few months before. It was his turn to care for her. He did so, devotedly, until July 1977, when she underwent emergency surgery and was hospitalized for nearly six months.

At about that time Morgenstern, the friend who had helped to look after Gödel in the years after Einstein's death in 1955, died of cancer. Gödel was thus left to fend for himself against his growing paranoia. In the face of that, he declined rapidly. His fear of poisoning led to self-starvation, from which he died on January 14, 1978.

COURTESY OF RICHARD ARENS

WALKS WITH ALBERT EINSTEIN on the grounds of the Institute for Advanced Study were part of the routine that kept Gödel functioning. This photograph is from 1954.

Adele Gödel survived her husband by three years. At her death, on February 4, 1981, she bequeathed rights to Gödel's papers to the Institute for Advanced Study. Although an outcast in Princeton's snobbish society, she was proud of her husband's work and probably realized that he would not have accomplished much had she not kept him functioning.

Gödel published remarkably few papers during his lifetime—fewer, indeed, than any other great mathematician except Bernhard Riemann—but their impact has been enormous. They have affected virtually every branch of modern logic. During the past decade, other papers of his have been translated from the obsolete German shorthand he used and published posthumously in the third volume of his *Collected Works*. Their contents, including his formalization of the so-called ontological argument for the existence of God, have begun to attract attention as well. At last, the breadth of his work is becoming known to those outside the mathematical community. SA

The Author

JOHN W. DAWSON, JR., catalogued Kurt Gödel's papers at the Institute for Advanced Study in Princeton, N.J. He has served as co-editor of Gödel's *Collected Works* since the inception of that project. He received his doctorate in mathematical logic from the University of Michigan in 1972 and is a professor of mathematics at Pennsylvania State University at York. He has a particular interest in axiomatic set theory and the history of logic.

Further Reading

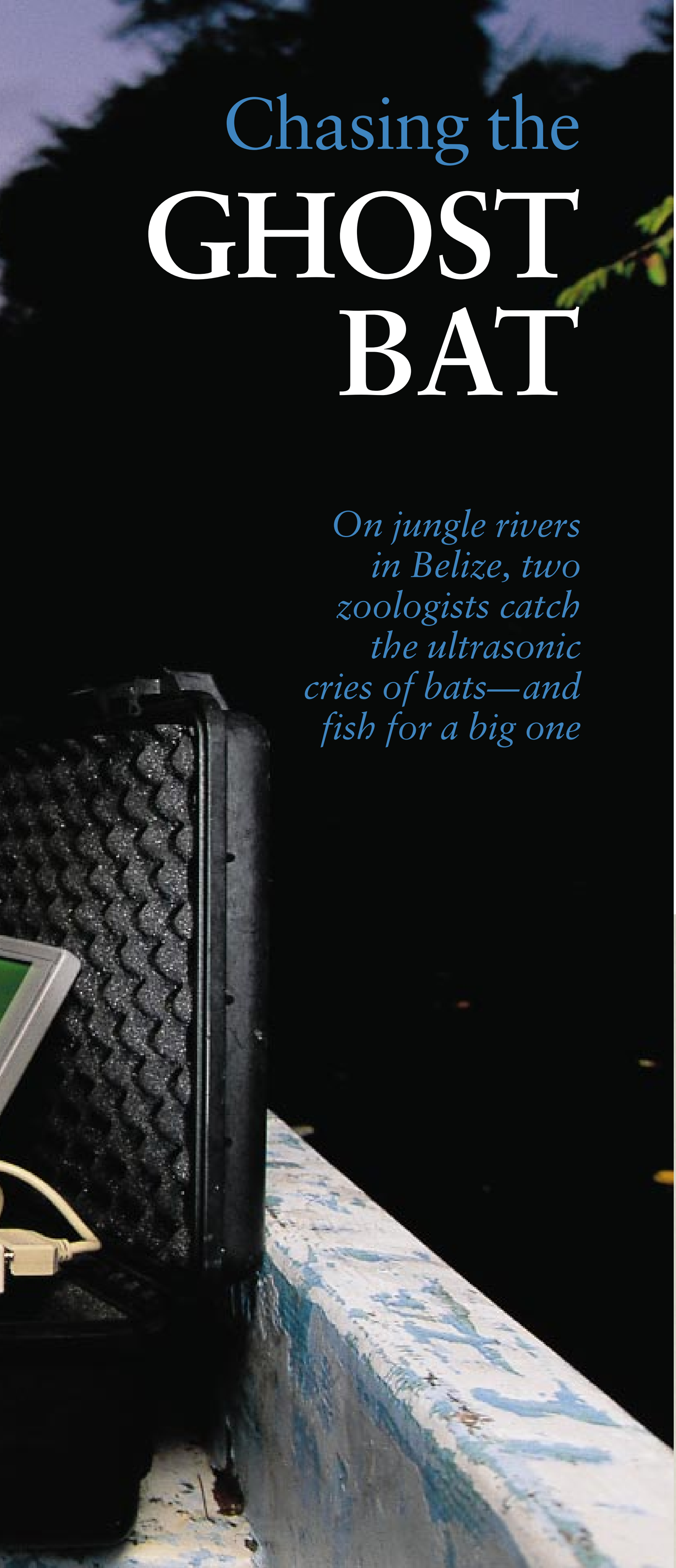
GÖDEL'S PROOF. Ernst Nagel and James R. Newman. New York University Press, 1958.

COLLECTED WORKS, Vols. 1–3. Kurt Gödel. Edited by Solomon Feferman et al. Oxford University Press, 1986, 1990, 1995.

LOGICAL DILEMMAS: THE LIFE AND WORK OF KURT GÖDEL. John W. Dawson, Jr. A. K. Peters Ltd., Wellesley, Mass., 1997.

GÖDEL, ESCHER, BACH: AN ETERNAL GOLDEN BRAID. Douglas R. Hofstadter. (Originally published by Basic Books, 1979.) Basic Books, 1999.


SYDNEY



Chasing the GHOST BAT

On jungle rivers in Belize, two zoologists catch the ultrasonic cries of bats—and fish for a big one

by Glenn Zorpette, *staff writer*

Photographs by Steve Winter

Off to the left of the narrow skiff, past the mangroves at the river's edge, the thick Belizean jungle is an indistinct black mass sliding by under a moonless, starry sky. In the chilly air a faint, salty scent signals that not far ahead lies the mouth of the Sarstoon River, with its treacherous shoals and maze of gill nets. To the right of the boat, the dim yellow lights of fishing huts wink like fireflies.

In the middle of the open boat, a few meters in front of its whining outboard motor, zoologist Bruce W. Miller wields a searchlight. He cuts long, sharp strokes in the gloom over the river. Beside him, his friend and collaborator Michael J. O'Farrell hunches forward on one of the skiff's hard seats. O'Farrell is bone-tired and muddy, and his entire nutritional intake today has been a mug of instant coffee and a few pieces of rye bread.

Suddenly, a large, light-colored bat flits into the bright beam, a ghostly night creature trapped in a sliver of brightness. O'Farrell snaps to attention, and as Miller struggles to keep the light on the dipping, swooping apparition, he and O'Farrell try to make out what species it is. But the animal vanishes, unidentified, within seconds.

O'Farrell sinks in his seat, crestfallen. Not two minutes ago he turned off his Anabat detector, a combination of software and a handheld device that turns an ordinary laptop computer into a sophisticated electronic ear that can record and display the ultrasonic cries of bats. From the shape of

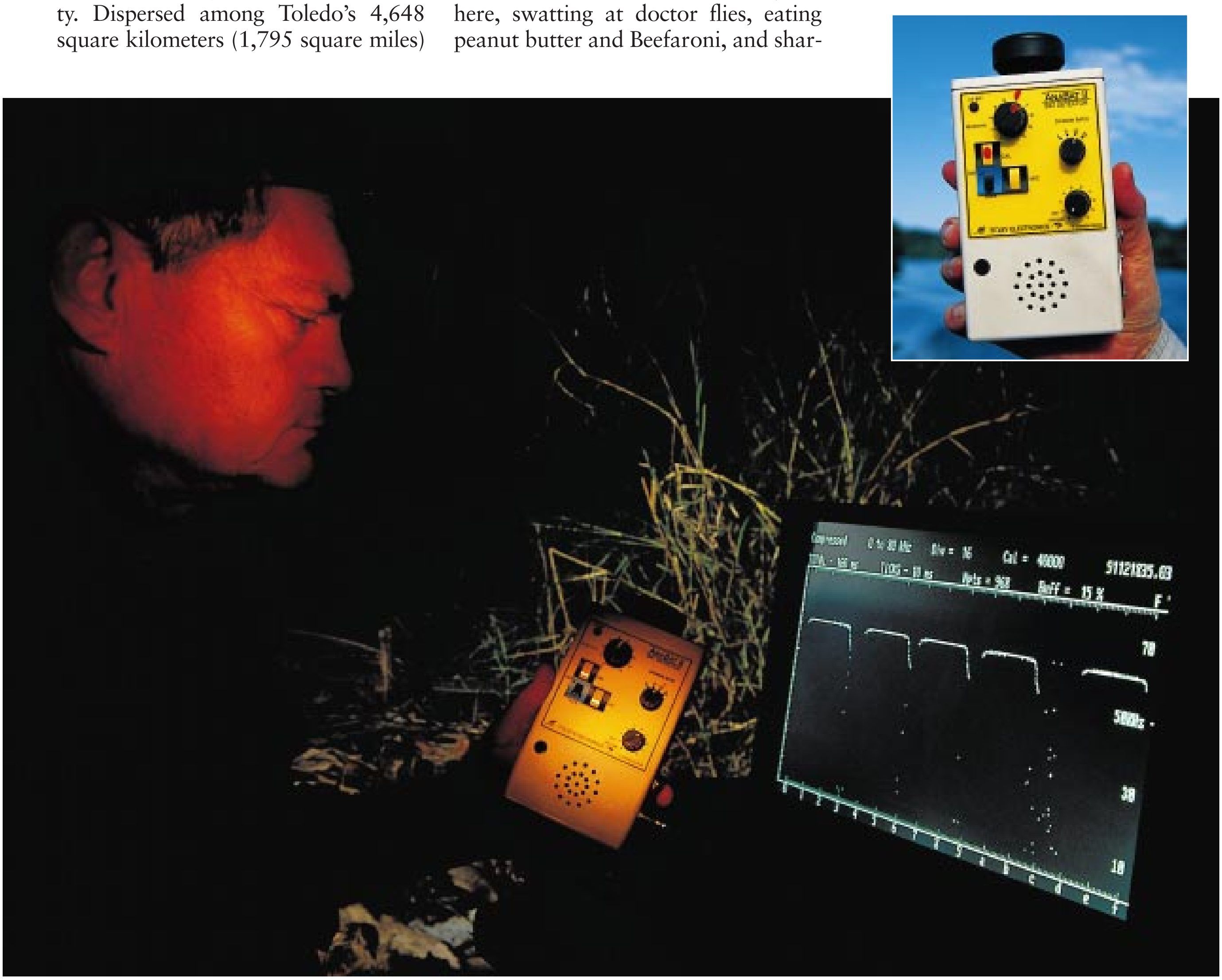
BAT MEN Michael J. O'Farrell (*far left*) and Bruce W. Miller record a bat's ultrasonic cry. The Anabat detector in O'Farrell's hand picks up the signals, which are analyzed in the small white box next to the laptop computer. Among the creatures they captured were common moustached bats, such as this one (*above*).

these calls, Miller and O'Farrell probably could have determined the species of the mystery bat.

And that, after all, is the main reason they have come to this corner of Central America. Belize is a naturalist's Eden, a nation the size of Massachusetts with fewer than a quarter-million people. But vast tracts of the country, including the entire southernmost Toledo district, have never been surveyed for their biodiversity. Dispersed among Toledo's 4,648 square kilometers (1,795 square miles) of jungle are one highway, a few roads, three small towns and a smattering of villages and camps. Like Commodore Matthew Perry arriving in Edo Bay, Miller and O'Farrell have come to the Sarstoon River to open up Toledo to biological surveying, starting with its bats.

Miller works full-time for the Wildlife Conservation Society, which is paying for most of the expedition. O'Farrell, a freelance biologist who makes his living mostly by surveying government lands for endangered species, paid his own way to be here, as he has four other times in as many years. In that time, Miller and O'Farrell have recorded and identified enough bats in Belize and the Americas to contribute six papers on vocal sequences and population distributions to such publications as the *Journal of Mammalogy*. By their own estimate, they have catalogued the ultrasonic calls of 68 percent of Belize's echo-locating bats.

But there are other reasons they are here, swatting at doctor flies, eating peanut butter and Beefaroni, and sharing a baffling chemical toilet with five other people. For one, the joy of being with a kindred spirit and doing something hardly anyone else can do in a place hardly anyone else has ever been.



ANABAT SYSTEM displays the strongest harmonic of a bat's ultrasonic call, plotting on a laptop screen that harmonic's frequency as a function of time. To the experienced eye, such as Miller's, the shape of this plot reveals the bat's species—this photo shows the peals of a common moustached bat. The detector (*inset*) picks up the ultrasonic signal and translates it into an audible sound.

Earlier in the day Miller and O'Farrell chugged several kilometers up the Sarstoon on the *Meddy Bemps,* an eight-meter-long former lobstering vessel. Miller peered through thick vegetation for little clearings in which they could set up their traps. In most cases, he and O'Farrell catalogue a bat's sound—"matching a voice to a face," Miller calls it—by catching the bat, releasing it and recording its emissions as it circles around near the detector.

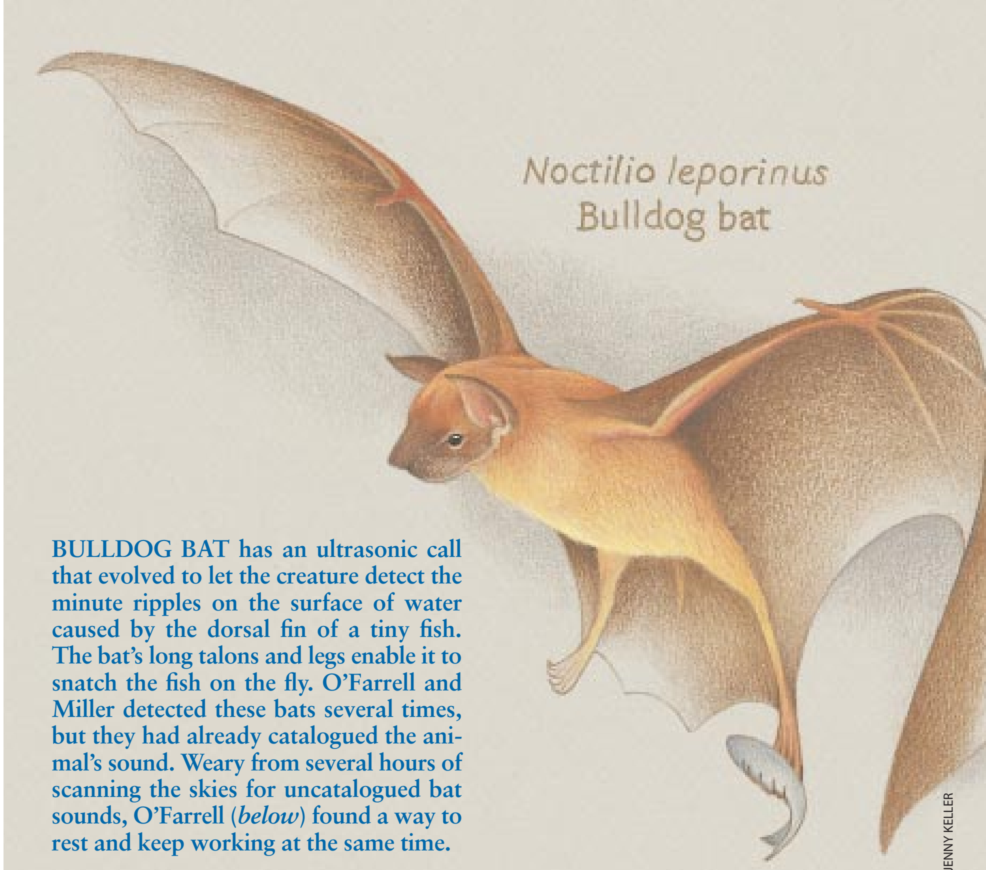
As the two men scanned the mangroves, Miller explained why the Toledo district is so important. The surrounding jungle, he said, is part of the Selva Maya, the largest block of contiguous tropical forest north of the Amazon. "Belize is a critical link because it's basically undisturbed, and you can have genetic interchange among the critters" through this forest from southeastern Mexico to Panama. Such liberty keeps gene pools from stagnating.

To protect the wildlife from human encroachment, scientists must know which species live here and which ones are truly in trouble. And Belize's 87 known species of bats, Miller explained, account for more than half of the country's mammalian diversity. In addition, he noted, bats play fundamental roles in the forest ecosystem. On a typical night the average insect eater can consume more than 1,000 bugs, including many that would otherwise harm vegetation. Fruit eaters drop seeds as they fly across open areas, stimulating reforestation. And bat guano is manna to the plant kingdom.

But Miller and O'Farrell also admitted that they would hate to leave Toledo without expanding their catalogue by matching at least one more voice to a face. After all, they are in an area that has never been surveyed, and it's quite possible that species that are rare up north are common here.

Saccopteryx leptura, the lesser white-lined bat, would be very nice. They are pretty sure it lives in Belize, and if they can confirm its vocal signature, they would have all the species of the genus *Saccopteryx* that are known to live in Belize. And once they nail down *Pteronotus gymnonotus,* the big naked-backed bat, they will have the vocal calls for all the mainland members of the family Mormoopidae.

They could not know then, of course, that their expedition would become a quest for a large white bat, a ghostly, flittering Moby Dick in miniature.



BULLDOG BAT has an ultrasonic call that evolved to let the creature detect the minute ripples on the surface of water caused by the dorsal fin of a tiny fish. The bat's long talons and legs enable it to snatch the fish on the fly. O'Farrell and Miller detected these bats several times, but they had already catalogued the animal's sound. Weary from several hours of scanning the skies for uncatalogued bat sounds, O'Farrell (*below*) found a way to rest and keep working at the same time.

JENNY KELLER

Later that day, after a two-hour search, Miller and O'Farrell found a suitable clearing and set up the traps. The four-meter-tall devices are called harp traps because they snare bats between two sets of vertical monofilament lines [*see photograph on next page*].

In the rosy glow just before sunset, the scientists prepared for the night's work. They transferred their gear to the skiff, and motorman Keith Mahler piloted it upriver, keeping near the mangrove-lined bank. O'Farrell, in safari shirt and headlamp, waved the Anabat detector toward the forest. Miller panned the searchlight across a riot of big cohoun palms, provision trees and calliandra beyond the mangroves.

Within minutes, they picked up a bulldog bat, a freetailed bat and a couple of common moustached bats. The Anabat squeaked, chirped and clicked, drawing horizontal lines or scattered dots on the laptop screen as it rendered the bats' ultrasonic squeals for human ears and eyes. To Miller and O'Farrell, intent in the bluish glow of their laptops as their little skiff floated down the pitch-dark river, the squiggles, lines, dots and curves told compelling stories of bats commuting, hunting, feeding and even fishing.

Suddenly, they picked up a short, mysterious signal at around 22 kilohertz, a signal they had seen before but had not yet matched to a "face." "Chances are it's one of the bigger freetails," O'Farrell declared. They detected the call several more times, then checked the traps. In the pouch lay two Mexican funnel-eared bats, a common moustached bat and a Thomas's fruit-eating bat. Back in the skiff, Miller and O'Farrell observed and measured the bats, penciling their findings in a notebook by the light of their headlamps.

JENNY KELLER

HARP TRAPS (*right*) snare bats between two sets of monofilament lines. As they fly toward the lines, bats detect the closer set but cannot pick up the set behind. They turn to fly past the first group but collide with the second and fall unharmed into the canvas pouch. The greater white-lined bat (*above*) never wound up in the researchers' traps; they also missed the more elusive lesser white-lined bat.

Despite the activity, O'Farrell said it had been a quiet night. "We should be picking up long-nosed bats, white-lined bats. We should be getting yellow bats and big brown bats," he complained. But he was intrigued by the 22-kilohertz calls. "We're trying to lay it off on Molossidae," he mused, referring to one of the nine families of bats in Belize. "But we could have one of the big-ass Emballonurids flying overhead."

In half an hour or so he would see a compelling piece of evidence—large and white, flapping over the skiff near the mouth of the Sarstoon. Too bad he would turn off his bat detector minutes before the bat flew overhead.

Mahler zigzags past the gill nets blocking the Sarstoon's mouth and heads toward Amatique Bay. Somewhere out there is the 15-meter ketch *Tempest,* which will be home for the next week if Mahler can find it. As Miller's teeth begin chattering from the damp cold, Mahler homes in on a faint light in the distance. Miller is in luck; it is the *Tempest*.

The next evening they set up the detectors on the ruins of what was once a refreshment stand. Tonight's aerial show features more "feeding buzzes." As an insect-eating bat swoops in on its prey, it increases the rate of its ultrasound pulses until the emissions, as heard through an Anabat, become a short, sharp buzz. The creatures also instinctively shift the pitch of their calls when they are in the company of other bats of the same species, so that they can distinguish their own echoes.

As the evening wears on, the researchers detect a greater white-lined bat, as well as moustached bats, freetailed bats and the mysterious 22-kilohertz signal. Then something different: an unknown member of the family Vespertilionidae, with a signal rising to 58 kilohertz.

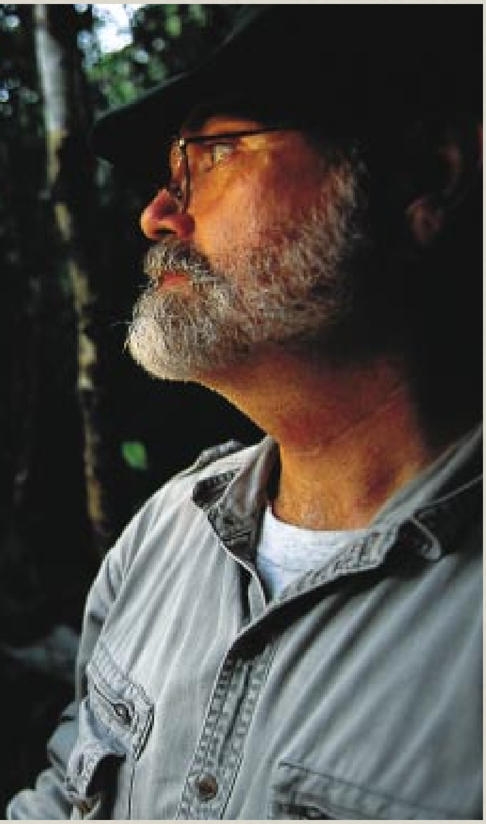
The following morning O'Farrell holds forth below deck on the *Tempest*. He is perhaps the only person in the world possessed of bountiful bat blarney. There was the time in the summer of 1994, he recounts, when he and Miller were surveying bats in Punta Gorda, Belize. Their innkeeper told them that he had seen bat heaven, and it was in the attic of a military building across the street. The next day a Belizean sergeant and half a dozen soldiers set up a tall iron ladder so that O'Farrell could see what species of bats were living in that attic before recording their calls.

After climbing up, O'Farrell found that the hatch to the attic was held down firmly, apparently by the weight of many, many years' worth of bat guano. "I was tapping it, and a little guano was coming out along the edges. I said, 'Hang on, guys, I'm really going to hit this.' Just as I said that, Bruce said something about everybody looking up, so they did." O'Farrell slammed the hatch with all he had, and "about a ton of guano came down. I looked down and saw all these black faces and white teeth."

But he and Miller had hit pay dirt, so to speak. Inside the attic were black mastiff bats—thousands of them. It was a simple matter to record them that evening as they popped out under the eaves of the building's tin roof. Presto: another entry in their catalogue of bat calls.

It looks like they will have no such luck today, though. The traps have snared only a single fruit bat. As they pack up the traps, talk gets around to O'Farrell's neighbors, who, he says, envy his adventures in the bush. "I tell them, 'Well, you know, it's not *all* glamour,'" he chuckles, as he swats doctor flies away from his mud-spattered clothes.

It is time to move on to the Temash River, about nine kilometers north. The brief trip along the coast gives the two time to discuss their use of electronic detectors in bat surveying, which is still somewhat controversial. In fact, the only



other researcher using the technique in Central America is Elisabeth Kalko of the University of Tübingen in Germany, who uses a custom-built system.

Anabat, which is commercially available, records and displays only the strongest harmonics of a bat's call. Some critics charge that these dominant harmonics are not enough to distinguish two species of the same genus. Supporters such as Miller retort that all it takes is sufficient practice.

Last year O'Farrell submitted to a three-day blind test conducted by the U.S. Forest Service. Asked to distinguish several species of *Myotis,* he scored 66.7, 76.4 and 84.3 percent correct. A control group—of some graduate students who attempted to identify the same bats using statistical methods—did not score above 68 percent.

"It's almost arrogant to say so," Miller volunteers, "but the technique, as we use it down here, is going to revolutionize the way people sample in the tropics." Traditional bat-surveying techniques, he explains, use only harp traps and mist nets. Neither do well at snagging high flyers, such as Molossidae.

Some bat researchers, however, grumble about Miller's and O'Farrell's refusal to release their huge catalogues of Anabat recordings. "It's not that we're unwilling to share," Miller insists. "If [other zoologists] don't have the experience to understand the data, it's not going to help them very much in the beginning. They could misapply the data."

Asked whether sharing the files wouldn't make it easier for more people to get started with the Anabat, O'Farrell argues it would not. Not having the files, he argues, "forces you to go through the same process we go through when we go into a new area—to have to lay hands on the animal and record the calls. It allows you to develop an intuitive feel that's very important."

Michelle Evelyn, a graduate student at Stanford University, says she asked for access to O'Farrell's files and was denied. She later paid $250 to take a two-day Anabat seminar with O'Farrell, biologist William L. Gannon and Chris Corben, the Anabat's inventor. She now defends Miller's and O'Farrell's unwillingness to share their large catalogues of Anabat records. "It's their library, and they spent five years building it. This is totally brand-new stuff, and they're at the forefront. They're publishing their findings; it's not like they're keeping their results secret." Miller and O'Farrell pledge that in time, they will make most of their recordings available, probably through a publicly accessible database now being created at the University of New Mexico.

Motoring 13 kilometers up the Temash, Miller finds only a single spot near the river with enough room to squeeze in the harp traps. The only sign of humanity occurs around midday, when half a dozen people speed by in a motorboat on their way to Crique Sarco, a settlement 30 kilometers upriver.

A full night's work nets just 29 Anabat files and nothing in the traps. But the quiet evening turns hairy on the ride back to the *Tempest*. As the skiff passes from river to sea, a strong wind and two-meter swells toss it, flooding its bottom. In the bow, O'Farrell sweeps the searchlight so Mahler can see the big upcoming waves. Miller, meanwhile, eyes the lamp nervously. Any water splashing on the hot light will shatter it, ending the expedition. Without illumination, the pitch-dark river is impossible to navigate.

As the skiff pulls alongside the *Tempest,* the waves shove one boat up violently as the other plunges. Mahler yells orders from the rear, and the scientists rise unsteadily to their feet, clutching their laptops. As the boats shoot by each other vertically, Captain Tom Bright of the *Tempest* leans over at just the right moment to deftly grab pieces of gear. At last Miller leaps to safety. O'Farrell follows, thanks in part to an adrenaline-fueled upward shove from a reporter.

On board the rocking and bobbing *Tempest* an hour later, Miller looks worn out. The reason isn't so much the wild ride or his dinner of beer, rice, canned tomatoes, bread and peanut butter. The day had turned up only "the usual cast of characters," he says. Their chances of extending their catalogues are dwindling. They have only two more nights to try before they must turn the *Meddy Bemps* over to another group of researchers.

The next day they decide to go deep upriver on the Temash, too far to come back to the *Tempest* at night. Sleeping on the hard decks of the *Meddy Bemps* is evidently a more appealing prospect than finishing the expedition without any new voiceprints for their catalogues.

Upriver that night, they decide to split up, each with a bat detector. O'Farrell cruises upriver on the skiff; Miller remains on the *Meddy Bemps*. O'Farrell's Anabat soon starts

MEDDY BEMPS **was once a lobstering boat in Maine. Miller and O'Farrell often spent afternoons on the boat scanning the riverbanks for clearings where they could set up their traps.**

to chatter as a trio of black mastiffs flutters right over his head in the fading light. The signals come faster and faster until it is clear that O'Farrell is in a "hot spot"—a cloud of insects on which groups of bats are gorging. The data are coming fast and furious: yellow bats, mastiffs, doglike bats and both species of white-lined bat—greater and the elusive lesser—at the same time. Over the next 45 minutes, he also picks up a few signals they haven't yet matched to "faces," squeals that appear to be from a Molossid of some kind and then a member of the family Vespertilionidae. "I have no idea which one," he comments. Then another doglike bat and an unidentified Emballonurid. The creature must be something unknown to Belize, O'Farrell says, because he and Miller thought they had accounted for all the Emballonurids known to live in the country. "We've got to lay hands on these puppies," he adds.

"Whoa!" he yells, after the Anabat crackles yet again. "There's our 22-kilohertz guy, giving us more behavior. That's just what I need."

The frenzy dissipates briefly and then builds to another crescendo as more bats swoop in for supper. Whatever is emitting the 22-kilohertz signal returns for seconds. Still, "our chances of identifying this guy on this trip are slim to none," O'Farrell says. They would have to catch the bat to prove it is the 22-kilohertz caller, and the odds of finding it in the traps are poor.

As the pace quickens, the 22-kilohertz signal sounds through the night several times, discernible only to bats and Anabats. Mahler beams the searchlight into the skies, hoping to spot the animal. Suddenly, he lights up a large white creature, about 15 meters away, flapping toward the palms. "Whoa!" O'Farrell shouts, eyes wide behind wire-framed glasses, veins popping out on his neck. "Look at that! Look at that! He's *white!*" The striking color and the shape of the 22-kilohertz signal, which appears to be that of an Emballonurid, suggest to O'Farrell that the bat is *Diclidurus albus,* the northern ghost bat.

"Nobody has been able to 100 percent identify *Diclidurus,* face and voice," he explains, after he has calmed down a bit. "Elisabeth Kalko in Panama has gotten signals and seen him in a spotlight, like we just did. She's published on hers, but she couched her terms, because she hasn't laid hands on the animal."

At 8:00, on the way back to the *Meddy Bemps,* O'Farrell tallies up the count: in about two hours, he has logged 183 files. Some bats were surely recorded more than once as they circled the area. Nevertheless, a stunning evening.

O'Farrell can hardly contain himself as the skiff approaches Miller on the *Meddy Bemps.* "Oh, boy, Bruce," he begins.

"We got 90-kilohertz Emballonurids," Miller responds.

O'Farrell plays his trump card: "How about a large white bat?"

Miller, absorbed by his laptop screen, seems unmoved. "Mmmm hmmm."

"It's our mystery 20-kilohertz guy," O'Farrell presses on.

"The twenty-two?" Miller says, suddenly very interested.

"That's the guy!" O'Farrell exults.

A moment later Miller is raving about their good fortune. "We've got Emballonurids out the wazoo," he says. "This has been just killer. Everything you could imagine."

The traps have snagged only a single fruit bat, but the paltry catch does nothing to dampen the researchers' spirits. Sitting together in the stern of the *Meddy Bemps,* as crickets shriek through the forest, they toast the evening's success with warm Belizean beer and review their records of the big white bat.

"Jesus, did we get bats tonight?" Miller asks.

But O'Farrell is a little worried. "Elisabeth was saying hers was up around 30?" he asks, meaning kilohertz.

"That's what she told me," Miller responds.

"I'd hate to prove her wrong," O'Farrell says, earnestly.

"Well, there are several species of *Diclidurus,*" Miller notes. "But the one collected here [in Belize] was *albus.*"

"We have finally hit pay dirt," O'Farrell concludes.

"This is not only the frosting on the cake," Miller agrees, "this is the candles on the cake."

At dawn the next day Miller already has the white bat on his mind. "We have to nail ourselves *Diclidurus,* that's for sure," he says.

During the trip back to the *Tempest,* a gentle rain begins to fall. Between sips of coffee on the ketch, Miller confesses his preoccupation: "This is more exciting than I had anticipated. I thought we would get *leptura* [the lesser white-lined bat]. But the ghost bat never entered my mind."

Through a downpour, the scientists motor back to the same sharp bend in the Temash where the ghost bat made its third ephemeral appearance. By 5:30 the skies have cleared, and O'Farrell is heating bags of curried lentils on the *Meddy Bemps*'s engine manifold. Miller, meanwhile, sets up an ultraviolet light to attract moths. Inland, the sky glows pinkish-purple. A flock of Montezuma's Oropendolas flies through the moist air. Howler monkeys roar at the approaching darkness.

Because Miller and O'Farrell know what they want, and because this evening will be their last in Toledo, they

DUSK ALONG THE SARSTOON RIVER found Miller (*left, below*) and O'Farrell setting up their bat-detection gear for the evening's work. A couple of nights later along the Temash River, about nine kilometers north, they recorded the calls of the magnificent northern ghost bat (*right*).

DAY'S END was when the researchers and motorman Keith Mahler set off in the skiff on the nightly search for bats.

decide to forgo the traps and "fish" for the great white bat. They'll bait a hook with a moth and wave it off the end of a long fly rod. With a great deal of luck, they may snare the bat's wing as it tries to sweep the insect into its mouth. The injury to the wing is minor, not unlike the tears the creatures commonly receive as they fly through the bush.

The first 22-kilohertz call arrives at 6:24. Thirteen minutes later there is another. "That's our guy, and he's jumping around," O'Farrell says. "He's starting to vary his calls."

"I'm getting a moth on," replies Miller, up on the bow. "We've got both *Diclidurus* and yellow bat," O'Farrell announces. Seconds later Miller snags a bat on the line, but it's the yellow. He frees the creature, and it flutters away, apparently unharmed. Miller turns for more bait to the huge assortment of moths, flying ants and flies crawling around under the ultraviolet light he's set up on the roof of the boat.

"Biggest-ass moth you can get," O'Farrell suggests.

"I see him, he's up high," Miller reports, as he waves the pole gently, the hooked moth fluttering from the end of its short line.

"He is feeding, he's active," O'Farrell replies, holding the Anabat detector aloft and staring at the laptop screen. "Whoa! He's throwing harmonics up"—aiming a wider ultrasonic signal at the moth to examine it in more detail. "He's foraging! Two good feeding buzzes, Bruce. We've seen just a beautiful amount of this guy's repertoire."

Miller switches bait, to a sphinx moth, an insect about as big as a hummingbird. The moth is so fat Miller can't get the hook all the way through its abdomen, which makes it less likely to snare a bat. Finally, the ghost bat swoops toward the bait but, puzzlingly, does not attack it.

With bugs crawling on his face, Miller looks like a character in a Clive Barker movie. But his attention remains fixed on the white bat, which flutters just out of reach. "I've eaten about half a pound of bugs up here," he gripes. "But it will be worth it if we get him." A note of dejection has crept into his voice.

And indeed, before long the big white bat vanishes into the jungle. Miller climbs down from the bow, blinking midges and gnats from under his eyelids. The white bat eluded them this time, but its vocal repertoire is imprinted permanently on their hard disks. That alone warrants several rounds of rum, drunk out of plastic cups until the wee hours.

Ashore at Placencia the next day, they wait for a taxi in the shade of some palms near the dock. "To have laid hands on it would have been a showstopper," O'Farrell says ruefully of the white bat. Nevertheless, both biologists seem fairly certain it was *Diclidurus albus*. "You can't be 100 percent positive," O'Farrell allows. "It may turn out to be a completely different bat, one only known from South America."

Miller now is headed back to Gallon Jug, Belize, to work on his Biodiversity Information System and other projects. O'Farrell returns to Las Vegas and his consulting business. But they will both probably dream about the great white bat that got away.

They're already planning a trip to Venezuela—it's big, absolutely bat-filled and, like most of Latin America, never explored with an Anabat. Who knows? Maybe they'll even find a few ghosts. SA

JENNY KELLER

by Shawn Carlson

Expert Secrets for Preserving Plants

The museum of natural history nearest you probably harbors an impressive collection of local plant life. Across the U.S., these archives provide an excellent physical record that current and future biologists can use to track how native plants have fared in response to natural and human forces. Historically, amateurs have played a key role in shaping the botanical record, most notably since the Northwest expedition of Meriwether Lewis and William Clark, who preserved and returned hundreds of plants that were then unknown to science. Today each new summer brings an army of botanical enthusiasts scouring the countryside, searching for fascinating flora.

To aid budding botanists, I thought I'd share some museum tips for specimen preservation. You can use these techniques to help add to the official record or simply to engage your family in a rewarding outdoor adventure. Just don't run afoul of the law. Whether on private or public land, collect only if you have permission to do so from the authority responsible for the property.

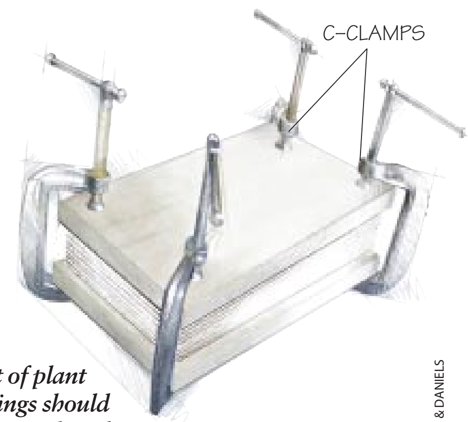
Specimen preservation begins in the field. I suggest photographing each plant before cutting it to keep a record of it in its natural setting. Also, mark on photocopies of a topographical map the exact locations of your finds. Paste these sheets into your field notebook. If the plant is under 15 centimeters (six inches) tall, collect the entire thing, roots and all. Otherwise, cut off a representative part, including flowers, fruits and any seed pods, which can often identify a plant better than its leaves. Tag each specimen with a small paper tab and record in your notebook the species' common name and scientific name if you know it, the date, and any details that a future botanist may need to know. Until you have finished your day's collecting, keep your cuttings hung upside down in the shade to minimize any crimping of their stalks as moisture begins to evaporate from their tissues.

Because cut plants deteriorate quickly, process them as soon as you get home. Begin by dipping each specimen in warm and slightly sudsy water, followed by gentle agitation in clean water to remove the soap. This process will kill bacteria and dislodge tiny crawlers. Thoroughly dry the foliage by blotting it with a paper towel.

Plants are best preserved by pressing and drying them. Begin by placing three layers of paper towels on top of a stiff board that measures about 30 by 45 centimeters (12 by 18 inches). Then gingerly lay out your cleaned plant, making sure to display different views (front and back) of its leaves. Large flowers should be split with a sharp knife and opened flat with their internal parts face up. Place three more layers of paper towels on top, followed by a sheet of corrugated cardboard and three additional layers of paper towels. Then lay out your next specimen. You can stack up to 10 cuttings this way.

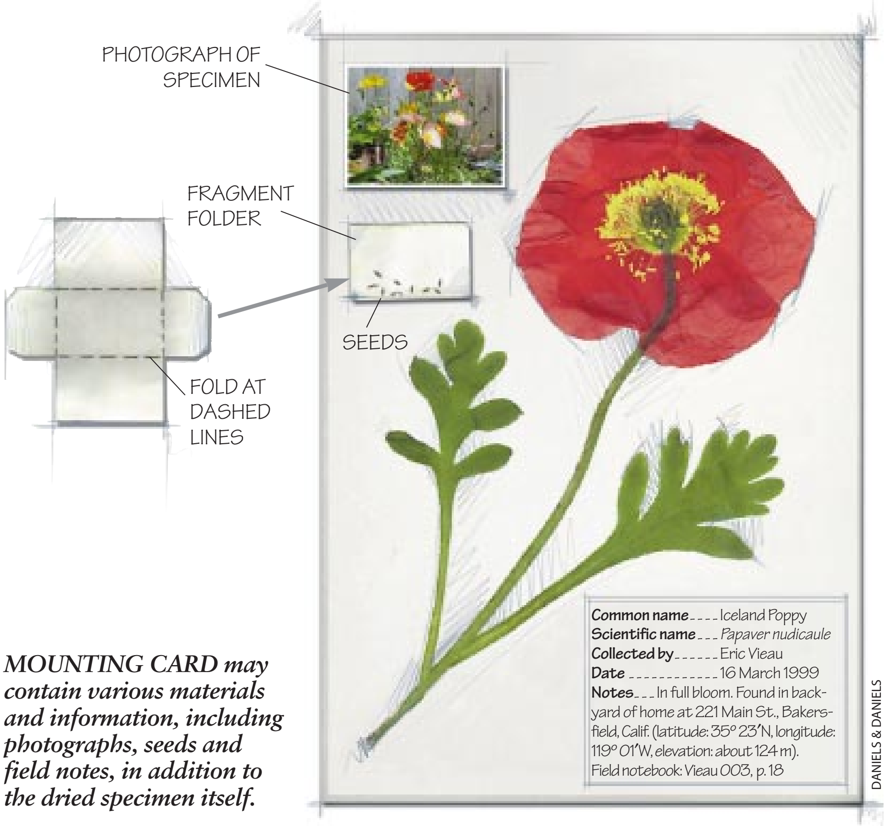
Place a second stiff board on top of the stack and apply steady, firm but gentle pressure to drive water out of the plant tissue and into the absorbent paper. Use a weight or four large C-clamps positioned near the corners. Or if you prefer, you can buy a professional press from a biological supply house. One of the largest is BioQuip in Gardena, Calif. (310-324-0620; product no. 3115; $40). Or check out Fisher Science Education in Burr Ridge, Ill. (800-955-1177; product no. CQS17670; $30).

Store your press on a warm, sunny windowsill. You'll need to refresh the paper every few days depending on how much water your specimens contain. Most cuttings do well with paper chang-



HOMEMADE PRESS drives water out of plant tissue, preserving the specimens. The cuttings should be layered between paper towels and corrugated cardboard (left). *C-clamps* (right) *help to secure the setup.*

DANIELS & DANIELS



***MOUNTING CARD** may contain various materials and information, including photographs, seeds and field notes, in addition to the dried specimen itself.*

es every two or three days, and they dry completely in about three weeks. But thick, fleshy leaves require daily replacements and can take four weeks to dry. Next, to kill any remaining tenacious pests, place the dried plants in a plastic bag and consign your collection to a freezer for at least three days.

Museum herbariums mount their specimens on cards measuring 29 by 42 centimeters (11½ by 16½ inches). BioQuip sells paper cards of that size for $1.70 per dozen (product no. 3135), and a buffered acid-free rag variety goes for $4.25 per dozen (product no. 3137). Fisher's price is $29 for 100 sheets (product no. CQS17676A). For those on a limited budget, ordinary card stock, though much smaller, works well and is available for under $10 in reams of 250 sheets from any office supply store. But if you want your collection to be studied one day by botanists yet unborn, stay with acid-free paper.

Because dried plants are quite brittle, use extreme care when mounting them. Dilute some white glue by about one third with water and smear a thin layer onto a cookie sheet. Coat the backside of your specimen by gently settling it into the liquid. Delicately remove the plant, blot it on a sheet of newspaper and position it onto the mounting card. Dab all parts of your specimen with a paper towel to remove any excess glue. Place a sheet of wax paper and cardboard on top and use your plant press to secure the arrangement until the adhesive sets.

Although my early efforts using ordinary Elmer's white glue have held up nicely now for some 25 years, most professionals rely on a concoction they call "botany paste." BioQuip sells two-ounce containers for a little over $3. (By the way, if you know a recipe for this substance, please share it on the Web-based discussion area for this project at the address given below.)

Transfer all the relevant information about each specimen from your field notebook to an acid-free paper label and glue it to the mounting sheet. Seeds and other loose parts can be stored by inserting them into thumb-size paper envelopes, known as fragment folders, which can then be glued or stapled to the sheet. You can easily make your own folders, or you can buy them precut from BioQuip in packages of 100 (product no. 3211BA; $15). And don't forget to include any photographs you took, which can be glued directly to the mounting cards. If the old adage is correct, each picture could save you a thousand words of exposition.

Last, you'll need to store your collection. My cuttings are organized inside loose-leaf picture albums that I keep inside two nested plastic trash bags. The specimens are contained within the innermost bag, which is tightly sealed. A fumigant bundle made of moth flakes wrapped in cheesecloth sits inside the outer bag next to the opening of the inner bag. Changing the moth flakes every six months or so has kept away pests.

Living near an ocean allows me to collect sea plants. These organisms, however, present two special challenges. First, a plant that has washed up onto the beach is often long dead and is probably already home to thriving colonies of bacteria. But sea plants are quite tough and can tolerate rougher handling than their land-bound cousins. So, as soon as I get them home, I submerge them in hot and very soapy water for 10 minutes to suppress any bacteria.

The second problem is more subtle. Seaweed, if treated in the usual way, will rot. That's because the salt in its tissues absorbs moisture directly from the air. Thus, the plant remains perpetually wet. Fortunately, the salt can be leached easily away by a thorough soaking in distilled water. Pour into a basin at least 50 times more water by weight than the plant and let things sit for eight hours. Then do it all again. Adding a few drops of bleach each time will help keep new colonies of bacteria from taking hold while the salt diffuses out of the cells.

Once disinfected and thoroughly leached, seaweed can be pressed like any other plant. Rather than spreading out the foliage by hand, however, try arranging the plant while it is still floating in the basin. Gently scoop a sheet of card stock underneath the seaweed and carefully bring them both out of the water together. This technique captures the plant's natural motion, creating a more beautiful and realistic-looking specimen. SA

The author gratefully acknowledges informative conversations with Judy Gibson of the San Diego Natural History Museum. *For more information about this and other projects from the Amateur Scientist, check out the Society for Amateur Scientists's Web page at www.thesphere.com/SAS/WebX.cgi. You may also write to the society at 4735 Clairemont Square, Suite 179, San Diego, CA 92117, or call 619-239-8807.*

by Ian Stewart

Crossed Lines in the Brick Factory

One of the charms of mathematics is how some very simple problems can baffle the best brains in the world for centuries. Examples include Fermat's last theorem, Kepler's conjecture and the four-color conjecture, all of which have been solved by mathematicians only in the past few decades. The four-color conjecture in particular attracted a lot of attention from recreational mathematicians, and it was in some ways a pity when it was proved, because a source of apparently endless fun had dried up. Given all the recent progress, it might seem that there are no interesting challenges left for the amateur to have a go at—but this is not the case, as we shall see.

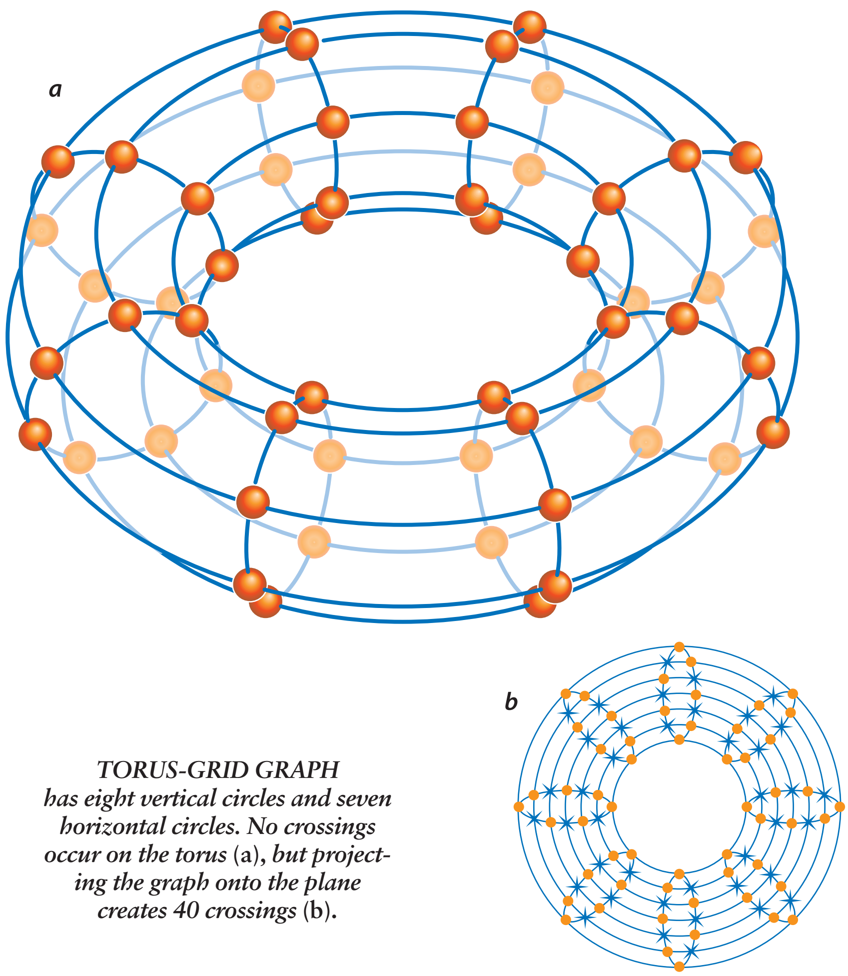
First, a few words about the four-color conjecture, which was originally posited about 150 years ago. The conjecture states that only four colors are needed in any two-dimensional map to ensure that no adjacent regions are colored the same. It was proved with computer assistance in 1976 by Kenneth Appel and Wolfgang Haken of the University of Illinois. The four-color theorem, as it is now called, belongs to the branch of mathematics known as graph theory. A graph is a collection of "nodes," represented by dots, joined by "edges," represented by lines. A two-dimensional map can be drawn as a graph—simply mark a node for each region on the map and draw edges between the nodes that represent adjacent regions. So the four-color problem can be rephrased as a question about coloring the nodes of the appropriate graph.

Graph theory is a source of numerous problems that are easy to state but tricky to prove. Many such problems concern the crossing number of a graph: the smallest number of times that two edges cross each other for a given number of nodes. (The edges must cross each other at isolated points.) In 1970 mathematicians Paul Erdös and Richard K. Guy wrote: "Almost all questions one can ask about crossing numbers remain unsolved." That remark is equally true today. It is very hard to prove much about crossing numbers, but recreational mathematicians can get a lot of pleasure from experimenting with various graphs and trying to reduce the number of crossings. It is conceivable that such experimentation might disprove some outstanding conjectures by yielding a graph with a crossing number that is less than the expected value.

Graphs with a crossing number of zero are fully explained by Kuratowski's theorem, which was proved by Polish mathematician Kazimierz Kuratowski. Such graphs are planar—the edges connecting the nodes do not cross one another at all. Consider the first graph on page 96, in which 10 edges connect 10 nodes. The edges cross each other four times, but in fact the graph is planar because the edges and nodes can be moved around so that the nodes form a ring and all the crossings are eliminated. This graph is called a cycle of 10 nodes and is denoted by the symbol C_{10}. Similar graphs with n nodes are called C_n.

Now consider the second graph, which is called a complete graph with five nodes. The 10 edges in this graph join each node to all the others. The graph is denoted by the symbol K_5, and analogous complete graphs for n nodes are called K_n. K_5 is not planar—no matter how the nodes and edges are rearranged, there will always be at least one crossing. Therefore, K_5 has a crossing number of one.

BRYAN CHRISTIE



TORUS-GRID GRAPH has eight vertical circles and seven horizontal circles. No crossings occur on the torus (a), *but projecting the graph onto the plane creates 40 crossings* (b).

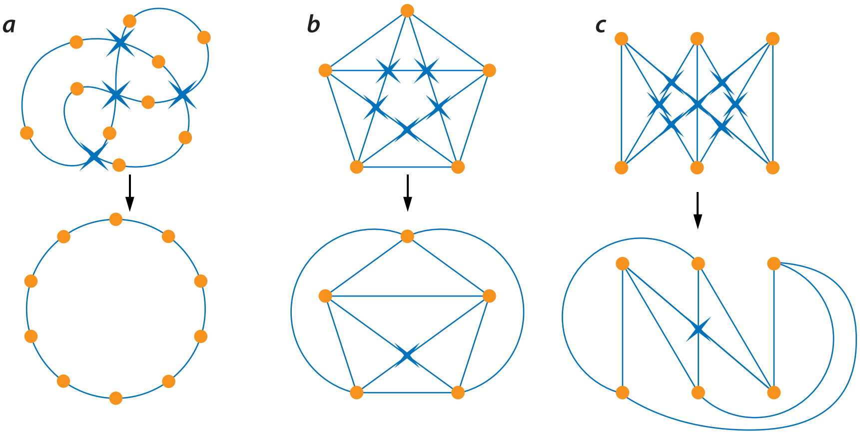
The third graph is an example of a complete bipartite graph. It has two sets of three nodes each, and each node in one set is joined to all the nodes in the other set. The symbol of this graph is $K_{3,3}$; it also has a crossing number of one. Similar bipartite graphs can be defined: if there are m nodes in one set and n nodes in the other, the graph is denoted by $K_{m,n}$.

The concept of crossing numbers arose in 1944, when Hungarian mathematician Paul Turán was working in a brick factory outside Budapest. The factory had a number of kilns where the bricks were baked and a number of storage yards. Railroad tracks ran from each kiln to each yard. Workers put the bricks onto a small truck, pushed it along the rails to a yard and then unloaded it. This task was relatively easy except where one set of rails crossed another. At the crossings the truck would often jump the rails, and the bricks would fall out.

An engineer probably would have considered how to redesign the crossings. Turán, being a mathematician, wondered how to create as few crossings as possible by redesigning the layout of the rails. After a few days he realized that there were unnecessary crossings in this particular factory. But the general problem continued to intrigue him. With m kilns and n storage yards, and assuming that every kiln has rails to every yard, the problem can be stated as: find the crossing number for all complete bipartite graphs $K_{m,n}$.

The problem remains unsolved. Nadine C. Myers of Hamline University recently noted in *Mathematics Magazine* (December 1998) that crossing numbers are known only for graphs with small numbers of nodes: complete graphs K_n when $n \leq 10$, and complete bipartite graphs $K_{m,n}$ when $3 \leq m \leq 6$. Very little is known about graphs with greater numbers of nodes.

Still another type of graph is the rectangular grid on a torus, shown in the illustration on the opposite page. Two families of circles appear in this graph: eight vertical circles with seven nodes each (denoted by the symbol C_7) and seven horizontal circles with eight nodes each (C_8). These circles can be drawn on the surface of a torus (which is the mathematical term for a doughnut) so that no crossings occur: the circles intersect only at the nodes. But when this



BRYAN CHRISTIE

GRAPH THEORY *involves determining the minimum number of crossings for different types of graphs. A planar graph* (a) *can be rearranged so that it has no crossings. A complete graph with five nodes* (b) *has a crossing number of one, as does a complete bipartite graph with two sets of three nodes* (c).

graph—$C_7 \times C_8$—is projected onto the plane, five crossings occur for each of the eight vertical circles, yielding a total of 40 crossings.

The same kind of projection can be carried out with m horizontal circles and n vertical ones, where we follow the convention that $m \leq n$. We find that each vertical circle intersects the innermost and outermost horizontal circles just once, at a node. Each vertical circle intersects the other $m - 2$ horizontal circles twice—once at a node, which represents a real intersection on the torus, and once between nodes, which is a result of projecting the graph onto the plane. So each vertical circle contributes $m - 2$ crossings, and the graph has a total of $(m - 2)n$ crossings.

It is widely believed that this number represents the fewest crossings possible for such a torus-grid graph; in other words, the crossing number of $C_m \times C_n$ is $(m - 2)n$. Yet this (m,n) conjecture has never been proved. It is known to be true when $3 \leq m \leq 6$ and when $m = n = 7$. The smallest unproved case is $C_7 \times C_8$, for which the conjectured crossing number is 40. Can you find a way to draw the graph with 39 or fewer crossings? If so, the (m,n) conjecture would be proved false. It may seem astonishing, but this problem has defied the combined brainpower of the world's mathematicians for years.

In 1997 Gelasio Salazar of Carleton University in Ottawa proved that if the crossing number of $C_m \times C_n$ is less than $(m - 2)n$, it cannot be much less. Nevertheless, Salazar's theorem leaves room for the possibility of a crossing number below the conjectured value. The (m,n) conjecture could very well turn out to be false, which would explain why it has been so hard to prove. Or the conjecture could be like Fermat's theorem, Kepler's conjecture or the four-color conjecture: true but hard to prove! SA

FEEDBACK

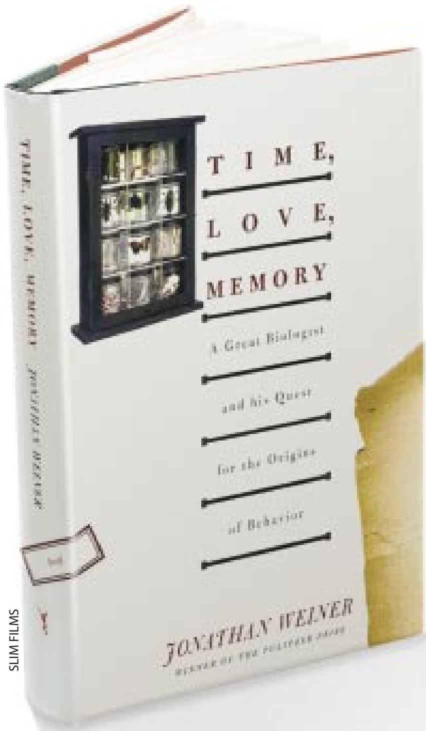
In "The Bellows Conjecture" [July 1998], I explained why it is impossible to create a polyhedral bellows—a polyhedron that changes volume as it flexes. A crucial feature of this theorem is that the polyhedron's faces must remain perfectly flat and the edges must not separate. Cardboard, however, is not completely rigid, so it is possible to create a cardboard model of a polyhedral bellows that changes volume because its faces distort or its edges stretch apart slightly.

David Briggs of Waltrop, Germany, has patented an ingenious design for such a bellows, which can be viewed at www.patents.ibm.com/details?patent_number=3993222 on the World Wide Web. Says the inventor: "The concept derives from a childhood experience: when I had squeezed too much toothpaste out of the tube, my father showed me how to get some of it back in by squeezing the tube 'the other way,' perpendicular to the first direction." —*I.S.*

OF FLIES AND MEN

Review by Dean Hamer

Time, Love, Memory: A Great Biologist and His Quest for the Origins of Behavior
BY JONATHAN WEINER
Alfred A. Knopf, New York, 1999 ($27.50)



SLIM FILMS

Behavioral genetics is a strange crossbreed with roots both in the hard, experimental sciences of genetics and molecular biology and in the soft, more observational disciplines of psychology and psychiatry. Among the recent spate of popular books about genes and behavior, most stress the soft side of the pedigree, typically relying on the now all too familiar stories of twins who, though reared apart, both drive the same model of car or flush the toilet thrice. It is also a field that tends to attract kooks, such as Francis Galton, who invented twin and adoption experiments in the late 19th century and also coined the term "eugenics," and Richard J. Herrnstein and Charles Murray, authors of the infamous *The Bell Curve.* No wonder, then, that behavioral genetics has developed such a flaky reputation.

In *Time, Love, Memory: A Great Biologist and His Quest for the Origins of Behavior,* Pulitzer Prize–winning author Jonathan Weiner takes a completely different perspective on behavioral genetics. The "great biologist" and seemingly unlikely hero of Weiner's book is Seymour Benzer, a scientist little known to the general public but idolized by biologists as the first to unite classical genetics with molecular biology. In telling Benzer's story, Weiner relates the development of behavioral genetics to the history of modern molecular biology, including anecdotes about Gregor Mendel and his rediscoverers, Thomas Hunt Morgan and the first fly gene mappers, Max Delbrück, Salvador Luria and the phage group, François Jacob and Jacques Monad, and, of course, James Watson and Francis Crick. It is a tale long on clever experiments and brilliant insights, and refreshingly short on politics and ideology.

The story starts in Bensonhurst, Brooklyn, with Benzer taking a look at his own sperm through his first microscope, a bar mitzvah present. Like so many of the great biologists of this century, Benzer began his professional career as a physicist. Then, in 1946, a friend gave him the book *What Is Life?,* by German quantum physicist Erwin Schrödinger, and Benzer's life was changed forever. Schrödinger's book was important not because it attempted to answer the question posed in its title—in fact, the book's main idea, that genetic mutations represent "quantum jumps," is plain wrong—but because it posed the gene question as *the* problem to solve.

The first third of *Time, Love, Memory* describes Benzer's defection from physics and development as a biologist as he wanders, gypsylike, from Caltech to Oak Ridge to Paris. The crowning achievement of this period in his career was the fine mapping of the *rII* gene of bacteriophage T4. Until then, chromosomes had been thought of as "beads on a string" in which the genes were inviolate units of structure and function. Benzer was the first to show that although the gene is, indeed, the fundamental unit of function, its structure can be further subdivided by mutation and recombination into what we now recognize as individual base pairs. It was the first but not the last time Benzer would use a very simple experiment—basically just mixing phage strains together—to prove an elemental principle of biology.

The second, and most important, section of the book describes what happened when Benzer got bored with *rII* and interested in behavior. Choosing the fruit fly as his experimental organism, he started plotting how to isolate mutations in interesting behavioral genes. Although his neurobiological colleagues mocked his plans as naive and simpleminded, Benzer soon proved them wrong by identifying single gene mutations for phototropism using an ingenious device constructed from nothing but a few test tubes and a fluorescent lightbulb. Within a few years, Benzer and his students had used similarly clever schemes to identify other genes involved with the internal clock, courtship rituals and learning behavior of flies. Identifying these genetic mutations affecting "time, love and memory" marked a revolution in the genetic study of behavior.

An Unlikely Hero

The final section of the book traces the outcomes of Benzer's work in the modern world of gene cloning and sequencing. The original clock gene, *period,* is now understood to make a timekeeping protein that is conserved all the way from fungi to humans. It is responsible for how fast a fruit fly beats its wings and, quite possibly, for whether you wake up early or late. The courtship mutants, such as *fruitless,* which were isolated elsewhere but first extensively studied in Benzer's lab, show that the sexual development of the body and the brain use the same starting signal but then branch out into distinctive pathways. The ability of a single protein to change how a fly relates to the opposite sex, and its own, has fascinating implications for our own, much more elaborate sexual desires and activities.

Benzer's learning mutants were for a long time ignored by most neurobiologists. What could the minuscule brain of a fruit fly tell us about humans? critics asked. With the remarkable discovery that fruit flies and mammals use the same fundamental biochemistry for long-term changes in neural function, however, these mutants have become key players in our understanding of how memory works.

The final chapters describe how scientists are trying to apply the genetic principles that Benzer discovered through his work with fruit flies to our own species. Sexual orientation, anxiety, thrill seeking and alcoholism are some of the traits that are being examined. Given that my laboratory at the National Institutes of Health is responsible for a goodly portion of the research discussed in these chapters, it was disconcerting to learn that "Benzer keeps a clipping file of genes-and-behavior headlines so that as they are discredited he can use them in his lectures as cautionary tales." A little later on, however, Benzer opines that he now "thinks it is possible to do good work at last" and that "thousands of solid links between genes and human behavior will be discovered over the next several decades."

Benzer is in many ways an unusual hero for a book about behavioral genetics. He focused exclusively on the topic for only a short part of his career, sandwiched between *rII* mapping and his current work on nerve cell development. He has not won a Nobel Prize or written any popular books; he is a "scientist's scientist" who cares more about the next experiment than about publicizing his work. And he apparently has no political ax to grind, or none that is revealed in the pages of *Time, Love, Memory*. The assorted critics of behavioral genetics, as described in the book, seem woefully partisan by comparison.

Time, Love, Memory is a beautifully written book that seamlessly weaves together science, history and personalities. Weiner makes behavioral genetics come alive by focusing on Benzer's life in the same way that he made evolutionary science exciting in *The Beak of the Finch* by following the lives of Peter and Rosemary Grant. The one criticism I have is the book's failure to provide any insight into Benzer's own views about the implications of his research. Does Benzer believe that behavioral genetics will one day explain his own quirks and foibles, such as his penchant to work through the night and his love of strange foods? Does he think it will someday be possible to change human behavior through genetics, and, if so, should we? Although Weiner stresses that Benzer is more impressed by facts than theories, still he must have *some* views on these topics.

Does Benzer believe that behavioral genetics will one day explain his own quirks and foibles, such as his penchant to work through the night and his love of strange foods?

This book could not have come at a better time. In just a few years we will know the complete sequence of the 100,000 or so genes that make up the human genetic blueprint. Many of these genes—perhaps more than half—play a role in the development and functioning of the brain, and that means in behavior. Still, leaders of the genome project consistently downplay the role of genes in behavior, presumably to protect their funding against political attack. Perhaps this book will help destigmatize the field by showing its connections to the mainstream of molecular biology. As long as behavioral genetics remains a scientific backwater, much of the genome sequence will look like uninterpretable gibberish.

Benzer's career was inspired by two books: Schrödinger's *What Is Life?,* which sparked his interest in genes, and Sinclair Lewis's *Arrowsmith,* read in his teens, which provided him with a role model for the pure scientist, dedicated only to the truth. Perhaps somewhere a student will pick up *Time, Love, Memory* and be inspired to study behavioral genetics despite its current unpopularity. And perhaps that student will one day become the scientist who discovers the key to autism, or depression, or schizophrenia, or any of the thousands of other behavioral conditions that cause so much human suffering. What more could one possibly ask of a book?

DEAN HAMER is the author (with Peter Copeland) of The Science of Desire *and* Living with Our Genes *and Chief of Gene Structure and Regulation in the Laboratory of Biochemistry at the National Cancer Institute.*

THE EDITORS RECOMMEND

Visions of Technology. Edited by Richard Rhodes. Simon & Schuster, New York, 1999 ($30).

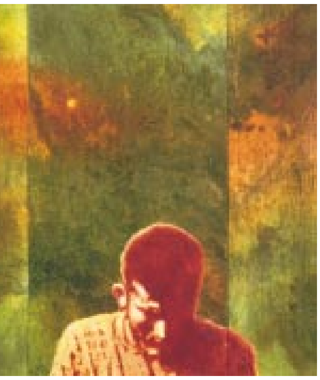
"The Western world has argued passionately about technology—what it is, where it's going, whether it's good or bad for us—throughout the twentieth century, even while inventing it at a ferocious and accelerating rate," Rhodes writes. "This anthology samples that vital debate." Rhodes, Pulitzer Prize–winning author of *The Making of the Atomic Bomb,* excerpts the writings of many people who either helped to develop technology or pondered its impact; his selections make rewarding reading. He begins with journalist Mark Sullivan, pointing out in the 1920s that the words "radio," "movie" and "aviator" were unknown in 1900, and he carries on with 213 more contributions from both well-known and obscure observers of the technological scene. The book is part of the Sloan Technology Series of the Alfred P. Sloan Foundation.

Noah's Flood: The New Scientific Discoveries about the Event that Changed History. William Ryan and Walter Pitman. Simon & Schuster, New York, 1998 ($25).

The tale of a massive, devastating flood appears not only in the Bible but also in other ancient writings, often in similar terms, suggesting that it records a real and singularly memorable event. Ryan and Pitman, who are senior scientists at Columbia University's Lamont-Doherty Earth Observatory, think the event might have been a huge and prolonged cascade of water from the Mediterranean that broke through a natural dam in the Bosporus Strait and plunged into what was then a freshwater lake and is now the Black Sea. They present both geologic and archaeological evidence for the flood, dating it at about 5600 B.C. "The Bosporus flume roared and surged at full spate for at least three hundred days," they write. The cascade inundated 60,000 square miles of land, forcing the people living in the region to disperse. The book explores the question of who those people were and where they went; it also examines the tradition of oral storytelling that could have passed the flood story from generation to generation.

A Cursing Brain?: The Histories of Tourette Syndrome. Howard I. Kushner. Harvard University Press, 1999 ($29.95).

One could doubtless read many books without coming on the phrase "ticcing coprolalics," but it is here, and it is serious business. It refers to the involuntary jerking movements (ticcing) and the untimely outbursts of cursing or foul language (coprolalia) emitted by people (mostly males) who suffer from Tourette syndrome. Kushner, a professor of the history of medicine at San Diego State University, reviews the history of efforts to understand and treat the affliction. Unfortunately, the cause is still unknown. Kushner believes the syndrome may be a reaction to a previous infection, but it has also been treated as a psychiatric problem. He expresses the hope that current research "will lead eventually to robust interventions aimed at the causes rather than the symptoms of these behaviors."



RICHARD L. DANA

The Biology of Violence: How Understanding the Brain, Behavior, and Environment Can Break the Vicious Circle of Aggression. Debra Niehoff. The Free Press, New York, 1999 ($25).

Niehoff, a neuroscientist, asks why some people are violently aggressive toward others and what can be done about it. Her answer to the first question is that a person's encounters with the outside world have lasting effects on the neurobiological processes that underlie behavior. "Negative interactions increase the perception of threat; over time, the process may develop into a 'vicious circle' that leads to violence." Her answer to the second question is counseling and perhaps medicine for the aggressive person and social intervention to deal with the environmental conditions that provoke violence. "Repairing communities, ensuring the welfare and safety of children, sheltering battered women . . . and actually caring for the mentally ill does cost money. On the other hand, the alternative—building, staffing, maintaining, and populating more prisons—is going to cost a fortune."

The Meme Machine. Susan Blackmore. Oxford University Press, 1999 ($27.95).

Jokes, fads, rumors and many other things spread quickly and widely among people. How so? Zoologist Richard Dawkins, in *The Selfish Gene,* coined the word "meme" for the entity that might play the role of gene in the transmission of words, ideas, faiths, mannerisms and fashions. It is not a physical entity, as far as anyone knows, but a characteristic trait of the human brain. "The thesis of this book," Blackmore writes, "is that what makes us different [from other animals] is our ability to imitate." Memes, she says, "are stored in human brains (or books or inventions) and passed on by imitation." They can pass vertically, as from parent to child, or—unlike genes—horizontally in peer groups and obliquely as from uncle to niece. Each of us is a meme machine.

A lecturer in psychology at the University of the West of England, Blackmore carries the idea far, examining the role of memes in such phenomena as the evolution of the enormous human brain, the origins of language, "our tendency to talk and think too much," altruism, and the evolution of the Internet.

First You Build a Cloud: And Other Reflections on Physics as a Way of Life. K. C. Cole. Harcourt Brace & Company, New York, 1999 ($13).

The notion that science is something outside our everyday experience is antithetical to Cole, an award-winning science writer. She maintains that "science is no more 'inaccessible' than looking out the window and wondering why a tree branches in a certain way or why (to ask an old but still wise question) the sky is blue." Although now, she notes, the instruments of science have vastly extended our senses, making it possible to "see" such things as atoms and quasars. With felicitous use of analogy and metaphor, Cole guides the reader gently through fields that anyone unschooled in physics might view as impenetrable: forces, quantum theory, relativity, entropy and many others.

The Hidden Forest: The Biography of an Ecosystem. Jon R. Luoma. Henry Holt and Company, New York, 1999 ($22).

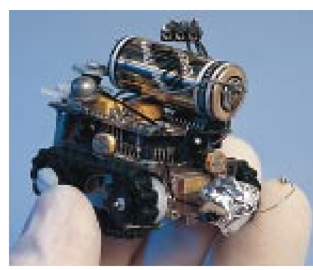
The forest—the H. J. Andrews Experimental Forest in Oregon—is in fact eminently visible, consisting of huge, old-growth conifers. But the researchers who have studied it closely since 1948 "have discovered a host of species previously unknown to science, and interactions in the forest ecosystem that no one previously imagined," Luoma writes, and that is the hidden forest. The studies, here and elsewhere, have dealt with the effects of the great diversity of materials that fall to the ground from the forest canopy; of the forest's insect life; of rotting logs; of flood, fire and clear-cutting; of volcanic eruption. Luoma, a contributing editor to *Audubon* magazine, thinks the work may lead to "a new sort of ecoforestry" that "could allow a nation to protect wild forests and have some lumber too."

The Search for Superstrings, Symmetry, and the Theory of Everything. John Gribbin. Little, Brown and Company, Boston, 1999 ($23).

Gribbin's aim is to tell "the story of the particle world, from the discovery of the electron to the search for a supersymmetric theory explaining all the forces and particles of nature in one mathematical package." He is good at this sort of thing, and he has turned out a clear and concise tale that nonetheless requires close reading by a nonspecialist because the subject matter is not the stuff of daily life for most people. Reading closely, one is guided skillfully through such concepts as quantum physics ("for beginners," Gribbin cautions), wave-particle duality, quark theory, string theory and supersymmetry. But, he says, there is an underlying caveat to keep in mind: "Over the past fifty years, physics has revealed a wonderland of a subatomic world, populated by all kinds of strange objects. We call these objects particles, for want of a better name. What they really are, we do not know."

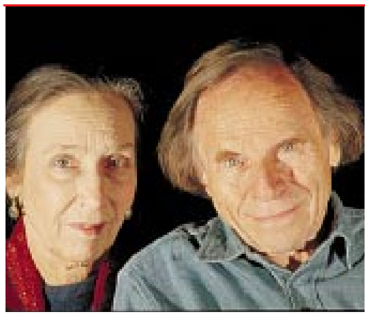
Who Gives a Gigabyte? A Survival Guide for the Technologically Perplexed. Gary Stix and Miriam Lacob. John Wiley & Sons, New York, 1999 ($24.95).

Stix (an associate editor at *Scientific American*) and Lacob (a freelance writer) provide a crackerjack tutorial in modern technology for those they call the technologically perplexed. Almost everybody could answer to that designation in one field or another. The fields that the authors discuss are computer hardware, software, telecommunications, lasers, genetic engineering, medical technology, molecular biology, materials science, energy, and environmental science. Numerous boxes focus a spotlight on such subjects as computer language, the electromagnetic spectrum and the polymerase chain reaction, and several of the chapters contain a helpful glossary of common terms in the field. The reward for the reader is a solid grounding in technological literacy. SA



HANK MORGAN *Science Source/Photo Researchers, Inc.*

COMMENTARY



WONDERS

by Philip and Phylis Morrison

First Comes the Thunder

DUSAN PETRICIC

Our flight began with a thunderous push; it would end just after the plane's undercarriage rumbled downward, suddenly relaxing all its tucked-in elbows as it slowed for touchdown. Seated at the very frontmost right cabin windows, we faced a rounded bulkhead that faintly outlined the exterior nose of our big jet. We would spend a tedious but luxurious 16 hours there between Delhi and New York, bucking all day the steady mile-a-minute westerly jet stream across the high deserts. Above our cabin ceiling the flight crew worked on their upper deck, inside the unique bulge that gives the 747 the organic look of some dolphin of the sky. Charmed by the attentive cabin crew, we enjoyed a first-class lunch, which began with caviar and ran on to an elegant Lucknow dish of stuffed chile peppers, ending with a classical Persian sweet, all almonds and cream.

Air-India pushed us along at altitude by the outpouring of hot gases from 10 tons of kerosene burnt each hour in the four gas turbines on the wings. Their summed power is some 110 megawatts thermal, available at a few seconds' notice from those responsive engines, each one weighing four tons, yet in all only a 20th part of the airplane's weight. Their power is no bad match for the capacity of an elderly working power plant in Cambridge, Mass., whose once stylish arched brick windows rise a couple of stories above the road we take home every day.

Jet flight depends on two distinct aerodynamic masteries: the one of very hot gas; the other of the free, cold atmosphere. In the colloquial speech of pilots, you won't get home if you can't light the fires. A hot tempest streams out of the big engine spools, smooth-spinning, adamantine structures of metal and ceramic, their surfaces worked as intricately as the tower of a southern Indian temple. The flame-filled engine surfaces are studded by tens of thousands of blades and buckets that mix and grasp the expanding combustion gases. Such engineering is part of fluid flow, but it is no part of aircraft design; engines are now the topic of a separate and arcane discipline that guards high skills and recherché materials—titanium, graphite and cobalt—in the engine nacelles, as indeed priests privately tend the powerful costumed images that inhabit and inform many a temple.

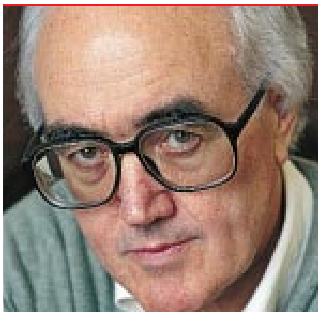
Henk Tennekes, a witty, thoughtful aeroengineer, illustrator, pilot and professor at the Free University, Amsterdam, closes a wonderful little book he has written with a chapter on the 747, an evolutionary account of a dominant, fully adapted species of technology. We readily accept that the friction of fast-flowing air on any airplane surface is a wasteful energy loss. But what theory and experiment demonstrate is that the plane's weight is supported by the energy spent in deflecting enough of the airflow downward to balance the insistent pull of gravity. That upward force, called lift, intrinsic to all wing-borne flight, is in no way frictional or inefficient. Unless the frictional force is kept below, say, a tenth of the lift provided, the craft becomes lossy, more puffin than petrel. It lacks finesse, as French engineers put it.

An airplane should be as fast as it can be. For North Atlantic runs—the cradle of the intercontinental passenger jet—it should be fast enough to fly the round-trip in under 18 hours. The 747-400 does that handily, and many such craft enjoy the daily routine of economical maintenance right in their home port. Their travel speed is close to that of sound. Indeed, it was chosen to be about Mach 0.83 for a margin of freedom from supersonic losses, which sap a plane's efficiency not through mere air friction but through dense shock waves that radiate copiously and loudly. The supersonic Concorde, a long-subsidized deluxe transatlantic service, serves 100 high-fare passengers each day at double speed. A 747 carries 350 seats and freight as well and burns the same amount of fuel per transit as the Concorde but with twice its range and no sonic booms. High Mach numbers seem to suit only the costly urgencies of war.

A transatlantic 747 travels at five sixths the speed of sound for about 2.5 cents per seat-mile. How does your van compare?

Tennekes holds that the Boeing 747 is one of the great engineering wonders of the world, like the Pyramids. Ocean liners were doomed early on by the jets, save for the joys of leisurely cruising, for big, slow boats are fuel-cheap and capital-dear, with easily 10 times the Boeing costs. The French TGV (Train à Grande Vitesse), perhaps the finest on rails, makes three short-haul trips at well

Continued on page 103



CONNECTIONS

by James Burke

Room with (Half) a View

DUSAN PETRICIC

I mentioned a while back that I live on the Thames within sight of the great Victorian railway bridge built by the great Victorian engineer Isambard Kingdom Brunel. He was half-French, and that first sentence was half-true, because one half of the bridge is obscured by the corner of the house next door to me.

As you'll know if you're a regular reader of this column, Brunel was the architect of the *Great Eastern,* the biggest steamship ever built at the time, which successfully completed the final attempt by Cyrus Field to lay the transatlantic telegraph cable in 1866. Funnily enough, long before they ever thought of using the *Great Eastern,* the ship was being built on one side of the Thames as they were putting together the cable on the other.

In preparation for the momentous event, Field had taken advice from Sam Morse, who had already done something similar, though on a smaller scale. Two years before he blew the U.S. Congress away with his famous 1844 demo, he had transmitted signals across New York Harbor with an insulated copper cable. This may have been why he had also given a bit of cable (and presumably a few hints) to a neighbor who, that same year, wanted to blow up a ship just off the end of Manhattan by detonating a mine under it—an explosive idea he wanted to sell to the U.S. Navy. The ship went down okay. But so did Sam Colt's fortunes when he wouldn't explain to the navy how he'd done it. His revolver hadn't been doing too well either. Then along came the U.S.-Mexican War, and suddenly Colt was back in the killing game. By 1855 he had the largest private armory in the world.

His only rival in sudden death was the Remington Company, which ended up solving a major concern of Northern troops in the Civil War. This was that while you were standing there ramming powder down your musket barrel, dropping in a ball, and then cocking and aiming, somebody shot you. Remington's breech-loading rifle changed all that and became the most successful military rifle in history. Sold more than a million to peace-loving nations all over Europe and the Middle East.

After the Civil War ended, thanks to Remington the pen became mightier than the sword for a while, when the company turned over some of the factory's now idle machine-tool lines to the production of a neat gizmo an inventor in Milwaukee had come up with. He had done so after reading a description of some Brit's attempt to do the same in the July 1867 edition of *Scientific American* (rah! rah!). Christopher Sholes's thing would become known as the Remington typewriter, and it eventually helped women freed from kitchen drudgery to become involved in office drudgery.

If you've ever had trouble with dialectical materialism, this is the guy to blame.

The guy who had helped Sholes with his uppercase machine was a lawyer, an innovative type by the name of Carlos Glidden. Noodling must have run in Glidden's family, because in 1874 a very distant relative of his named Joseph, living in De Kalb, Ill., patented another device that was to become almost as popular with troops and farmers as was the Remington (rifle, not typewriter): barbed wire. Three years later Glidden sold his shares in the Barbed Fence Co. to Washburn Manufacturing in Worcester, Mass. That place was already producing Glidden's raw material: since 1868 Washburn had been up and running with a new kind of wiremaking mill, developed by a Brit named George Bedson. This process could turn 20 tons of wrought iron into ¼-inch wire in 10 hours. A little earlier Bedson had also invented a continuous process for dipping wire into molten zinc and galvanizing it so that, protected against wind and weather, it was available to Ezra Cornell as he strung his telegraph wires all across America, thus making himself rich enough to found a university in Ithaca, N.Y.

But back to Washburn and Co. Sometime around 1842 they had turned down an offer from a young German engineer living in Pennsylvania who had come up with a way to make wire rope by spinning the strands of wire on site. He had stumbled on the idea while working on a curious system known as a portage railway. Before proper railroads superseded them, now and again canals would bump up against a mountain, and the only thing their builders (like the young German) could do was to stick the canal barges on flatbeds and haul them on rails up and over the mountain to the other side. Hauling was done with hemp hawsers. Which often broke. Hence the German's wire ropes.

Washburn and Co. rejected his invention; perhaps they felt that there just weren't enough canal-mountain interfaces to justify it. They must have kicked themselves when, in March 1855, the first train (carrying the Prince of Wales and a deluge of publicity) crossed the Niagara on a bridge suspended from those very wire ropes. And imagine how they felt in May 1883 when the whole of New York shut down for what was called the People's Day, and another bridge, once again hanging from John A. Roebling's wire ropes, was declared open, named one of the Wonders of the World, and finally United the States by linking Manhattan and Brooklyn.

Years before, in Berlin, Roebling had apparently been persuaded to emigrate to America by his friend the great philosopher G.W.F. Hegel. If you've ever had trouble with dialectical materialism, this is the guy to blame. Everything, Hegel said, contains contradictions within itself, and the tension between these contradictions is the driving force behind change, which happens when the contradictions are resolved. Get it?

In 1844 these musings changed the course of history when a 24-year-old German journalist in Paris incorporated a version of them in "Economic and Philosophic Manuscripts." One of those works you can't pick up—it talked about Hegel's tension in terms of class war, and resolution in terms of the inevitable triumph of the proletariat. Because the only safe place for this kind of madness in the mid-19th century was Britain, the author, Karl Marx, high-tailed it to London.

Where by 1884 the executive of the Social Democratic Federation included Marx's daughter Eleanor. That year, when the SDF was infiltrated by anarchists, Eleanor decamped with nine other members of the committee, including a wallpaper maker and designer of rustic furniture named William Morris, who then founded his own, more democratic Socialist League. At art evenings held by the league in his London home, Morris read poems, George Bernard Shaw tinkled the ivories, and *Chants for Socialists* were sung by assembled members under the direction of one Gustav von Holst, an English-born trombonist.

Holst later dropped the "von" during World War I, when he was put in charge of music for the troops in Salonika and Constantinople. After the war he returned to fame and fortune with the first performance of the piece for which he is perhaps best known: the "Planets" suite. I sometimes play it while looking out at my half-view of Brunel's bridge, partially blocked by the corner of that house I mentioned at the start. The one in which Gustav Holst lived. SA

Wonders, *continued from page 101*

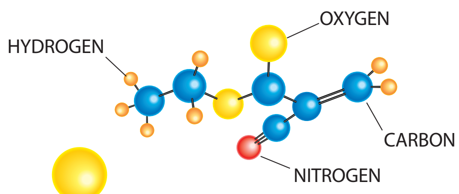
under jet speed, 700,000 seat-miles a day. A transatlantic 747 produces three times TGV's seat-mile output at half its price, or about 2.5 cents per seat-mile. How does your van compare?

Well over a thousand 747s are now in service, an investment rising into the $200-billion range. But there is more to this engineer's wonder. Once the cruising speed was fixed safely below the speed of sound, almost no choice was left the designer. At reasonable finesse, the wing loading is fixed by the speed, given the altitude. The cold, thin stratosphere, some 65 degrees below zero Fahrenheit, is entered about six miles high, and the temperature falls only slowly much beyond that. Engines like cold air, but lift depends on the mass of air deflected downward. A universal trend runs from wren to jumbo jet that neatly relates wing loading to speed at a given air density. Wings grow big as their load increases. The 747 design emerged 30 years ago from these first principles: cruise efficiently at nine miles a minute, fly 33,000 feet high and take off at about 400 tons weight. The 747, its lift 15 times its drag, is no bigger than it should be.

Could there be a smaller version? Only by compromise. It would fly with disproportionately bigger, dearer, draggy wings. Swifts and swallows fold their wings at top speeds to cut drag, but so far only expensive military craft follow their example and not airliners, even though at landing, its fuel gone, the 747 is much lighter and needs less wing area than it does at takeoff. A much larger plane meets still more troubles. Try for 1,000 tons and 1,000 seats? Even titanium all around won't be enough to support a fair payload, and safe runways will become demandingly long. But maybe a less ambitious 747-600 will arrive one day. During our single journey, we saw 747s in the insignia of airlines from five continents. The 747 now has a pan-European competitor, worthy enough, though no marvel; Airbus sales are close to Boeing's in this time of complex international financing and amazingly low fuel prices.

Our printed source is *The Simple Science of Flight,* by Tennekes. Its text is instructive fun; his rich drawings include flies, falcons, paper airplanes and maple tree keys. Save up for a 747-400 trip and seek a window seat, even at night. SA

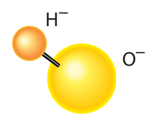
INSTANT GLUE



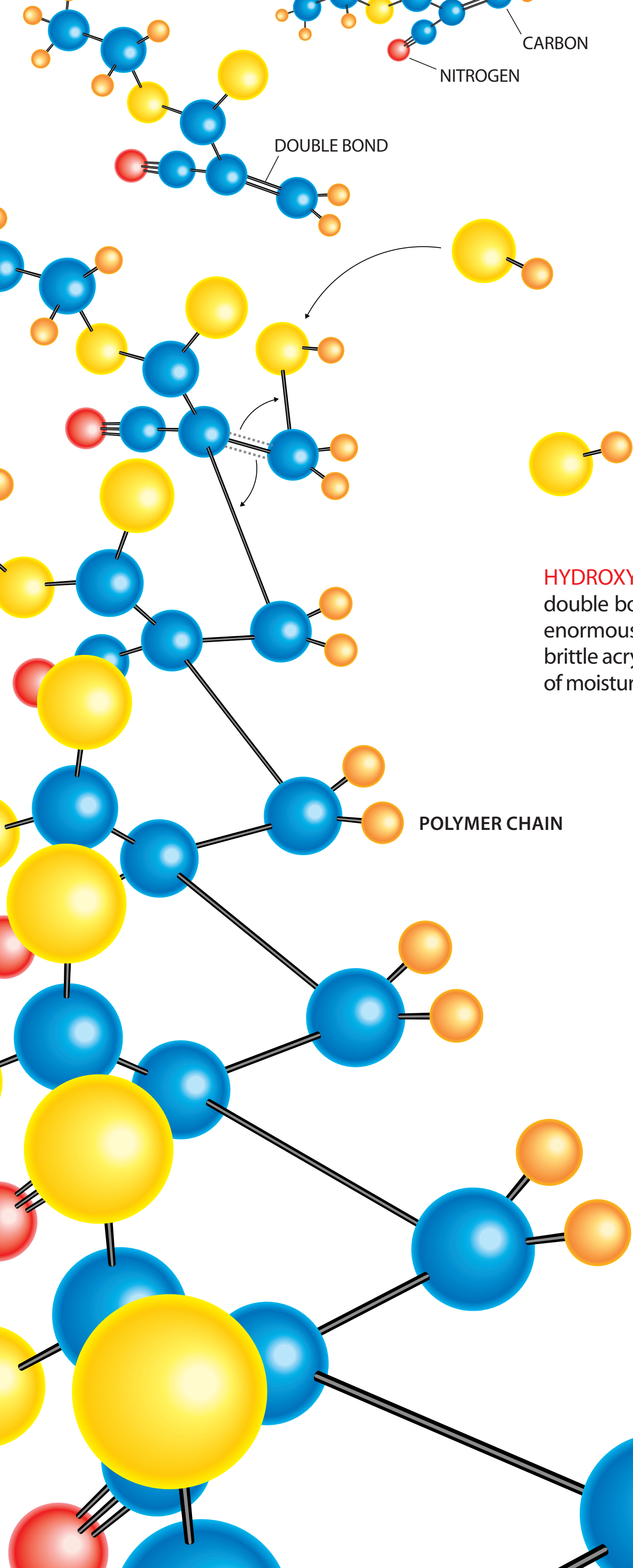
by Louis A. Bloomfield
Professor of Physics, University of Virginia
Author of How Things Work: The Physics of Everyday Life

Nearly all glues are plastic polymers—giant molecules that cling to themselves and the surfaces they touch, like sauceless spaghetti noodles left overnight in a bowl. But while the plastic molecules in most household glues are dissolved in a liquid that evaporates as the glue dries, the molecules in Krazy Glue—and other instant glues—do not form until you squirt the liquid out of the tube. Krazy Glue is remarkable because it is almost pure ethyl-2-cyanoacrylate, a simple molecule that polymerizes rapidly when exposed to moisture. Each glue molecule contains an unusually fragile double bond between carbon atoms, one that is easily attacked by the hydroxyl ions found in most airborne moisture.

ILLUSTRATIONS BY GEORGE RETSECK



HYDROXYL ION

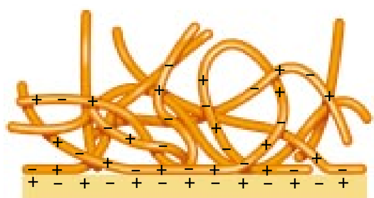


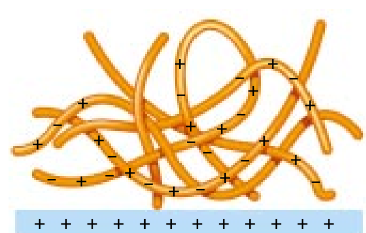
POLYMER CHAIN

HYDROXYL IONS alter the Krazy Glue molecules, transforming their double bonds into single bonds and causing them to link together in enormous chains. As a result, the liquid glue quickly becomes a hard, brittle acrylic plastic. Because most surfaces are coated with a thin layer of moisture, Krazy Glue starts to harden the moment you apply it.

ADHESION is strongest when surfaces are polar, meaning that they have localized accumulations of positive and negative electrical charge. Krazy Glue itself forms a polar plastic, and polar materials attract one another by bringing their oppositely charged regions as close together as possible. Because most ordinary surfaces are polar, Krazy Glue binds tightly to them. Its container, however, is made of polyethylene, a waxlike plastic that is almost completely nonpolar. With no localized charges to hold it in place, Krazy Glue barely sticks to the tube and pulls away cleanly each time you open the lid.

POLYMERIZED GLUE CHAINS


GLUE STICKS TO POLAR SURFACES, SUCH AS A TABLE


GLUE DOES NOT STICK TO NONPOLAR SURFACES, SUCH AS THE CONTAINER TUBE