(ALMOST) HUMAN FOSSILS • DARWINIAN CHEMISTRY • MISMANAGING RAIN FORESTS

SCIENTIFIC AMERICAN

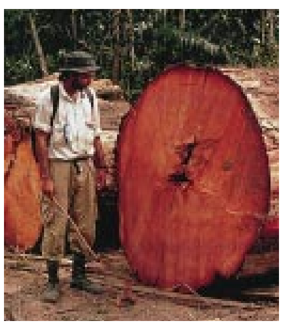
APRIL 1997 $4.95

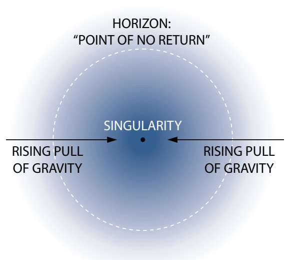
BLACK HOLE PARADOX:
DATA LOST IN
COLLAPSED STARS
MAY NOT BE
GONE FOREVER

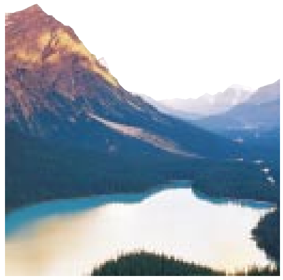
Why things go wrong.

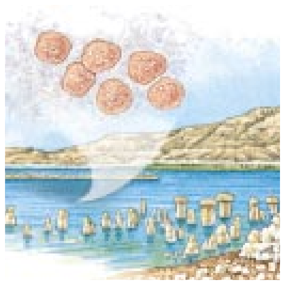
SCIENTIFIC AMERICAN

April 1997 Volume 276 Number 4









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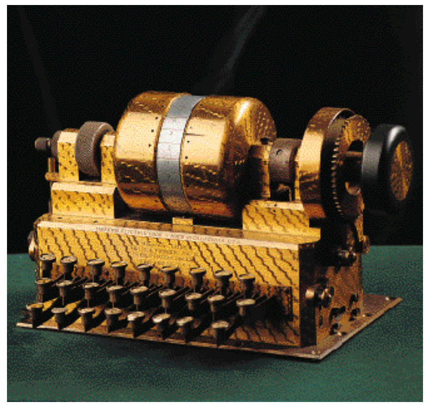
REVIEWS AND COMMENTARIES



About the Cover

When bad luck comes your way, take some comfort in knowing that Murphy's Law is an unwritten amendment to the more formal laws of probability, aerodynamics, meteorology and other sciences. Painting by Jana Brenning and Tomo Narashima.

From the Editors

Seriously, We're Not Kidding

Something about April Fools' Day makes magazine readers cynical. Every year around now we get at least a few letters saying, "All right, very funny. You really had me going there for a minute. Until I realized I was reading the April issue, I almost fell for that article on _____." And then they point to some piece on physics or biology or social science that seemed too far-fetched to be plausible. The only problem is that the articles in question are completely on the level. Would we lie to you?


JASON GOLTZ

IS MURPHY ALL WET? No, scientific truth is just stranger than fiction.

Not that *Scientific American* hasn't sneaked in a few...ah...diversions for alert readers over the years. Martin Gardner, Douglas R. Hofstadter and A. K. Dewdney, during their years as the math and computer recreations columnists for this magazine, frequently used their April outings to present brainteasers dressed up as actual inventions or situations. The "Amateur Scientist" column has also had a card or two up its sleeve on occasion. I have always been fond of a contribution from that renowned physicist Antoni Akahito, who in 1989 described how to build the ultimate particle accelerator, a very rewarding and manageable amateur project if you have enough free weekends to assemble a structure as wide as the solar system. And then there was the time art historian Ricardo Chiav'inglese explained how computers could restore and enhance children's finger paintings.

But the feature articles have always been real. If some of them have seemed astounding, chalk it up to what the noted scientist J.B.S. Haldane meant when he wrote that "the universe is not only queerer than we suppose, it is queerer than we *can* suppose." Not surprisingly, some of the discoveries described in *Scientific American* could make a skeptical mind balk.

Take the issue in your hands, for example. Seen through a thin veil of suspicion (brought on by having sat on one too many whoopie cushions, perhaps), don't many of the described ideas stagger the imagination? Does it really seem likely that erosion could make mountains higher? That cells could live in boiling water? That replacing trees might hurt rain forests? Or, most unbelievable of all, that Murphy's whimsical Law might have a scientific foundation (see page 88)?

Science at its most wonderful can clothe the nakedly impossible in a fabric of facts. As you read, be skeptical enough to consider the evidence and arguments presented by the authors, but keep an open mind. Rest assured that we're not trying to fool you, that everything in this issue is real. Even the "Letters to the Editors" on page 10....

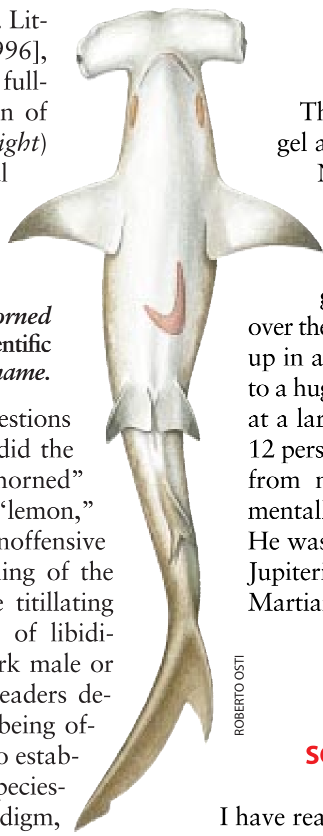
JOHN RENNIE, *Editor in Chief*
editors@sciam.com

LETTERS TO THE EDITORS

ICHTHYPORN

This morning my sister-in-law alerted me to the danger of so-called ethnoporn—the shameless pandering to Eurocentric male sexual repression that has resulted in countless images (in supposedly scientific magazines) of naked African women in a frontally exposed position. I was sure that *Scientific American* would be taking the lead in condemning this disgusting vice, which disgraces the good name of anthropologists and ethnographers everywhere.

Imagine my surprise then, on reading your otherwise excellent article "Sharks and the Origins of Vertebrate Immunity," by Gary W. Litman [November 1996], when I came across the full-frontal nude illustration of the horned shark (*right*) showing the poor animal in an unnatural, highly vulnerable and demeaning position.



ROBERTO OSTI

EXPOSED! Picture of horned shark disgraces Scientific American*'s good name.*

I believe several questions need answering. Why did the author choose the "horned" shark? Why not the "lemon," "basking" or another inoffensive shark? Does the coupling of the horned shark with the titillating picture show evidence of libidinous intent? Is the shark male or female? I think your readers deserve to know who is being offended. In attempting to establish a gender/race/age/species-neutral scientific paradigm, we cannot be too careful.

HUGH DENDY
Kelowna, British Columbia

OUT OF THIS WORLD

To send a message faster than the speed of light, you could build a machine like the one I have designed. The machine is made up of two pulleys, each with a braking system connected by a belt, and one of the pulleys has a motor. When you start the motor, both pulleys will spin at the same speed. If you then apply the brake at one end, you will stop or slow both ends at the same time.

If you place one end of the device near the earth and the other near a distant place, such as Pluto, you could, by applying the brake on the earth side, send a message (Morse code style) to an observer on Pluto. The person on Pluto could send a response by applying his own brake, and the whole conversation could take place in seconds instead of the hours that it would take a radio message to travel this distance.

TYLER BURRY
Moncton, New Brunswick

The article by Jeffrey S. Kargel and Robert G. Strom in the November issue ["Global Climatic Change on Mars"] stirred memories of information I myself gleaned from space people over the years. In 1962 I was picked up in a small ship and transferred to a huge one where they seated me at a large, round table with 10 or 12 persons. The one directly across from me nodded and conveyed mentally that he was from Venus. He was blue-eyed and blond. The Jupiterians look like our Japanese; Martians our German.

V. VAWSER
Prescott, Ariz.

SCIENCE PROJECTS

I have read that scientists work with large snakes to improve and create new breeds of the animals. I am a Neodruid, and snakes in particular are deeply religious animals. Neodruids accept science and are grateful for the partnership. I do not have a snake, though. I was wondering if science was going to make the magnificent, ancient big boa with its glittering, iridescent gold pattern in a small version?

PAULA MORROW
via e-mail

If we could create and control microscopic wormholes, then it would be possible to construct a computer made out of wormholes. If such a device existed, could a problem be solved in no time or even before it was submitted to the computer?

JON MILLER
Yucaipa, Calif.

AN EVIL EYE

I have a friend who believes in playing a board game that is supposed to connect your inner thoughts to the other side of the world. You are also supposed to be able to move objects that are placed on the board. The name of the game is the "Squeeji board." Could there be some magnetic force or some sort of strange power that the human mind can use to actually move an object around on the board? Could there really be evil powers watching us or what?

SHAUN LEE
via e-mail

LETTERS WE NEVER FINISHED

I have hesitated to write this letter fearing that when you discover its contents, you will throw it into the wastebasket without reading it further. But I am not a "Crack Pot." If you will take just a few minutes to look at the rest of this letter, you will see that I have made a significant discovery.

D.V. TAYLOR
Royal Oak, Mich.

I wrote to *Scientific American* about my invention but failed to get a reply. One of those cute dolls in the office dropped it into the scrap basket. Don't get the idea I am trying to lie to you or anything. Everything I have written is completely true.

P. F. MAGEE
Berlin, Md.

Letters may be edited for length, clarity and humor. Because of the considerable volume of mail received, we cannot answer all correspondence.

50, 100 AND 150 YEARS AGO

APRIL 1947

"The new camera of Edwin H. Land, founder and president of the Polaroid Corporation, is appraised by experts as one of the greatest advances in the history of photography. The Land camera is similar in many respects to the ordinary camera. However, after you snap your picture, exposing a section of film in the ordinary way, you turn a knob which pulls a length of film and printing paper through a slot to the outside of the camera. Glued across the paper, at intervals representing the length of one print, are a series of narrow, metal-foil envelopes, or 'pods,' each containing a quantity of a thick, sticky paste. As you turn the knob, the little 'clothes wringer' squeezes open one of the pods, and the paste is spread evenly between the negative and the paper. The sandwich now in your hand is a miniature darkroom. You wait for about one minute, then you peel apart the layers, and there is your finished picture, neatly framed in a white border."

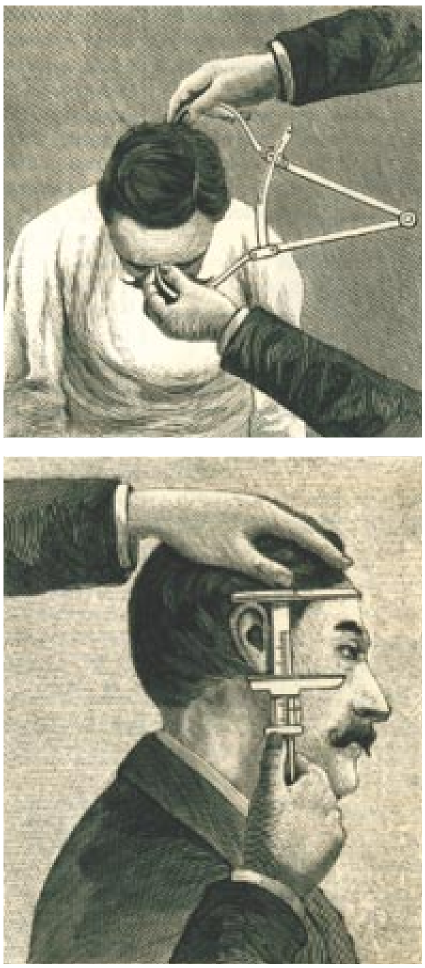
"The agricultural insecticides and fungicides industry has called upon all concerned with the production of food, fiber, and forage crops to utilize fully the chemical weapons already available in conquering the pests that now destroy large shares of the output of our agriculture. Spraying and dusting from the air has reached the point where an acre in a large farm can be treated effectively in two to four *seconds*."

APRIL 1897

"The closed cylinder engine is finding a formidable rival in the steam turbine or rotary impact engine. In these latter machines the energy of the steam is utilized by discharging it at an enormous velocity against the buckets of a wheel. The steam acts merely by its velocity and not, as in the expansion engine, by pressure. A 300 horse power De Laval steam turbine is running very successfully at the Twelfth Street station of the Edison Electric Illuminating Company, New York City. The turbine wheel has a diameter of 29 $\frac{1}{2}$ inches, and runs at 9,000 revolutions per minute."

"It is said that 95 per cent of visual hallucinations in delirium tremens consist of snakes or worms. Investigation in the alcoholic wards of Bellevue Hospital with the ophthalmoscope reveals some interesting facts. In all sixteen cases examined the blood vessels of the retina were found to be dark—almost black—with congested blood. These blood vessels, which are so small and semitransparent in health, assume such a prominence that they are projected into the field of vision, and their movements seem like the twisting of snakes."

"Dr. Alphonse Bertillon's system for establishing criminal identification records has received its most extensive trial in France, where it has been carried out for over ten years with the thoroughness for which the police of that country are famous. This system is based on a record of the measurement of certain unchangeable 'bony lengths' of the body. The illustration shows the practical operation of the Bertillon system as adopted by the police department of the city of New York." [*Editors' note: Bertillon's system was superseded by fingerprinting, introduced at Scotland Yard in 1901.*]



Measuring features for criminal records

APRIL 1847

"It is stated by Prof. Faraday that by pouring melted zinc into water, and often repeating the process, the zinc becomes soft and malleable, losing none of its tenacity, but is capable of being spun into the finest wire, pressed into any required thinness."

"The force of expansion—A bar of iron heated so as to increase its length by a quarter of an inch, exerts a power against any obstacle attempting to confine it, equal to that required to reduce its length by compression by a quarter of an inch. Experience has taught engineers that it is dangerous to attempt to confine such a force as this, particularly in the metallic constructions which are now so common. In lengthy iron pipes for the conveyance of gas and water, some of the junctions are rendered moveable, so that by the end of one pipe, sliding into that of another, the accidental changes in length due to variation in temperature are provided for."

"Philadelphians are in a high state of excitement, respecting the newly invented 'baby jumpers.' Imagine a cord fastened to the ceiling, and thence diverging into several cords, which are fastened to a child's frock by attachments to the belt. The cord is elastic, and the child may be left to itself and will find its own amusement in the constant jumping up and down and about, which its movements occasion."

NEWS AND ANALYSIS

IN FOCUS

SMALL (LENDING) IS BEAUTIFUL

Microfinance is proving that the poor are creditworthy, but will the movement try to grow too fast?

Seamstresses, carpenters, street vendors and the proprietors of other small businesses in Bolivia would typically be shunned by banks. For these people, the only possible sources for loans have traditionally been family members or moneylenders charging up to 10 percent interest daily. Yet 72,000 of them have been welcomed at BancoSol, turning that institution into the bank with the largest customer base in the country. The bank's decision is neither lunacy nor charity but rather a new financial experiment.

BancoSol has become a prominent example of an approach to banking, now growing in popularity internationally, that demonstrates that borrowers without collateral can often be very good credit risks, faithfully paying back loans of as little as even $100. As such, "microcredit" may prove to be an important means of attacking poverty at its roots.

The lenders who provide this financing have begun to show that credit schemes for the poor need not rely on handouts. BancoSol is one of the few instances in which institutions originally subsidized by either government or private aid groups have become largely self-sustaining, covering expenses and the cost of capital. The Bolivian bank has placed certificates of deposit in capital markets in the U.S. and Europe.

The experience of BancoSol and other lenders such as Bangladesh's Grameen Bank inspired a recent gathering in Washington, D.C., of some 2,500 representatives of organizations

GABRIELA ROMANOW

CHILI VENDOR IN LA PAZ, BOLIVIA, is a customer of BancoSol, which makes loans to the poor.

from 113 countries who pledged to expand greatly the scope of their efforts. The Microcredit Summit, organized by RESULTS Educational Fund, a nonprofit group closely affiliated with the Grameen Bank, endorsed a plan that calls on governments, financial institutions and aid groups to work toward a goal of extending loans to 100 million of the world's poorest families by the year 2005.

"We are here to herald an innovation in banking that has the potential to strike a blow to poverty in my country and in countries all over the world," proclaimed Sheikh Hasina, prime minister of Bangladesh. Her sentiments were seconded by an audience that included presidents, another prime minister, a chief executive, four first ladies, two queens and some borrowers from Asia, Africa and Latin America.

Microfinance, which encompasses both lending and savings for the poor, has become the idea of the moment in the beleaguered international aid community, wracked in recent years by substantial funding cutbacks. Although the template for a microfinance institution varies, the core concepts are often similar. A lending institution compensates for the lack of collateral (land or some other asset) by making individual loans to members of a so-called peer or solidarity group. Each member assumes responsibility for guaranteeing the payback of loans granted to every other member. BancoSol and Grameen report that less than 3 percent of loan repayments are late and that default rates are still lower—a record that is superior to that of corporate customers in many developing nations.

Microfinance is not confined to the Third World. It was no happenstance that a sprawling convention hotel in Washington was chosen as the summit meeting place, rather than quarters in La Paz or Dhaka. In fact, BancoSol and Grameen have served as models for legions of U.S. copycats, most of which are run by small nonprofit groups. The idea of pulling oneself out of poverty by building a food stand in La Paz—or a hairstyling salon in Chicago—has a universal attraction. And the notion holds an appeal to a federal government pledged to ease people off welfare. In a survey, the Aspen Institute in Washington, D.C., found that the nearly 250 "microenterprise" programs in the U.S. last year represented more than a doubling from four years earlier.

The Washington public-relations spectacle obscured the fact that people's banking is not a new concept. Small credit unions emerged in Germany during the 19th century as an alternative to charity. Credit unions persist to this day, of course, though many now serve a more middle-income clientele with consumer loans. In the past 20 years, a few nonprofit institutions and specialized banks have succeeded in attracting astounding numbers of poor borrowers. Grameen, which lends almost entirely to women, and a unit of Bank Rakyat Indonesia each have two million borrowers.

Growth of microfinance at the rates anticipated by conference organizers will prove challenging. "The desire to inject tens to hundreds of millions of dollars in the Grameen bandwagon may come without the patient, two-decade buildup of human capacity, educational programs and local accountability that characterized the original," says Daniel M. Kammen, a professor of public and international affairs at Princeton University. "If you don't go through this evolutionary process, you might end up getting the poor more in debt."

Reaching 100 million families—from a current level of eight million—will require $21.6 billion in additional funding and the training of more than 500,000 new managers and fieldworkers who administer the programs. Since 1995, the World Bank has increased support for microcredit, and proposed measures from Congress and the Clinton administration seek to augment funding.

But aid packages will not be enough. If the microfinance movement wishes to meet its goals, one estimate suggests that $8 billion, nearly 40 percent of the total goal, must come from commercial sources. Some novel approaches to finding private capital have begun to emerge, such as investment funds that put money in a portfolio of microfinance institutions. Another option is for a small nonprofit lending agency to become a bank. Prodem, a Bolivian nonprofit that made small loans, transferred most of its assets to establish BancoSol in 1992, a move that provided access to significantly larger capital sums to meet burgeoning loan demand.

The flow of money, however, is still a trickle. Carter Garber, a Washington-based development finance consultant, made a rough estimate that no more than half a billion dollars has been garnered for microfinance from private lenders during the past 10 years. Investors still face substantial risks. Last year, for example, Accion International, the Massachusetts group that played a key role in setting up BancoSol, had to help reorganize another project in which it holds an equity interest. The intervention occurred when a Colombian finance company, called Finansol, saw its portfolio of microloans go sour.

	Prodem 1991	BancoSol 1996
Number of active clients	19,901	71,745
Average loan size	$285	$661
Total loan portfolio	$4.6 million	$47.4 million
Late payment rate	0.2%	2.6%
Loan default rate	0.0%	0.54%
Return on assets	–	2.4%

CAPITAL AVAILABILITY for small clients increased after nonprofit leader Prodem created BancoSol **(office in La Paz shown at right).**

ACCION INTERNATIONAL

Other risks abound. Microfinance, some observers say, could become an all-encompassing approach rather than a tool within a larger antipoverty strategy. At worst, token aid to these projects may be used to justify cuts in programs for public health, education or agricultural assistance.

Microcredit, moreover, may not reach the very poorest. David Hulme of the University of Manchester and Paul Mosley of Reading University found that borrowers with at least some assets benefited most from small loans, whereas the most impoverished sometimes found that conditions worsened as they dug deeper into debt. Instead of focusing solely on loans for small businesses, Hulme and Mosley suggest that poverty reduction measures should focus on savings programs and loans to tide a family through emergencies—measures that have been adopted by some microfinance programs. Some of the most renowned institutions have assumed educational and social functions. Grameen has begun to explore the possibility of providing access to leased cellular telephones that can be shared by groups of borrowers.

Imperfections aside, the most successful institutions have succeeded where conventional aid has often foundered. They have had a substantive impact on raising household income and the status of poor women. In short, they may become a critical component in addressing the seemingly intractable problems of poverty in the developing world and in the industrial inner city. —*Gary Stix*

GEOLOGY

HOT-SPOTTING

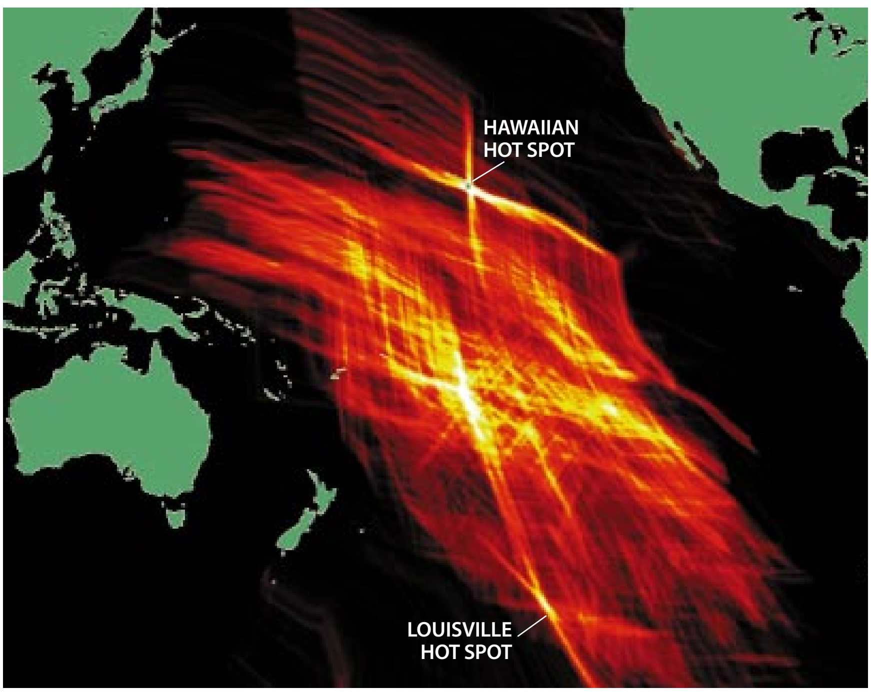
A new way emerges to find the earth's hidden heat sources

Like stationary blowtorches suspended below a slab of moving steel, geological "hot spots"—concentrations of heat buried deep within the earth's mantle—scorch the tectonic plates that pass over them. The marks left take the form of volcanoes, typically arrayed in loose chains that reflect the episodic bursts of magma from below. Geologists sometimes struggle to identify these ancient volcanic footprints and to track them back to the deeply seated source of heat. But a novel method presented by Paul Wessel and Loren W. Kroenke at a recent meeting of the American Geophysical Union offers a way to locate hot spots under the ocean more easily—and perhaps more precisely—than ever before.

Their technique, dubbed hot-spotting, depends on a new appreciation of some basic geometry. Previously, geologists required the ages of the various volcanoes created by a hot spot to determine its position. Knowing the past motions of the overlying plate relative to fixed hot spots, they could trace backward along a chain of volcanoes and project to the site of rising magma. But doing so for an oceanic plate is a challenge, because ascertaining the ages of dormant, submerged volcanoes (seamounts) is plagued with difficulties, including the problem of getting samples. Hence, this approach, called backtracking, is often not able to locate hot spots with great accuracy.

Wessel began his studies of the Pacific plate with the standard backtracking procedure in mind, but he made a mistake in programming his computer to carry out the numerical manipulations needed. "Instead of getting the expected path [along the seamount chain], I got another one," he recounts. After searching for the bug in his software, Wessel eventually recognized that his error was not an error after all. The curious path he calculated for the position of a volcanic seamount over a continuum of ages, he realized, spanned all the possible locations for the hot spot that had formed it.

Without knowing the age of the volcanic edifice, he could not discern where along this track the hot spot might be. But Wessel took an extra step that proved key: "I tried to plot several seamounts, and then I noticed that the lines intersected." Indeed, applying this procedure to all the volcanic seamounts and islands created by the archetypal Hawaiian hot spot (members of the so-called Hawaiian-Emperor chain) created a bold X on his map, marking the site of ongoing volcanism.



PAUL WESSEL

X MARKS THE HOT SPOT beneath Hawaii, from which outpourings of magma have built the chain of volcanic islands. Another X locates the Louisville hot spot in the South Pacific.

Locating this prominent heat source in the middle of the Pacific was not a particularly noteworthy achievement. After all, anyone living on the big island of Hawaii knows a hot spot lies below. But Wessel and Kroenke used their technique to improve the assessment of how the Pacific plate moved in the past. And that refinement allowed them to learn quite a lot about other Pacific hot spots.

The most dramatic results came when Wessel and Kroenke automated their hot-spotting procedure and applied it to the vast set of Pacific seamounts that had been mapped by satellite radar altimetry (information that was only recently declassified). With their technique, they found that many of the less pronounced volcanic chains produced blurred foci, indicating, perhaps, that the underlying hot spots may themselves be moving. They also noticed that the X marking the Louisville hot spot in the South Pacific was not where it was supposed to be. The location they obtained was, in fact, about 400 kilometers south of where most others had figured the hidden heat source must reside.

Curiously, only a few years ago instruments in French Polynesia had detected strange seismic rumblings emanating from this very locale, but geophysicists did not know quite what to make of them. "We located the source, we pointed to a map, and we said, 'Hey, there's something going on there,'" explains Emile A. Okal, a seismologist at Northwestern University. He and his French colleagues then convinced Louis Géli of the French oceanographic research agency IFREMER to survey the site, and the resulting expedition was completed last year.

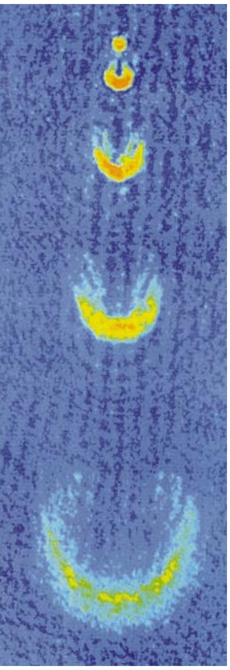
Géli and his co-workers found "very fresh" volcanic rock lying just below the surface of the sea. Radiometric dating of at least one sample indicates, according to Géli, "zero age, within the accuracy of the measurement." Thus, this site appears to have all the obvious markings one would expect for an underlying hot spot. Géli and his team are now trying to establish whether the volcanic rocks recovered indeed carry the geochemical signature of the Louisville hot spot.

Okal, who had vaguely suspected that the Louisville hot spot might have caused the recent seismic activity in the area, is particularly impressed with what Wessel was able to achieve using only the positions of seamounts, without their difficult-to-determine ages. "It's phenomenal what he was able to do by throwing away half the data," Okal quips. Yet Wessel is not boastful about devising a new methodology: "It just came out because I screwed up." *—David Schneider*

IN BRIEF

Atomic Blast

It's not a phaser weapon from *Star Trek,* but physicists at the Massachusetts Institute of Technology have developed a laser beam made of atoms. Lasers typically consist of light beams in which the photons are all in the same quantum state and their wavelengths also match. To make an atom laser, the team needed atoms in like quantum states, traveling in step. For such coordinated particles, they turned to Bose-Einstein condensates, first observed two years ago. This state of matter forms when atoms are cooled to a few billionths of a degree above absolute zero and their quantum states merge. Generating a laser from this atomic blob required some trickery. The group used a radio-frequency signal to knock loose a narrow beam of sodium atoms. The researchers verified its coherence by monitoring atomic interference patterns and by plotting the density of the atoms as they fell together in space and gradually dispersed (*photograph*). They speculate that the laser could find several applications. For example, it might improve the precision of atomic clocks or afford workers greater control in placing atoms on surfaces such as computer chips.



MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Lands of the Free . . . and Few

The first county-by-county census of endangered species in the U.S., published in *Science* in January by Andrew P. Dobson and his colleagues at Princeton University, produced some surprising results. Among them, it seems that the most threatened populations inhabit three states—California, Florida and Hawaii. Concentrating conservation efforts in these regions, then, may offer greater rewards. Moreover, the survey also found that critical tracts are typically found on private land. For this reason, many ecologists suggest that the government offer tax incentives to property owners as part of the Endangered Species Act.

More "In Brief" on page 26

BOTANY

SALIVATING FOR SAFFRON

Spain starts to look for the genes that make the spice

In La Mancha, the land made famous by the wandering Don Quixote, farmers bend low over purple blankets of crocuses to gather the buds that house the world's most expensive spice, saffron. For the past few years, cultivation has fluctuated because of the weather, and competition from other countries has hurt exports. To combat those threats, Spanish researchers are now considering biotechnology approaches to increase production.

Famous for its color, flavor and aroma, La Mancha saffron can command as much as 125,000 pesetas (about US$925) per kilogram, as compared to the 30,000 to 40,000 pesetas ($220 to $295) per kilogram for saffron from countries such as Iran and Greece. Such disparity in prices tempts some unsavory characters to pass off the less expensive kind as Spanish. This chicanery, in turn, has prompted the formation of a regulatory body that will provide a seal authenticating La Mancha saffron. The group's president, Antonio Garcia, says he is committed to "protecting the singularity of Spanish saffron."

In the meantime, researchers at the University of Castilla–La Mancha are trying to make the Spanish version more available. During the past two years, they have relied on traditional plant-breeding techniques, such as studying cultivation and identifying the heartiest specimens of *Crocus sativus* and cloning two or three with the best features. They have found that they can boost production by manipulating water level, sunlight and other factors. But the tricky part—making sure the treasured stigmas, the female organ of the flower that makes up saffron, retain their savory qualities—has proved elusive.

Hence the interest of saffron scientists in molecular biology and genetics. The Castilla–La Mancha researchers are particularly keen on U.S. studies of the "lab weed" known as *Arabidopsis thaliana.* That work demonstrates that distorting certain genes can lead to the modification or multiplication of sexual organs. One gene, called *Superman* when mutated, can double the number of stamens, the male parts of the flower. Jody Banks, a botanist at Purdue University, says that a similar genetic ap-

CEFRAN

MEN OF LA MANCHA
harvest crocuses by hand—a reason why saffron, made from the stigmas, is pricey.

proach might increase the saffron yield.

Finding those genes, though, won't be easy for Castilla–La Mancha. One of its plant geneticists, Horatio López Córcoles, laments that budgets are tight—well below $500,000 a year—so sequencing saffron could take some time. (He notes that the U.S. and Britain spend more on researching saffron, but for medicinal rather than culinary reasons.) Still, scientists and paella enthusiasts alike are hoping that all the work on Spanish saffron amounts to more than tilting at windmills. *—Erica Garcia*

FIELD NOTES

A GOLF CART, IT ISN'T

We drive GM's new electric vehicle

Southern California is a place where Ferraris and Lamborghinis hardly raise an eyebrow. So what's an attention-seeking automotive enthusiast to do? My advice is: get an electric vehicle.

This past February I drove General Motors's new EV1 and other electrics in and around Pasadena, Calif., and found that the vehicles attracted questions, comments and sometimes even small crowds. Undoubtedly, the vehicles' sleek shapes—whose favorable aerodynamics wring the most out of a battery charge—had a lot to do with it.

The GM car has the distinction of being the first EV by a major automaker in the past 70 years that was designed from the ground up as an electric. What this achievement demanded, first and foremost, was an extremely low coefficient of drag; at 0.19, the EV1 handily beats Chevrolet's Corvette, whose coefficient of 0.29 leads the industry among gasoline-powered cars.

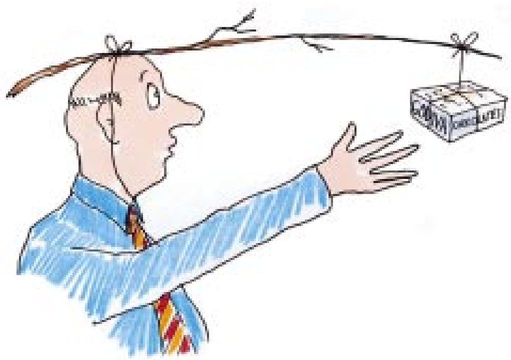
These kinds of facts and figures come rapid-fire from Rick Ostrov, who is orienting me at the Saturn dealership in Monrovia. Compact, fit and sporting aviator glasses, Ostrov looks more like a fighter pilot than the 40-something marketing specialist and avid surfer that he actually is. "What this is about is sustaining the planet," he says, just before I hop into the driver's seat. "We tell our clients that they are becoming test pilots for the 21st century."

To start the EV1, the driver punches a five-digit security code into a keypad,

ANTI GRAVITY

Separate but EQ

Bad news for readers of this magazine: it's not enough to be smart anymore. That's the sobering message from the folks behind the BarOn Emotional Quotient Inventory, which is being billed as the world's first commercially available test for measuring "emotional intelligence." Israeli psychologist Reuven Bar-On, who according to promotional materials has spent more than 16 years honing the EQ test, defines emotional intelligence as "capabilities, competencies, and skills that influence one's ability to succeed in coping with environmental demands and pressures and directly affect one's overall psychological well-being." Forrest Gump's IQ might be a number Tiger Woods would be proud to shoot, but his EQ could top the charts.


MICHAEL CRAWFORD

Speaking of boxes of chocolates, at a January press conference in New York City to launch the test, reporters each got a small box of Godivas. Steven Stein, a clinical psychologist behind Multi-Health Systems, the Toronto company marketing the BarOn test, told us we were free to eat the chocolate—but if we could make it through the press conference without opening the box, we would get a second box.

Stein explained that this trial by chocolate evoked the classic "marshmallow test." In the early 1960s examiners would give three- and four-year-olds a marshmallow. The children were told that if they could hold off eating it until the examiner returned from some nonexistent errand, they would get a second marshmallow. Only about 15 percent of the kids withstood the marshmallow temptation, with the other 85 percent becoming the people who lean over the tracks to see if a train is coming. This test of "impulse control," one of Bar-On's components of emotional intelligence, turned out to be the single most important indicator for how well those kids adapted in terms of number of friends and performance in school, according to Stein. (This reporter, being a nonchocoholic, glommed the two boxes of chocolate and gave them to lady friends—which may yet provoke a more accurate test of impulse control.)

The BarOn test itself consists of neither chocolate nor marshmallows, and unlike some psychological exams, it's not designed to uncover nuts. Bar-On and Stein see the test as a tool to create emotional profiles, which can be used to match people to suitable careers or to identify and improve weak areas. The test lists 152 statements, including "I like everyone I meet" and "I do very weird things," which subjects judge themselves to agree or disagree with on a five-point scale. The statements cover five areas: intrapersonal, interpersonal, adaptability, stress management and general mood. Those areas can then be further broken down. For example, general mood consists of optimism and happiness. (Yours truly scored a full 20 points higher in happiness than in optimism. I'm still pretty happy, but I doubt it will last.)

In developing the test, Bar-On administered it to more than 9,000 subjects in nine countries. The large pool includes enough journalists for a comparison between purveyors of print versus broadcast news. "We found that people in the electronic media tend to be more optimistic than those in the print media," Stein said. That difference can be easily explained. A few years back, this writer covered an auction of vintage Rolls-Royces and Bentleys for another publication. A prominent television journalist, who is safer left unidentified, also showed up. My optimism took a permanent hit that day, for whereas I was scrambling for a story, he came to shop. Although he might have a strong faith in the future, my broadcast brother could afford to be more lenient with his impulse control: if he opted to eat his marshmallow, he could always afford another Bentley-load. *—Steve Mirsky*

In Brief, continued from page 24

Still Going . . .

It's the Energizer Bunny of the space program. Pioneer 10, launched back in 1972 to study Jupiter, recently pulled off some high-flying acrobatics. The maneuvers were needed to point Pioneer 10's antennae toward the earth to improve reception; its signal had become increasingly weak in recent years. To muster enough power, the probe—now the farthest in deep space, 6.6 billion miles from the earth—had to turn off its transmitter, a risky gamble, project manager Larry Lasher feared. But after 90 minutes of spinning in the dark, Pioneer 10 sent word to NASA scientists announcing its success. All hope the trusty probe will keep transmitting data on intergalactic space for years to come.

NASA

Winging It

The antics of stub-winged stone flies may help explain how, evolutionarily speaking, insects first took off. James H. Marden of Pennsylvania State University reported in *Nature* this past January on some new ideas he came up with while watching stone flies gliding on water. Some used their tiny wings as sails. Others flapped them and moved faster. And Marden discovered another posture: some flies lifted their four front legs into the air; only the back two remained in contact with the water's surface for stability. At higher air temperatures, insects in this last position became airborne for short distances. Thus, Marden suggests that by "surface skimming," as he calls it, insects may have developed the ability to produce thrust and lift.

Color Me Well

A pill's hue appears to affect its potency, researchers at the University of Amsterdam confirm. Anton J. M. de Craen and his colleagues reviewed 12 previous studies on the matter and summed up the results as follows: people tend to find warm-toned pills stimulating, whereas cooler blue or green capsules calm them. The team emphasizes that if a pill's coating has the same effect on the psyche as its contents do on the body, people might be more willing to take their medicine.

More "In Brief" on page 28

presses a button labeled "run," then shifts into drive. While accelerating, I hear a vaguely futuristic whirring; to bystanders outside, however, the car is silent.

After satisfying themselves that the test driver is not sluggish or deranged, EV proponents generally encourage him or her to stomp on the accelerator, possibly to preempt any golf-cart analogies that might lurk. I am only too happy to oblige. Officially, the EV1 gets to 60 miles per hour (96.6 kilometers per hour) in less than nine seconds, a figure that compares well with gasoline-powered sports cars.

GM says the EV1 will go 110 to 145 kilometers between charges, depending on driving conditions. Non-GM testers have claimed results a tad lower, especially on urban streets. The vehicle is available only in southern California and Arizona, partly because cold weather adversely affects the lead-acid batteries and shortens the car's range. And the vehicle can only be rented, because several issues—such as the fact that the batteries wear out after a few years—make it impractical to sell.

GM has not revealed the so-called incremental cost of building each EV1 (a cost that does not include the $350 million that GM spent to develop the car). Knowledgeable outsiders, however, have estimated that each one costs at least $100,000 to build. Nevertheless, GM rents the car through its Saturn dealerships as though it had a sticker price of $34,000; state and federal tax credits then bring the monthly payment down to about $515 in California, with a $2,400 down payment. The equipment needed to charge the vehicle can be rented for an additional $50 a month.

GLENN ZORPETTE

ELECTRIC VEHICLE
is charged with an inductive "paddle" inserted near the front bumper.

At the end of January, after about seven weeks of availability, a total of 124 EV1s had been leased to a carefully screened group, chosen in part for their ability to understand and work around the vehicle's limitations. The EV1's flashy introduction was fueled by an initial advertising budget said to total $8 million (GM won't confirm this figure, either).

In response to some skeptical questions, Ostrov surprises me: "This car is not the answer. It is the beginning of the answer." And at this stage it has more to do with perceptions than with the biosphere. "The kids I surf with," he adds, "I can tell them, 'Hey, the future can be exciting and fun in a sustainable planet. It doesn't have to be golf carts or *Soylent Green.*' " —*Glenn Zorpette*

MEDICINE

STOPPING STROKES

Drugs in development may protect the brain from harm

Ten years ago medicine offered no means for treating ischemic strokes, those that result from blocked blood flow to the brain. Doctors could give patients little more than comfort, as neurons deprived of oxygen died, destroying an unpredictable mix of memories and motor skills. Then in the early 1990s, hospitals began making use of tissue plasminogen activator (tPA), a drug that by dissolving clots could minimize the damage done. It has dramatically improved the outcome in many cases. As research continues, however, it is becoming clear that clot-busters are only the beginning. "This is a continuing story," says Dennis Choi of Washington University School of Medicine. "And the rumble behind tPA in the pipeline is very exciting."

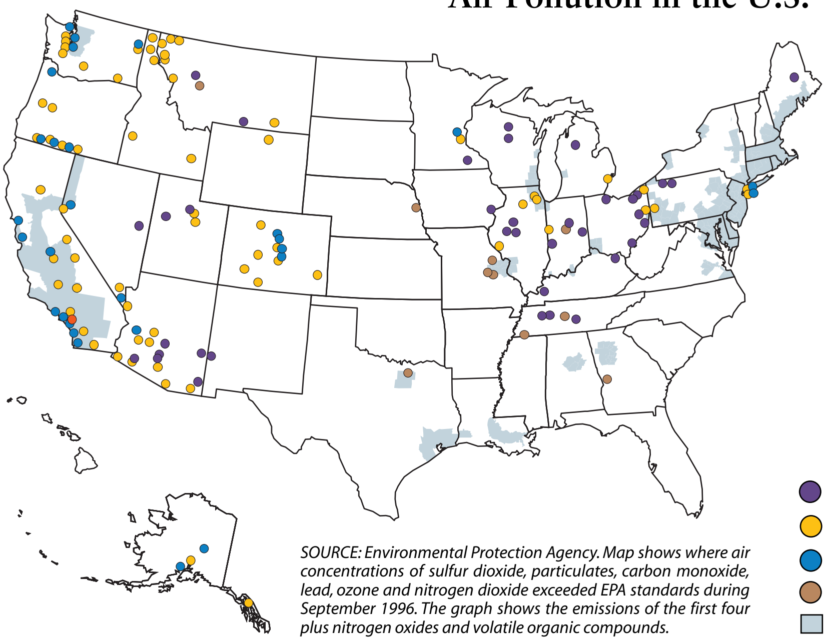
Indeed, recent studies have revealed several ways in which physicians might someday prevent—and not just limit—the impairment ischemia causes. They are rapidly finding better methods for protecting neurons against excitotoxicity, a process in which overactive proteins poison cells. And they are developing tactics to halt programmed cell death, or apoptosis. "The two pathways may occur in parallel in ischemia," Choi says, "and so we may need to develop combined drug interventions."

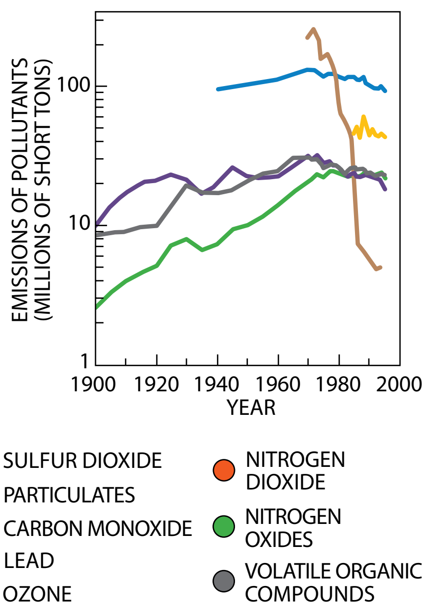
In hopes of stalling excitotoxicity, scientists have long tracked the effects of glutamate. This neurotransmitter floods the brain within hours after injury and opens NMDA receptors, porelike molecules that help to regulate the flow of charged ions in and out of brain cells. When NMDA receptors are overstimulated, they stay open, and affected neurons swell with toxic levels of sodium and calcium. Many cells die, but the natural acidity in the brain after a stroke typically turns NMDA receptors off within minutes—which presumably helps to keep the total damage in check.

Recently researchers have solved this puzzle with the discovery that glutamate-induced cell death can also be mediated primarily by other receptors, called AMPAs. Save during brief moments in fetal development, AMPA re-

BY THE NUMBERS

Air Pollution in the U.S.





SOURCE: Environmental Protection Agency. Map shows where air concentrations of sulfur dioxide, particulates, carbon monoxide, lead, ozone and nitrogen dioxide exceeded EPA standards during September 1996. The graph shows the emissions of the first four plus nitrogen oxides and volatile organic compounds.

The worst air pollution disaster ever recorded was in December 1952, when a temperature inversion trapped soot, sulfur dioxide and other noxious gases over London, killing 4,000. Nothing as dramatic has ever happened in a U.S. city, nor is it likely to, thanks largely to the efforts of the Environmental Protection Agency and various state agencies. Still, it is likely that thousands of Americans die prematurely every year because of air pollution.

The EPA has focused on air concentrations of six pollutants: ozone, nitrogen dioxide, sulfur dioxide, carbon monoxide, particulates (soot) and lead. (The concern here is ground-level ozone, not ozone in the stratosphere, which blocks ultraviolet rays.) The first five adversely affect lung function, exacerbating problems such as asthma. In addition, carbon monoxide, sulfur dioxide and particulates contribute to cardiovascular disease; the last also promotes lung cancer. Lead causes mental retardation in children and high blood pressure in adults. Nitrogen oxides and sulfur dioxide are the principal contributors to acid rain, and ozone damages crops and trees.

For each pollutant, the EPA has designated a maximum air concentration compatible with good health. The map shows areas where concentrations of the six pollutants were above the maximum in September 1996, a fairly typical period. Southern California has long had the biggest problems, with Los Angeles, for example, having 103 days during 1995 in which one or more pollutants exceeded the standard. Still, this level marks an improvement over the 239 days recorded in 1988. In contrast, no metropolitan area east of the Mississippi registered more than 19 days above the maximum, and almost half registered two days or fewer. Over the past decade or so, air quality in the East has improved, but ozone and several other pollutants remain substantial problems in many areas. Stringent new standards for ozone and particulates proposed by the EPA for adoption later this year would result in many new areas failing to comply. These areas are mostly east of the Mississippi, with the East North Central and Middle Atlantic states, the Carolinas, Tennessee and Kentucky being particularly affected.

The graph shows the dramatic fall in lead emissions since 1970, which stems from the elimination of leaded gasoline. Emissions of the other pollutants, with the exception of nitrogen oxides, have been on a downward trend since the early 1970s. Air concentrations of the six pollutants are also heading down, except for ozone, which is rising. Ozone, now the most widespread air pollutant, is not emitted directly but emerges from the interaction of other gases, notably nitrogen dioxide and volatile organic compounds. In 1995, 47 percent of emissions of the six pollutants came from transportation, mostly motor vehicles; another 26 percent was of industrial origin.

—Rodger Doyle

RODGER DOYLE

In Brief, continued from page 26

Black Holes Bare All?

Having conceded one bet in February to fellow physicists Kip S. Thorne and John P. Preskill of the California Institute of Technology, Stephen W. Hawking of the University of Cambridge has gambled again. Two T-shirts and £100 poorer, he asserts that no general way will be found for producing singularities—infinitely dense points at the core of black holes—outside of black holes. Originally, Hawking bet that such naked singularities simply could not exist, but a computer simulation constructed by Matthew Choptuik of the University of Texas proved him overly confident. If somehow the so-called event horizon surrounding a black hole could be stripped away, a bared singularity would lie below and perhaps produce a flash of light. Of course, event horizons themselves have only recently been detected. Ramesh Naryan and his co-workers at the Harvard-Smithsonian Center for Astrophysics studied x-ray novae, using the orbiting ASCA telescope, and found that four novae thought to harbor black holes gave off less light than those containing neutron stars. Naryan interprets the dimness as evidence of gas energy vanishing beyond an event horizon. Wagers, anyone?

FOLLOW-UP

Hold the Lox!

Mad cow disease could drift downstream on the food chain. This degenerative neurological disorder, like other spongiform encephalopathies that infect humans and animals, may arise from prions, which are abnormal versions of amyloid protein (PrP). Researchers at the National Institutes of Health and the University of Milan recently found normal PrP in the brains of spawning salmon. Because the protein may, in rare circumstances, be able to convert to an infectious form, farm-raised salmon, like beef, could in theory pose a public health threat. Previously, PrP had been detected only in mammals. (See December 1996, page 16.)

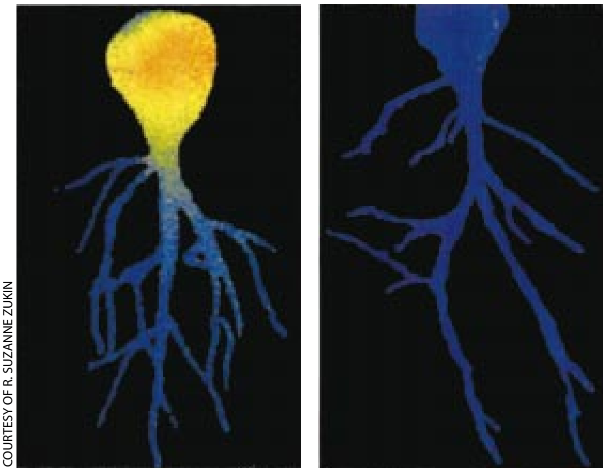
JEFF FOOTT *Bruce Coleman Inc.*

—*Kristin Leutwyler*

ceptors repel ions that have a strong positive charge, such as calcium, because one of AMPA's constituent subunits, called GluR2, places a like charge in the middle of the channel pore. In the past year R. Suzanne Zukin and Michael Bennett of the Albert Einstein College of Medicine, William Pulsinelli of the University of Tennessee and John Connor of the Lovelace Institutes in Albuquerque demonstrated that ischemia inactivates the *GluR2* gene. Zukin theorizes that the initial influx of calcium into NMDA receptors may flip this genetic switch.

Without GluR2 subunits, AMPA receptors become calcium permeable and so key players in excitotoxic cell death. Using a dye that shifts color when it binds to calcium, Zukin showed how powerfully AMPA receptors change character 24 to 48 hours after a stroke. She blocked all other channels by which calcium might enter single neurons taken from gerbils 30 hours after a stroke. "In healthy controls, there was no color change when the AMPA receptors were activated," she comments, "but in the stroked animals, it was remarkable." Investigators are now in search of safe compounds that can block calcium-permeable AMPA receptors. So far only toxic varieties have emerged. But less specific AMPA blockers prevent cell death in animal models even when they are administered as late as 24 hours after ischemia.

For tackling apoptosis, Choi and his colleagues have tested a drug called ZVAD, which inhibits a protein that prompts apoptosis during development. In cultured cells, the compound was neuroprotective. George S. Robertson of the University of Ottawa has shown that the neuronal apoptosis inhibitor protein (NAIP) is also effective. He discovered the NAIP protein and gene while studying children who lack them and suffer from spinal muscular atrophy. In one study, Robertson introduced the *NAIP* gene, by way of a virus, to vulnerable neurons in rats after ischemic attack and found that it reduced brain damage by more than 60 percent. In another study, he employed a drug, K2528, that causes animals to produce more NAIP protein. This therapy, too, proved beneficial; the drug should enter clinical trials within the year.



COURTESY OF R. SUZANNE ZUKIN

***AFTER STROKE IN HAMSTER NEURONS, AMPA receptors are unable to block an influx of toxic calcium ions* (left), *as they normally do* (right).**

As an added bonus, K2528 exhibits some antiexcitotoxic effects. Other drugs may also tackle excitotoxicity and apoptosis simultaneously by sweeping up certain free radicals, which provide a crucial step in both processes. Zinc ions have recently been implicated in excitotoxicity and apoptosis, too. Choi's laboratory found that binding zinc before it enters susceptible neurons helps to preserve them after ischemic insult.

Moreover, drugs for ischemia could prove useful for treating other conditions. K2528 may well mitigate brain damage brought on by Alzheimer's disease, in which apoptosis may play some role. And Zukin notes that chemicals blocking glutamate-induced cell death may similarly lessen the impact of epilepsy, head trauma, Huntington's disease and AIDS encephalopathy. "There is a barrier of inertia based on the historical notion that you could do nothing about brain damage," Choi states. "Now there is hope." —*Kristin Leutwyler*

ASTRONOMY

THE GREENING OF EUROPA

Are the satellites of giant planets a place to look for life?

In Arthur C. Clarke's new book *3001* (the third sequel to *2001*), he envisions Jupiter's large moon Europa as the home to a diversity of lifeforms that evolved around hydrothermal vents deep beneath Europa's global ice sheet. Clarke's writing, though fiction, builds on a very real sense of excitement in the scientific community: images from the Galileo spacecraft hint that liquid water—one of the necessities for the life that we know—may lurk below Europa's surface.

More than a decade ago the Voyager spacecraft revealed Europa as an unusual world: swathed in ice, marked by a network of mysterious brownish lines, and geologically young. Last December 19, Galileo whizzed just 692 kilometers (430 miles) above the surface of the satellite; the resulting snapshots (available at http://www.jpl.nasa.gov/galileo/) capture a dynamic topography marked by formations that "appear to be remnants of ice volcanoes or geysers," reasons Ronald Greeley of Arizona State University.

These discoveries provide insight into the amount of heat trapped inside Europa. Its surface temperature averages a chilly –200 degrees Celsius. Gravitational interactions among Jupiter's moons transfer energy to Europa's interior, however. If the energy flow is great enough, it might be sufficient to melt the underlying layers of ice, creating a vast ocean. The Galileo images show that "there was enough heat to drive flows on the surface," Greely reports, although they do not yet prove the presence of liquid water below.

The heightened interest in Europa comes at a time when scientists are increasingly considering the possibility that satellites, not just planets, might support conditions suitable for life. Within the past two years, astronomers have discovered possible planets circling eight sunlike stars. These giant worlds probably offer poor prospects for terrestrial-type biologies. But in a recent paper in *Nature,* Darren M. Williams, James F. Kasting and Richard A. Wade of Pennsylvania State University suggested that possible large moons orbiting two of the planets might fall into the "habitable zone" where life can arise.

The analysis is highly speculative, the Penn State authors admit. Nobody knows whether the newfound planets have any satellites at all, nor is it clear how likely it is that even giant planets will have satellites massive enough to hold on to a substantial atmosphere and to generate a protective magnetic field. On the other hand, the example of Europa suggests that there is some flexibility in the rules for habitability.

Indeed, common notions regarding habitable zones may be grossly conservative, argues Christopher F. Chyba of the University of Arizona in a commentary accompanying the *Nature* paper. Williams and his colleagues focused on environments that could allow liquid water and solid surfaces. But Chyba recalls that the late Carl Sagan envisioned life-forms that could thrive among the clouds of Jupiter; in the other direction, Thomas Gold of Cornell University suggests that simple organisms may thrive deep in the earth's interior. "It shows how little we understand life even on our own planet," Chyba reflects.

If Europa does have a buried ocean, does it contain life? Chyba responds with another question: "Can an ocean of liquid water persist for 4.5 billion years and *not* have life in it?" he asks. But a couple dozen kilometers of ice would pose a formidable barrier to direct contact between us and any possible them—a sobering reminder that we are still absolute beginners at exploring the worlds around us. *—Corey S. Powell*

PROFILE: DAN FARMER

From Satan to Zen

It has been said that "Internet security" is an oxymoron. Privacy, accountability and restricted information, the argument goes, are technologically incompatible with a public network exploding in size and software complexity. If so, then it is little wonder that Dan Farmer, at age 34, is already widely acknowledged—begrudgingly, by some—to be one of the world's elite Internet security experts. In his life and in his work, Farmer thrives in the thin gray area where mutual exclusives meet.

In many respects, Farmer fits the profile of a security guru. After a stint in the U. S. Marine Reserves, his first steady job was tracking down hackers for the Computer Emergency Response Team at Carnegie Mellon University. Later, Silicon Graphics hired him as a "network security czar." Now he commands consulting fees as high as $5,000 a day and testifies before Senate committees on securing federal computer systems.

Yet when Farmer attends conferences, he blends right in with the hackers who flock around him as though he were a rock star. At his modest house in Berkeley, Calif., he greets me at the door unshaven, in shredded black leather pants and stocking feet. His curly red mane intertwines with a silver ring piercing his right eyebrow, hangs past thick, unfashionable glasses and overlaps a conspicuous rainbow-colored "PRIDE" logo emblazened on his T-shirt. Directing me to a chair surrounded by empty wine bottles, an unmade futon, a partially disassembled computer and a shoulder-high scratching post for his cat, Flame, Farmer pops a U2 compact disc into the stereo and selects a bottle of cabernet from the dozens of high-priced wines racked in his living room.

As he lights up a half-smoked clove cigarette and blows smoke rings between sips of wine, I begin to see just how appropriate it was that, two years ago, Farmer adopted the Internet alias satan@fish.com, juxtaposing symbols of evil and righteousness. Then he was putting the final touches on SATAN, a program that would bring him international notoriety—and would cost him his czarship at Silicon Graphics. Hackers break into networks by exploiting bugs or careless configurations in the software at system hubs. SATAN contained a database of these holes and could systematically probe a network for such weaknesses. Other programs, such as COPS, which Farmer wrote six years earlier, performed similar tasks. But SATAN differed in at least two important ways. COPS examined one's own computers; SATAN could probe any site on the Internet. "It raised an issue that affects everything on the Net: the same tools that help the good guys help the bad guys," says William R. Cheswick, a senior network security researcher at Lucent Technologies's Bell Labs. "As Isaac Asimov said, 'A blaster points both ways.'"

Perhaps the more important difference, suggests Wietse Venema, a computer scientist at the Eindhoven University of Technology in the Netherlands and coauthor of the program with Farmer, was the tool's provocative name. "The press coverage I got in Europe was a lot friendlier," Venema recalls. "I felt a bit of pity for Dan" as the media seized on predictions by doomsayers that Farmer's free release of SATAN would lead to widespread hacker invasions.

Venema's pity may have been premature. SATAN propelled Farmer's meteoric rise in commercial value, which is all the more surprising when held against his slow start. Reared in Bloomington, Ind., Farmer disliked his first computer class at Indiana University, which was taught by the renowned mathematician (and former *Scientific American* columnist) Douglas R. Hofstadter. Switching to Purdue University and wending his way from astronautics through math back to computer science, Farmer recalls an unremarkable college career, sufficiently unpleasant that he interrupted it to join the Marines. (Yet when he was recalled for service during the Gulf War, Farmer declared himself a conscientious objector and was discharged.) Back at Purdue, his grades fell short of graduation requirements, so he convinced computer scientist Eugene H. Spafford to supervise his development of COPS.

"COPS was one of the first Internet security tools ever written; it was my ticket into the field," Farmer says. Maybe so, but SATAN was his ticket to fame, and Farmer smiles widely as he says, "If I have become the Barry Manilow of security—the popular version of the thing—that's fine, although I'm really not socially equipped to deal with it."

Able and willing need not go together;

M. HALLAHAN *Network Images*

INTERNET SECURITY GURU DAN FARMER
thrives in the gray area between thwarting hackers and encouraging them.

Breaking and Entering

There's no shortage of work for security consultants like Dan Farmer.

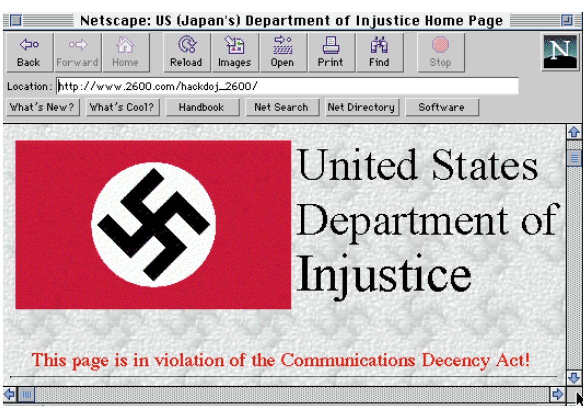
Estimated number of hacker attacks on Department of Defense networks in 1995:	250,000
In 1996:	500,000
Estimated percentage that are successful:	65
Estimated percentage detected by the DOD:	Less than 1
SOURCE: Defense Information Systems Agency	
Average number of potentially damaging hacker attempts on Bell Labs networks in 1992, per week:	6
Average number of less threatening attacks, per week:	40
Average rate of attacks in 1996:	No longer tracked
SOURCE: William R. Cheswick	
Percentage of banks in recent survey that report plans to offer Internet banking services in 1997:	36
Percentage of existing bank Web sites found to have potentially significant security holes:	68
Percentage of Web sites selected at random with such holes:	33
SOURCES: Datapro Information Services Group; Dan Farmer	

Farmer continues to seek, and receive, popular attention. History proved Farmer right about SATAN. "It was really a nonevent in security," Cheswick observes. But in December, Farmer again courted controversy when he used an updated version of SATAN to scan, without permission, 1,700 World Wide Web sites maintained by banks, credit unions, newspapers, federal agencies and pornography purveyors (the last because they depend on the ability to conduct electronic transactions securely). About two thirds, he reported in an on-line summary, are running bug-ridden software that make them easy targets for amateur hackers to disable and potentially damage.

Farmer did not publish the list of vulnerable sites, and he insists that his probe only deduced vulnerabilities but did not test them. Nevertheless, worries Steven M. Bellovin, a network security analyst at AT&T Labs–Research, "what Dan did is questionable because he was looking for security holes in other people's servers without their consent." Cheswick agrees but points out that "bad people run these kinds of sweeps and tests all the time as anonymously as they want, and we can't stop them. If my site was probed 100 times this week and Dan's was one of them, that's fine with me. At least with his scan, we're getting some research data."

Farmer himself admits to some qualms. "If I saw some guy walking through my neighborhood checking doorknobs, it would give me a weird feeling. I think permission should be asked. I guess that makes me a hypocrite. But I don't like being in the gray area," he asserts, despite appearances to the contrary. Of course, Bellovin notes, "What makes Dan unique is that he is willing to do this, whereas most other [security experts] are not."

That 68 percent of the Web sites maintained by banks and 70 percent of those managed by newspapers appear wide open to attack may shock casual Net surfers, but Farmer and his colleagues were not surprised. "I suspect that many of the systems are even more vulnerable than his survey indicates," Bellovin remarks. "There are many problems you can't detect until you actively try to exploit them," Spafford agrees. "What did surprise me is that out of 1,700 targets, only four responded to my probes," Farmer says. "If you're in a bank, and someone is testing all the windows, wouldn't you expect a security guard to stop him? On the Internet, that's not happening."



DEFACED WEB SITE *embarrassed the U.S. Department of Justice with its sophomoric graffiti. This and other hacked sites are archived at http://www.2600.com/hacked_pages*

Most banks' Web sites still contain only advertising and company information, but that is changing. As more people read news, bank and shop on-line, the potential wages of Internet crime mount. "What if I break into Reuters or Associated Press and change a wire report to say that Bill Gates has died?" Farmer speculates. "Microsoft stock would go down like a rock. Maybe it would recover in a day or two, but wouldn't that be a good opportunity for someone to exploit?" Businesses on the Net are at risk, Cheswick says, because "we haven't learned what the fraud rate on the Internet is yet; that makes it hard to get the business model right. And on the Net, it is very easy to steal secrets and never be detected."

Pressed for solutions, the researchers can suggest few. "A lot of machines come out of the box insecure," Cheswick notes. Silicon Graphics workstations, he says, ship with some 70 security-related programs installed; a bug in any one can compromise all the files on the machine. "New computers should come locked up and force you to click a little box that says, 'Screw me' or 'Insecure,' when you turn off the security options. That way the people who have less time or less of a clue will have some idea of what they've done." Bellovin suggests that software vendors must be held responsible for the bugs in their products. "It may happen by regulation or by lawsuit or by insurance fiat, but it has to happen at some point."

For his part, Farmer is designing a new tool that will both identify the security holes on a computer and automatically download the software patches to plug them. Yet even as he works to raise the alarm and muster technology in defense of the Internet, Farmer professes an almost fatalistic pragmatism. "By and large, people really don't care about security," he says. "To some degree, even I don't care. I take the standard precautions, but people still break into my machine. I mean, I don't even lock my door when I go out at night. If it takes an additional 5 percent of my time to run a really secure ship, I'd just as soon go see a movie or drink some more wine." Perhaps that explains why his recent report is signed with a new handle, buried significantly beneath a spinning yin/yang disk: zen@trouble.org

—*W. Wayt Gibbs in San Francisco*

DEFENSE POLICY

PLAYING NICE

The Pentagon tries to share R&D weapons costs with allies

Last December armaments directors from the U.S., Germany and Italy gathered in Huntsville, Ala., home to the U.S. Army's Missile Command. Their purpose was to sign an agreement linking the three countries in the development of a defensive weapon known as the Medium Extended Air Defense System. Long a priority for the U.S. Army, MEADS, as it is called, will be the last line of defense against ballistic and cruise missiles for maneuvering troops—a mobile, more advanced cousin of the Patriot system used to defend against Scud missiles during the Persian Gulf War.

But MEADS has attained importance beyond its future battlefield role. It has been selected by the Clinton administration as the test case for a new kind of international cooperative development, the harbinger of what former defense secretary William Perry hopes will be a "renaissance in armaments cooperation."

During the cold war, the U.S. generally did not share research and development costs. To ensure that its forces could fight alongside Allied troops equipped with similar weaponry, the U.S. preferred instead to sell finished weapons systems. Under pressure to control spending, the Clinton Pentagon believes that increasingly expensive defense technology can be developed for less if several countries share costs from the start.

Past U.S. efforts to collaborate on defense technology with allies, however, have seldom worked out well for anyone. During the 1980s, for instance, the U.S. began to develop the so-called Terminally Guided Warhead (TGW) for its Multiple Launch Rocket System with the U.K., France and Germany. After years of cost overruns and schedule delays, the TGW was canceled, in part because the U.S. chose to build another warhead, the Brilliant Antiarmor Submunition. The other partners were not pleased—rankled mostly because the warhead chosen had been developed secretly while the four partners were spending hundreds of millions of dollars on the TGW project. But despite such previous failures, Perry told Congress last year, the U.S. has resolved to "carry through on her promise to improve her recent record in armaments cooperation."

MEADS is the first real test. The U.S., with its far larger military and industrial base, will pay for 60 percent of MEADS's first phase; Germany is responsible for 25 percent, and Italy 15 percent. But all involved are members of the North Atlantic Treaty Organization, and the program will be run according to NATO's one-country, one-vote system. "There are no junior partners," says Brigadier General Hunrich Meunier, the German officer who leads the MEADS program office in Alabama. That should encourage Germany and Italy to stay with the program, despite their smaller financial contributions.

On the industrial side, two teams made up of U.S., German and Italian companies have been formed. One features U.S. defense giant Lockheed Martin; the other includes the American firms Raytheon and Hughes Aircraft. Europe's smaller industrial base, however, forced Germany and Italy to split up three companies equally: each company has representatives on both teams, but they are divided by what program officials call "Chinese walls" to ensure proper competition. In 1998 one team will be chosen to produce MEADS if the partners remain committed to it. Competition, Under Secretary of Defense for Acquisition and Technology Paul G. Kaminski insists, is key to successful international cooperation. It's also what has been missing in the past, he says: "When there isn't any real incentive for good performance, people naturally get lazy."

It is too soon to tell if the new arrangement will work. Cooperation complicates matters, requiring the approval of multiple defense ministries, legislatures and executives. France, once the fourth partner, has dropped out, citing budget constraints; the French may market a competitor to MEADS. Congress has added billions of dollars to other missile defense programs since Republicans won a majority in the House and Senate in 1994, but defense committees have consistently attacked MEADS, in part because of its international flavor. (Critics fear that the technology could more easily fall into the wrong hands.) This has put the Clinton administration in the unusual position of defending one vestige of Ronald Reagan's Strategic Defense Initiative, while canceling or delaying other SDI-spawned programs.

Other pitfalls loom. The partners have committed only to early development, not production, and the U.S. has no money budgeted for MEADS beyond

SYGMA

***MISSILE DEFENSE FOR BATTLEFIELD SOLDIERS—** more advanced than this Patriot missile fired during the Persian Gulf War—could become a model program for the international development of weapons.*

1998. And a former member of the Republican-majority Congress, William S. Cohen, is the new defense secretary. So far Cohen has hewed to the Clinton defense agenda, and during his Senate career he was a staunch supporter of missile defense programs. But the Pentagon is in the middle of a top-to-bottom review of defense priorities that may lead to dramatic changes, and MEADS could fall victim to budget cuts. And many within the U.S. military, like their congressional counterparts, are wary of international cooperation. Finally, some defense contractors object because cooperative development could threaten the lucrative business of selling American weaponry overseas.

Still, advocates are fighting. Perry told Congress that "our armaments base is in real danger of facing 'closed shops' in many parts of the world." Should the U.S. cut funding for MEADS, he warned, "the repercussions could be disastrous." Without MEADS, the U.S. could be shut out of future international opportunities, and without international cooperation, MEADS most likely will be unaffordable, Kaminski says: "I doubt that the resources will be there for the U.S. to go it alone."

—Daniel G. Dupont in Washington, D.C.

PHARMACEUTICALS

DREDGING THE DIGESTIVE SYSTEM

Polymer-based drugs sweep out cholesterol and other undesirables

Most drugs work by tinkering with the complex machinery of cells. Some interfere with the chemical messages cells send to one another. Others flip cellular switches to make them do something they normally wouldn't. However they work, the best drugs are usually those that home in on particular cells and tweak them in just one way.

So it might seem strange that GelTex Pharmaceuticals, a tiny six-year-old drug company in Waltham, Mass., is developing two drugs that it hopes will pass right through patients without directly affecting a single cell. GelTex's drugs are composed of polymers—huge molecules that are no more digestible than a bit of plastic wrap stuck to a hard candy.

Although they never enter the bloodstream, these polymers offer more benefit than just roughage. GelTex handpicked the compounds for their ability to soak up particular chemicals on their sojourn through the digestive tract. One polymer, named RenaGel, "contains a molecular docking slip into which phosphate fits very happily," explains Dennis Goldberg, GelTex's head of research. That can help patients with chronic kidney failure, who often have trouble getting phosphorus out of their bloodstream. When levels rise too high, the body starts leaching calcium from the bones to restore balance. The process can weaken bones and harden blood vessels, so nearly all the half a million or so people currently on dialysis take calcium tablets. But the supplement's effect on phosphorus is weak, requiring up to 20 pills each day; in some, the treatment causes calcium overload.

HIGH-CHOLESTEROL DIETS
have put some 65 million Americans at risk of heart disease.

RenaGel tablets contain no calcium. Swallowed with food, they expand into a gel that binds up much of the phosphate as it moves through the intestines. In phase III clinical trials completed in January, 172 patients were able to keep phosphorus levels safely under control with just six to 12 tablets a day. The company hopes to get the drug to market later this year.

RenaGel is really just a warm-up for the drug GelTex hopes will be its blockbuster: CholestaGel. Some five million Americans spend $6 billion a year on cholesterol-lowering drugs, yet the National Institutes of Health estimates that eight million more people in the U.S. have enough cholesterol coursing through their veins to warrant drug treatment.

Cholesterol can be reduced significantly by eating less of it and by exercising more. That is evidently easier said than done, so GelTex has formulated a molecular net to help those who help themselves all too often. The CholestaGel polymer does not bind cholesterol directly. Instead it seizes onto bile acid, which the liver synthesizes from cholesterol ferried in by low-density lipoproteins. As the gel dredges bile acid from the system, the liver secretes more, drawing cholesterol out of the blood vessels where it is most dangerous.

The strategy is not entirely novel: two licensed drugs, Bristol-Myers Squibb's Questran and Upjohn's Colestid, use other chemicals to achieve the same effect. But because they require unpleasantly high doses and often produce bloating or constipation, the existing bile binders are not very popular. GelTex's phase II trials completed in January suggest that lower doses of CholestaGel can knock 20 to 30 percent off patients' cholesterol levels without the bothersome intestinal symptoms.

Despite the encouraging results, GelTex is stepping slowly. Whereas many upstart drug firms leap from successful phase II trials directly to pivotal large-scale studies, GelTex has opted for more small tests; it just started its fourth phase II trial on CholestaGel and a second phase III on RenaGel. It is all part of a philosophy, says president Mark Skaletsky, of avoiding surprising side effects.

—W. Wayt Gibbs in San Francisco

MATERIALS SCIENCE

PLASTIC POWER

Lightweight batteries show their muscle in demonstrations

Batteries are heavy, as anyone who has lugged around a portable computer can testify. And in applications ranging from satellites to battlefield equipment, their weight is more than just an inconvenience. It seriously limits the performance of equipment. Researchers at Johns Hopkins University have developed a promising fix: a battery made entirely of plastic. The device was widely believed an impossibility a few years ago. But in March, Joseph J. Suter of the Applied Physics Laboratory was scheduled to demonstrate it to the U.S. Air Force, which sponsored the development—a plastic battery capable of powering a two-way radio for an hour.

The all-plastic battery has had to overcome several technical hurdles, the most obvious being that plastics are usually electrical insulators. That can be changed, however, by incorporating "dopants" into certain types of polymers. Dopants are substances that either supply extra electrons to conduct charge or, alternatively, take electrons away to create "holes"—places in a molecule that conduct charge by accepting electrons. Compounds called polypyrroles are now in use in commercial cells in combination with metals. But batteries made entirely of polypyrroles have not achieved high enough voltages to be useful.

MARTIN H. SIMON SABA

***ALL-PLASTIC RECHARGEABLE BATTERY** can produce up to three volts.*

Recently Theodore O. Poehler and Peter C. Searson of Johns Hopkins have made multiply rechargeable, thin-sandwich cells that produce up to three volts—a useful number. They used as electrodes carefully chosen combinations of plastics identified as fluorophenylthiophenes; a polymer gel containing a boron compound connects the electrodes. The cells can store more electrical energy per gram than lead-acid or nickel-cadmium cells, although not yet as much as lithium batteries. But Suter, who fashions the plastic cells into useful designs, points out that their lack of metal content makes them safer and more environmentally friendly than batteries containing lead, cadmium or lithium. Battery researchers generally "believe we will move to polymer or plastic batteries," Suter asserts.

Another advantage of the plastic batteries is that they are flexible. That means it should be possible to fit them into awkward spaces. One early demonstration project will utilize the batteries in combination with solar cells in a Global Positioning System receiver for hikers. A panel of the cells is also slated for testing in 1998 on a satellite. A chain of burger vendors has even inquired about using them in talking paper bags, Suter says. He is now discussing with battery manufacturers how to roll up the devices to make AA-size cells.

Plastic batteries have some drawbacks. They need special electronics to charge them optimally. They also have to be hermetically sealed, which was a difficult part of the development, Suter notes. Moreover, terrorists could find them useful for building undetectable letter bombs, a fear that prompted him to turn down inquiries from a researcher in Iraq. Batteries produced to date have been deliberately made visible on x-ray machines by incorporating metal grids.

None of these obstacles looks likely to prevent the batteries from being commercialized, Suter declares. And Poehler says new electrode materials now in early testing may store 10 times more energy than even fluorophenylthiophenes. Plastic batteries, if they find real-world applications, could be a money-spinner. The Johns Hopkins team expects this summer to be issued patents covering all types of polymer batteries.

—Tim Beardsley in Washington, D.C.

MICROELECTRONICS

CHECK YOUR BAGS

Electronic tags could match passengers with luggage

Baggage reconciliation—making sure each piece of luggage is linked to an accompanying passenger—remains an important means of combating terrorism on international flights. But the White House Commission on Aviation Safety and Security, informally known as the Gore commission, recommended in February that only limited baggage matching be introduced by year's end on domestic journeys. The recommendation to match only the bags of passengers fitting a certain profile was made for logistical reasons.

The need to pick out unmatched bags from an airplane cargo hold might create significant delays within the U.S. system of hub airports, which links a high volume of passengers to connecting flights. Retrieving stray luggage can take from a few minutes to up to an hour with the current baggage-matching procedures, which rely on simple visual inspection or on bar codes optically scanned at close distance.

The Clinton administration has indicated that it is still committed to match every bag to a passenger as soon as new technology is mature enough. Wireless technology that could help locate unattached bags and, more generally, streamline baggage handling has begun to emerge. An electronic tag would be affixed to each bag and would store the identity of the passenger and other information, such as destination and baggage weight. If the airline computer showed that a passenger had not boarded the airplane, a baggage handler could scan the baggage compartment with a handheld reader that could be pointed in different directions. Like a Geiger counter, the needle on the reader might jump as a worker approached the bag from as far away as 10 feet.

Semiconductor manufacturers—Texas Instruments, Motorola, Micron Technology and several smaller companies—have developed electronic tags. The most advanced tag integrates memory, a processor, a transmitter and a receiver on a single chip, which is combined with a miniature battery and antenna. Future versions may allow the microwave-frequency signal to be encrypted.

Last year the Federal Aviation Administration began a testing program for electronic tags, notes Buzz Cerino, who manages an airport security program at the FAA's Technical Center in Atlantic City. Interest may continue to grow. The International Air Transport Association is expected to recommend a standard for the tags this year.

Wireless technology may also contribute to the airport of the future. Executives from Micron Communications, a division of the chip company whose tags are being tested by the FAA, envisage a wireless device that would function as an electronic boarding pass and would keep track of the location of luggage within the airline's system. The card would alert the airline of a passenger's arrival. A greeting would flash on a screen at the entrance to the airport, directing the passenger to the correct gate. Antennas dispersed throughout the airport could track the passenger's whereabouts for security and for providing an alert of a schedule change. The network of antennas could be used with the pass for finding lost luggage that bears the electronic tags.

Making baggage tags smart will not come cheap, although costs have begun to drop because the circuit elements all reside on a microchip. For the technology to be marketable, manufacturers will need to sell a tag for a dollar or less. That amount is still a lot more than the five cents or so for a bar code, although time savings and other efficiencies may make up for the additional outlays. John R. Tuttle, chairman and president of Micron Communications, suggests that passengers might buy their electronic boarding pass and baggage tags for under $10, an expense he compares to obtaining a driver's license. Tuttle's idea is just one of a number of suggestions on the table. But if a workable plan can be formulated, checking your bags may take on new meaning in an era of wireless communications.

—Gary Stix

ETIENNE DE MALGLAIVE *Gamma Liaison*

***MATCHING PASSENGERS WITH BAGGAGE** using electronic tags may avoid having travelers disembark to identify luggage.*

CYBER VIEW

Cracking the U.S. Code

Late last winter a graduate student at the University of California at Berkeley needed only three and a half hours to crack a message encoded in the strongest legally exportable cipher in the U.S. He used the spare processing cycles of a few hundred workstations on the campus network. Although computer scientists and high-tech companies all agree that more secure codes should be widely used, the U.S. government continues to come down hard on would-be purveyors of cryptography. And courts in California and Washington, D.C., have issued diametrically opposed opinions about the legitimacy of government controls over cryptographic software.

It has been almost five years since Daniel J. Bernstein, now a professor at the University of Illinois, first asked the State Department whether he could be jailed for distributing a technical paper on cryptography and two pages of program code illustrating the results of his research. He has yet to receive a straight answer.

The point of Bernstein's paper was to demonstrate that some innocuous-looking and widely used mathematical functions could encrypt files as well as more obviously dangerous algorithms. When he first asked the State Department for separate rulings on the paper and the programs, the Bureau of Politico-Military Affairs claimed that the paper served as documentation for the programs. So they combined the requests and denied them both, citing the International Traffic in Arms Regulations (ITAR), which govern publication of cryptographic information. But in mid-December federal Judge Marilyn Patel ruled that ITAR was a classic example of unconstitutional restraint on free speech and that Bernstein could not be prosecuted under them. At the end of the month, the Clinton administration issued new regulations that transfer jurisdiction to the Commerce Department but otherwise could subject Bernstein and anyone else who teaches or writes practical information about cryptography to heavy fines or jail terms.

The new regulations also contain a peculiar clause that forbids bureaucrats deciding whether to grant an export license for an encryption system from taking into account whether equivalent or identical software is already available overseas. Software firms and individuals such as Bernstein had previously tried to bolster their cases with lists of the nearly 2,000 strong-encryption software packages available outside the U.S.

About the time that Bernstein's travails were beginning, Bruce Schneier authored a book entitled *Applied Cryptography,* which discusses many commonly used ciphers and included source code for a number of algorithms. The State Department decided that the book was freely exportable because it had been openly published but refused permission for export of a floppy disk containing the

DAVID SUTER

same source code printed in the book. The book's appendices on disk are apparently munitions legally indistinguishable from a cluster bomb or laser-guided missile. In early 1996 federal Judge Charles R. Richey dismissed the lawsuit to overturn this decision, brought by Schneier's collaborator, Philip R. Karn, Jr. Richey cited among other things a clause in ITAR that exempts decisions under them from judicial review.

The new regulations do not contain the exemption from review (which Patel had declared unconstitutional). As a result, in January an appeals court in Washington returned Karn's case to Richey, who will determine whether the other reasons he gave for dismissing the case still hold. In the meantime, Karn's disk cannot legally leave the country, even though the original book has long since passed overseas and all the code in it is available on the Internet.

At the heart of both cases is the argument over whether software is a text or a machine. Bernstein and Karn argue that their right to free speech is being violated, but government lawyers contend that the regulations simply prohibit the export of dangerous equipment for concealing information. On the one hand, programs—even in the form of 1's and 0's—can be protected by copyright like other texts. On the other hand—even when described in plain English—they can be patented like other machines. And many computer scientists agree that the best way to explain how a computer program works is simply to give people the code to study.

Advances in computer science are not clarifying matters either. Automatic-programming systems, which transform abstract mathematical specifications into working code, could generate encryption programs from high-level descriptions, says Alan Goldberg, a researcher at the Kestrel Institute in Palo Alto, Calif. (The basic recipe for the strongest public-key cryptographic systems, for example, is: "Treat the characters in the message as digits in a very large number, raise that number to a power, divide it by another very large number and output the remainder.")

Future generations of automatic-programming software, Goldberg says, might even be able to take the basic requirements of cryptography—such as the fact that each bit of information in the input is spread throughout the entire encrypted message—and apply a series of expansions and transformations that would ultimately result in working programs. It would be difficult for the government to argue that such general instructions are readily distinguishable from ordinary speech.

No amount of logic chopping will lead lawmakers out of this dilemma, says Randall Davis of the Massachusetts Institute of Technology. He contends that the fundamental premise of arguments over software's status is flawed because it is both text and mechanism. Any rules based on the notion that these two categories are distinct must eventually come to an impasse, whether they deal with patents, copyrights, munitions or the First Amendment. To date, Davis has little in the way of a grand synthesis between the two apparently incompatible classifications, but it seems clear that something is needed soon before the thus far irresistible tide of software innovation strikes the immovable wall that is the law. *—Paul Wallich*

Can Sustainable Management Save Tropical Forests?

Sustainability proves surprisingly problematic in the quest to reconcile conservation with the production of tropical timber

by Richard E. Rice, Raymond E. Gullison and John W. Reid

To those of us who have dedicated careers to conserving the biodiversity and natural splendor of the earth's woodlands, the ongoing destruction of tropical rain forest is a constant source of distress. These lush habitats shelter a rich array of flora and fauna, only a small fraction of which scientists have properly investigated. Yet deforestation in the tropics continues relentlessly and on a vast scale—driven, in part, by the widespread logging of highly prized tropical woods.

In an effort to reverse this tide, many conservationists have embraced the notion of carefully regulated timber production as a compromise between strict preservation and uncontrolled exploitation. Forest management is an attractive strategy because, in theory, it reconciles the economic interests of producers with the needs of conservation. In practice, sustainable management requires both restraint in cutting trees and investment in replacing them by planting seedlings or by promoting the natural regeneration of harvested species.

Most conservationists view this formula as a pragmatic scheme for countries that can ill afford to forgo using their valuable timber. We, too, favored this strategy until recently, when we reluctantly concluded that most of the well-meaning efforts in this direction by environmental advocates, forest managers and international aid agencies had a very slim chance for success. Although our concerns about the effectiveness of sustainable forestry have since mounted, our initial disillusionment sprang from our experiences trying to foster such practices in South America seven years ago.

A Disenchanting Forest

It was our interest in trying to preserve the Amazonian rain forests of Bolivia that brought two of us together for the first time in 1990, for a chance meeting at the bar of the sleepy Hotel El Dorado in downtown La Paz. Gullison had just arrived from Princeton University to conduct research on the ecology of mahogany (*Swietenia macrophylla* King), the most valuable species in the tropical Americas. Rice was about to return to Washington, D.C., after working with the Smithsonian Institution at the Beni Biosphere Reserve, located next to the Chimanes Permanent Timber Production Forest, a tract of half a million hectares in lowland Bolivia. In the mid-1980s the International Tropical Timber Organization selected the Chimanes Forest as a model site for sustainable management, and we were both eager to help that program advance.

Although our first exchange over beer in La Paz was brief, by the end of the conversation we had agreed to collaborate further. Within a year we secured funding for what eventually became a four-year study. At the outset, our intention was for Gullison to establish how best to manage mahogany production from an ecological standpoint and for Rice to develop the economic arguments needed to convince timber companies to adopt policies based on these scientific findings.

As time passed, Gullison and his Bolivian field crew made steady progress in understanding the ecology of the forest. Mahogany seedlings, it turned out, grew and prospered only after sizable natural disturbances. In the Chimanes region, younger mahogany trees stood only near rivers where floods had recently swept the banks clear and buried competing vegetation under a thick blanket of sediment. Such disturbances in the past had created

RAYMOND E. GULLISON

CENTURIES-OLD MAHOGANY log awaits cutting at a Bolivian sawmill. Logging of mahogany (*Swietenia macrophylla* King), one of the most valuable tropical woods, occurs in many parts of Central and South America, including Guatemala, Belize, Bolivia, Peru and Brazil.

widely dispersed pockets where seedlings could grow, eventually producing groups of trees of approximately uniform age and size. For the problem at hand, this aspect of the ecology of mahogany was quite alarming: it meant that uncontrolled logging would invariably obliterate the older stands, where nearly all trees would be of a marketable size.

Those worries were exacerbated by the realization that there would be little natural growth to replace harvested trees even if the loggers cut the forest sparingly. Mahogany seedlings (and those of certain other tropical tree species) cannot grow under the shady canopy of dense tropical forest. With natural regeneration unlikely to prove adequate, human intervention would be needed to maintain the mahogany indefinitely.

How could a helping hand be provided? In theory, loggers could create the proper conditions for new mahogany to grow by mimicking nature and clearing large openings in the forest. But the effort would be enormous, and judging from previous attempts elsewhere to do just that, costly periodic "thinnings" would be required to remove competing vegetation. Such efforts to sustain the production of mahogany could disturb so much forest that the overall conservation objectives would surely be compromised. Hence, winning the battle for mahogany might still lose the war to preserve biodiversity. Appreciation of this difficulty led us to question what exactly it was we were trying to achieve.

Money Matters

Just as Gullison was discovering the difficulties of regenerating mahogany, Rice was finding that timber companies working in the Chimanes Forest had no economic incentive to invest in sustainable management. This conclusion was not entirely surprising given global trends: less than one eighth of 1 percent of the world's tropical production forests were operating on a sus-


MICHAEL M. STEWARTT


ROBIN B. FOSTER

LOGGED FORESTS can differ dramatically in the level of disturbance they experience. Loggers operating under strict regulations felled nearly all the trees at this locale on Vancouver Island in Canada (*top*), whereas their counterparts working with scant government oversight in southeastern Bolivia (*bottom*) downed only the tiny fraction of growth that contained commercially valuable timber.

tained-yield basis as of the late 1980s.

Logging, as typically practiced in the tropics, rapidly harvests the most highly valued trees. The number of species extracted may be as low as one (where there is a specialty wood, such as mahogany) or as high as 80 to 90 (where there is demand for a wide variety). Logging companies generally show little concern for the condition of residual stands and make no investment in regeneration. This attitude emerges, in part, as a matter of simple economics. In deciding whether to restrict harvests, companies face a choice between cutting trees immediately and banking the profits or delaying the harvest and allowing the stand to grow in volume and value over time. Economics, it seems, dictates the decision.

In choosing the first option, a company would harvest its trees as quickly as possible, invest the proceeds and earn the going rate of return, which can be measured by real, or inflation-adjusted, interest rates. Because risks are considerable and capital is scarce, real interest rates in developing countries are often much higher than in industrial countries. For example, real interest rates on dollar-denominated accounts in Bolivia have averaged 17 percent in recent years, compared with 4 percent in the U.S. Similarly high rates of interest are common in most countries in Latin America. Thus, companies that rapidly harvest their assets can invest their profits immediately and generate continuing high rates of return.

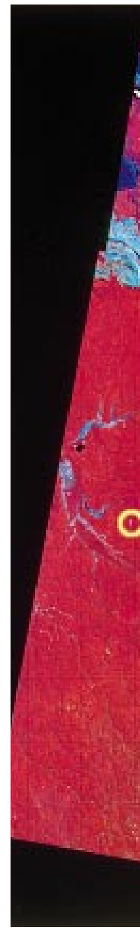
The benefits of delaying harvests, in contrast, are small. From 1987 to 1994, real price increases for mahogany averaged 1 percent a year, whereas the average annual growth in volume of commercial-size mahogany trees is typically less than 4 percent. This combination of slow growth rates and modest price increases means that mahogany trees (as well as most other commercial tree species in the American tropics) rise in value annually by at most 4 to 5 percent—about the same as would be earned by a conservative investment in the U.S. and much less than competitive returns in Bolivia.

The value of the trees left to grow, moreover, could easily plummet if wind, fire or disease destroyed them or if in the future the government restricted logging. Therefore, choosing to leave mahogany growing amounts to a rather uncertain investment—one that would provide, at most, a rate of return that is essentially the same as could be obtained by harvesting the trees and banking the profits safely. Like most other businesspeople, who are unwilling to make risky investments in developing countries unless offered considerably higher returns, loggers choose to cut their trees as quickly as they can.

After making a careful analysis of the economics of logging in the Chimanes region, we discovered that unrestricted logging is from two to five times more profitable than logging in a way that would ensure a continued supply of mahogany. From a purely financial perspective, then, the most rational approach to logging appears to be exactly what timber companies are doing—harvesting all the available mahogany first, avoiding investments in future harvests, and then moving on in sequence to all species that yield a positive net return. Adam Smith's invisible hand, it appears, reaches deep into the rain forest.

The incentives driving uncontrolled logging prove especially powerful in developing countries, where government regulation is, in general, quite weak. The national forest authority in Bolivia, for instance, receives annually less than 30 cents for each hectare of land it administers. (The U.S. Forest Service, in comparison, gets about $44.) With such slim support, government regulators in Bolivia are hard-pressed to counterbalance the financial rewards of cutting all the valuable trees at once, and it is no wonder that few timber companies there invest any effort to help the targeted species regenerate.

JENNIFER C. CHRISTIANSEN



SATELLITE VIEW (*right*) of Amazonian forests (*red areas*) shows little damage from timber operations on the Bolivian side of the border. (Logging has occurred throughout this part of Bolivia, including in the recently expanded national park.) But widespread colonization and subsistence farming near paved highways on the Brazilian side have denuded the land of forest cover (*white areas*), as has the clearing done for large-scale cattle ranching. Other unforested areas (*blue*) include swamps and, at higher elevations, natural grasslands.

The Value of Sustainability

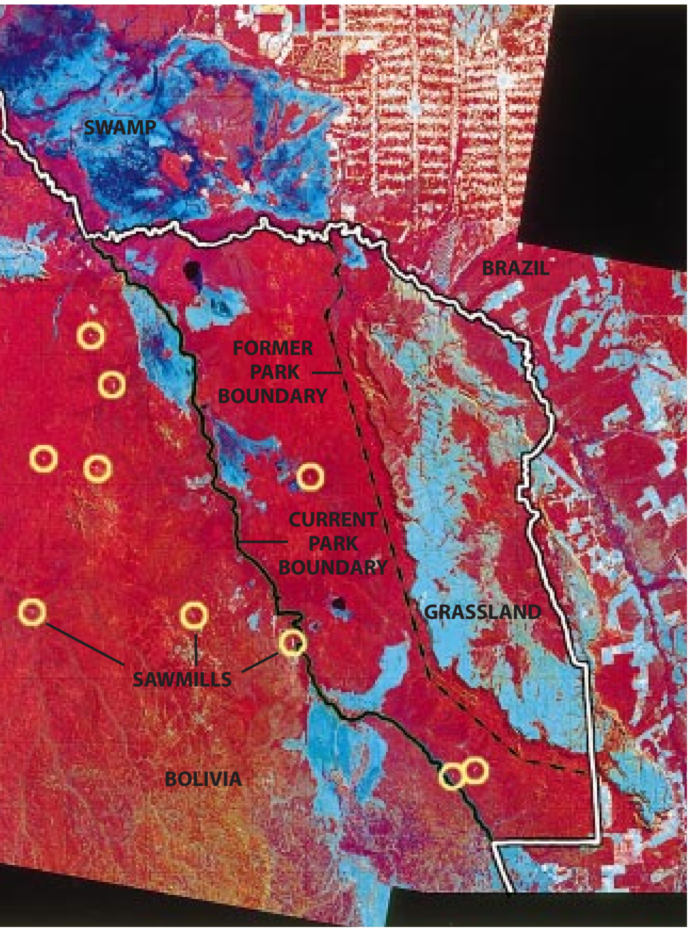
After spending some time in the Chimanes region of Bolivia, we decided to investigate how severely logging there had injured the local environment. We quickly found that, although clearly unsustainable for mahogany, the physical effects of logging on the forest as a whole have been relatively mild. Because only one or two mahogany trees grow in a typical 10-hectare plot, road building, felling and log removal disrupt less than 5 percent of the land. We estimate that current logging practice causes considerably less damage than some forms of sustainable management (which require more intensive harvests of a wider variety of species). Indeed, a more sustainable approach could well double the harm inflicted by logging.

Sustainability is, in fact, a poor guide to the environmental harm caused by timber operations. Logging that is unsustainable—that is, incapable of maintaining production of the desired species indefinitely—need not be highly damaging (although in some forests it is, especially where a wide range of species have commercial value). Likewise, sustainable logging does not necessarily guarantee a low environmental toll. Ideally, companies should manage forests in a way that is both sustainable for timber and minimally disturbing to the environment. But when forced to choose between unsustainable, low-impact logging and sustainable, high-impact logging, environmentalists should make sure they pick the option that best meets their conservation objectives. If the maintenance of biodiversity is of paramount importance—as we believe it should be—a low-impact (albeit unsustainable) approach may be the preferable choice.

Yet the quest to sustain the yield of wood indefinitely has become a central theme in efforts to preserve tropical forests. And conservation-minded people have proposed several strategies to overcome the economic obstacles to sustainable forest management. Their approaches, however, often fail to distinguish between the profitability of logging existing forests and the profitability of investing in regeneration. In the absence of strong governmental control, both must be financially attractive to succeed.

Efforts to increase the utilization of lesser known tree species provide an informative example. Some advocates of sustainable management contend that boosting market demand for lesser known species will make it worthwhile to maintain a production forest that otherwise might be converted to farmland or rangeland. Yet there is nothing—such as faster growth or a brighter price outlook—to suggest that investments in regenerating these species will be any more attractive than investments in regenerating currently targeted species. Larger markets for secondary species may only increase the number of trees that are harvested unsustainably.

A parallel argument can be made with regard to secondary, or value-added, processing. Such processing (of logs into furniture or plywood) is often said to have the dual advantages of allowing the use of a wider variety of species while providing a stronger economic incentive to manage forests sustainably. In fact, the promotion of value-added processing in many countries has actually reduced their overall earnings (because large subsidies are needed to attract the necessary investment) while greatly increasing both the pace and scale of forest destruction.



COURTESY OF COMPTON TUCKER *NASA Goddard Space Flight Center*

Arguments promoting secure land tenure suffer from a similar limitation. Environmental advocates point to the lack of long-term access to timber resources as a major cause of unsustainable management. The commonsense argument favoring tenure security is that, without it, timber companies will be reluctant to invest in future harvests. Yet ensuring that companies are, in principle, able to benefit from nurturing forest growth does nothing to provide the practical financial incentives to foster such practices. More secure land tenure makes investments in regeneration possible for timber companies to consider; it does not, however, automatically make these investments economically worthwhile. In fact, rather than promoting investments in regeneration, more secure tenure may simply lower the risk of making larger investments in logging equipment, thus encouraging swifter liquidation of the resource.

This very issue brought Reid to our team in 1994. Rice had met Reid two years earlier in a torrential storm in the heart of the Petén, Guatemala's heavily forested northern province. Logging there had been suspended by government decree, but Guatemala's policymakers were considering turning large tracts of forest over to companies under contracts that would have endured for 25 years.

We agreed that such lengthy tenure for loggers probably would not solve the problems of unsustainable logging and an expanding agricultural frontier. It could, we feared, hurt the thousands of people who roam these woods in search of chicle latex (a gum), ornamental palm leaves and allspice—all valuable products for export. So when local authorities drafted a proposal to allow timber interests long-term concessions in hopes of promoting sustainable management, Rice called Reid to ask whether he would like to examine that policy in detail. Six weeks later the Guatemalan government had our report, which demonstrated the hefty cut in profits that companies would have to absorb to manage these forests sustainably. As a result, the plan was shelved, although pressure remains to turn the forest over to the logging industry.

Certifiably Green

Many people concerned with the future of the rain forest view timber certification, or "green labeling," as the prime means of providing the economic incentive needed to spur sustainable management. Such certification programs call for voluntary compliance with established environmental standards in exchange for higher prices or greater market access, or both. While experts debate whether certification actually leads to higher market prices, the more important question is whether the premiums consumers are willing to pay for certified products are sufficient to bring about the necessary changes. Our economic analysis of the Chimanes operations indicated that for valuable species such as mahogany, current patterns of unsustainable logging can be as much as five times as profitable as a more sustainable alternative. Yet consumers appear to be willing to spend, at most, 10 percent more for certified timber than the price they would pay for uncertified wood products. The gap is enormous.

Nevertheless, certification has the potential to be an important tool for forest conservation, as long as these efforts concentrate on low-cost modifications that are sure to reduce environmental damage (such as preventing loggers from hunting forest animals) rather than expensive changes that bring doubtful benefits. Although there is not yet broad consumer demand for certified wood, there does appear to be a growing niche that could be filled if the costs of being green are kept to a minimum. In the meantime, it would be best to avoid altering the economic incentives facing all logging operations, such as increasing tenure security or promoting lesser known species, simply to benefit the small number involved with certification. Without much broader acceptance of certification, such policies may only speed the degradation of tropical forests.

What to Do?

The management of tropical forests for sustainable timber production is unlikely to become a widespread phenomenon, at least in the near future. Contrary economic incentives, limited government control and a lack of local political support will consistently thwart the best efforts in that direction, particularly in developing countries. Environmentalists need to recognize this reality. Although we see no easy solutions, there are a few strategies that deserve greater attention.

One possibility is to provide timber companies with low-interest loans to fund regeneration and the protection of biodiversity. Logging that includes these activities is not sufficiently profitable at the high interest rates typical in developing countries, but it could become so if funded by cheaper capital, perhaps provided by development banks or conscientious investors.

Another option is to promote the preservation of large forested areas within and around timber concessions. Such set-asides would be relatively inexpensive to monitor and could aid substantially in the conservation of biodiversity. Rather than just keeping forest cover, such protected areas could maintain forest that had nearly its full complement of species and old-growth structure. Ideally, these lands should be contiguous with,

Vive la Différence

Why protect tropical forests? For one, because they harbor most of the planet's biodiversity, an umbrella term for the variety of ecosystems, species and genes present. Scientists estimate that tens of millions of species exist, but they have described between only 1.4 and 1.5 million of them. Half the species identified so far live in tropical forests, yet biologists suspect the proportion could reach 90 percent if a full tally were ever accomplished.

Some examples help to put the biological abundance of tropical forests in proper perspective. In one study, a single hectare of rain forest in Peru was found to house 300 tree species—almost half the number native to North America. In another assay, scientists counted more than 1,300 butterfly species and 600 bird species living within one five-square-kilometer patch of rain forest in Peru. (The entire U.S. claims 400 butterfly species and just over 700 bird species.) In the same Peruvian jungle, Harvard entomologist Edward O. Wilson uncovered 43 ant species in a single tree, which he pointed out was about the same number as exists in all of the British Isles.

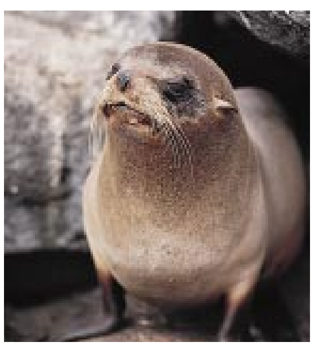
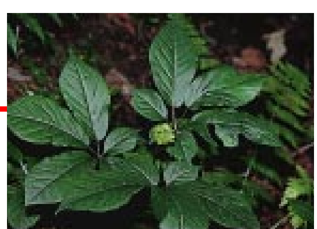
Such diversity of plant and animal life is important to humans because it is essential for creating food, medicines and raw materials. Wild plants, for example, contain the genetic resources needed to breed crops for resistance to pests and disease. And about 120 clinically useful prescription drugs come from 95 species of plants, 39 of which grow in tropical forests. What is more, botanists believe that from 35,000 to 70,000 plant species (most drawn from tropical forests) provide traditional remedies throughout the world. Take away the places where such species live, and myriad medicines become lost forever.

One means to protect biodiversity is the Convention on International Trade in Endangered Species (CITES)—the 1973 treaty that helped to keep elephants and gorillas from becoming extinct. Bolivia, which is second only to Brazil in mahogany exports, recently asked the U.S. to join it in gaining protection for mahogany (*Swietenia macrophylla* King) under the CITES accord. The proposal seeks to include mahogany among the items in Appendix 2 of the treaty, which would require countries to monitor their exports to ensure that international trade does not threaten the species. (Appendix 1 of the CITES treaty includes those species that are already endangered and prohibits their export for international trade.)

The U.S. Fish and Wildlife Service agreed in January to request protective measures for mahogany during the next CITES meeting in June. Although the full implications of this proposal remain unclear, we hope this action will focus much needed attention on the question of how best to conserve biodiversity in tropical forests that are being logged. *—R.E.R., R.E.G. and J.W.R.*





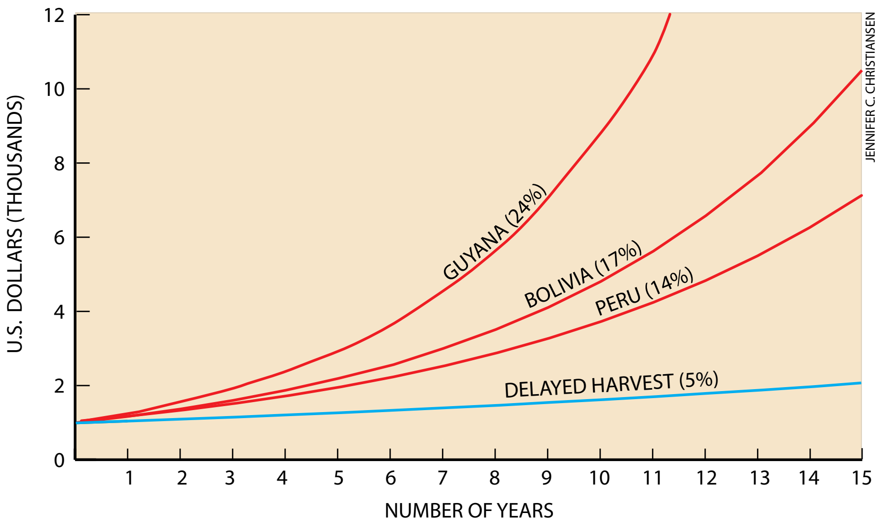
MONITORED CREATURES already listed in Appendix 2 of the Convention on International Trade in Endangered Species include, among hundreds of others, (*left, from top to bottom*) orchids, poison-dart frogs, chameleons, hummingbirds, staghorn corals, Galápagos fur seals and American ginseng plants.

PHOTOGRAPHS (*top to bottom*): MICHAEL FOGDEN *Bruce Coleman Inc.*; NORMAN OWEN TOMALIN *Bruce Coleman Inc.*; NORMAN OWEN TOMALIN *Bruce Coleman Inc.*; JOSEPH VAN WORMER *Bruce Coleman Inc.*; RICHARD G. FAIRBANKS; TUI DE ROY *Bruce Coleman Inc.*; D. LYONS *Bruce Coleman Inc.*

or near, other intact forest. To minimize the cost, we suggest focusing on commercially inoperable areas, such as places too steep to log or forests that have been lightly logged in the past.

Although such set-asides may be among the less economically productive areas under their control, timber companies are likely to resist any restrictions at all on their movements. In Bolivia the government is addressing this difficulty by offering loggers a financial reward for preservation. Under a law that has just been approved, the Bolivian government will collect a flat tax (of around $1 per hectare a year) for logging privileges. Timber companies can, however, designate up to 30 percent of their concessions as off-limits to logging, and the lands thus specified will be exempt from taxation. This policy should encourage loggers to protect their commercially marginal lands, and it may soften their resistance to having other areas set aside for the protection of the environment.

Finally, in forests such as Chimanes, where uncontrolled logging is selective and settlement pressures are low, accepting some elements of the status quo may prove to be the best available option. As in many areas of the Bolivian lowlands, logging in Chimanes is almost certain to continue long after the mahogany has been exhausted. In fact, the current pattern of selective harvest of a large number of commercial species, one or two species at a time, is a process that in some areas could require decades to complete. The challenge facing conservationists under such circumstances is not so much to convince the timber companies to stay and log sustainably for the long run but rather to institute some form of protection for old-growth forests while the opportunity remains.



FINANCIAL REWARDS that can be earned by harvesting trees worth US$1,000 and investing the proceeds at the real interest rates available locally (*red*) outstrip the return attained by letting the trees grow in size and value before cutting them down (*blue*).

Environmentalists also need to remember that many threats to tropical forests would continue even if sustainable management were to become widely adopted. National agricultural policies, road development and colonization can each pose a far greater danger to tropical forests than unsustainable logging. Reducing the destruction caused by these forces could do much more for forest conservation than revamping current forestry practices.

Clearly, no single strategy will work indefinitely or for all forests. Our prescriptions (particularly for old-growth set-asides) might ultimately succumb to the same forces that now frustrate sustainable forest management. Over time, producers will have an ever greater incentive to enter currently uneconomic areas. So, in the absence of determined government oversight, these alternatives, too, would fail just as surely as efforts to impose sustainable forestry. Our set-aside proposal differs, however, in that it delivers real and immediate environmental benefits by protecting old-growth forest. Furthermore, it relies on straightforward restrictions about where logging occurs rather than on complicated technical rules dictating how logging is to be done.

Although far from providing fully satisfying solutions, the measures we suggest may be the most realistic means to harmonize conservation with tropical timber extraction, until such time as political and economic change in the developing world brings a widespread demand for more effective protection of these majestic tropical forests. SA

The Authors

RICHARD E. RICE, RAYMOND E. GULLISON and JOHN W. REID came to study the problems of tropical forests from quite different perspectives. Rice obtained a bachelor's degree in economics at Grinnell College and went on to earn a master's in economics and, in 1983, a doctorate in natural resources from the University of Michigan. He is currently the senior director of the resource economics program at Conservation International in Washington, D.C. After graduating from the University of British Columbia with a degree in zoology, Gullison studied ecology and evolutionary biology at Princeton University, where he completed a Ph.D. in 1995. He now teaches at the Imperial College of Science, Technology and Medicine in London. Reid earned a master's degree in public policy at Harvard University before joining Conservation International in 1994. His work there focuses on natural resource economics and policy issues concerning conservation in the tropics.

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Black Holes and the Information Paradox

What happens to the information in matter destroyed by a black hole? Searching for that answer, physicists are groping toward a quantum theory of gravity

by Leonard Susskind

Somewhere in outer space, Professor Windbag's time capsule has been sabotaged by his arch rival, Professor Goulash. The capsule contains the only copy of a vital mathematical formula, to be used by future generations. But Goulash's diabolical scheme to plant a hydrogen bomb on board the capsule has succeeded. Bang! The formula is vaporized into a cloud of electrons, nucleons, photons and an occasional neutrino. Windbag is distraught. He has no record of the formula and cannot remember its derivation.

Later, in court, Windbag charges that Goulash has sinned irrevocably: "What that fool has done is irreversible. Why, the fiend has destroyed my formula and must pay. Off with his tenure!"

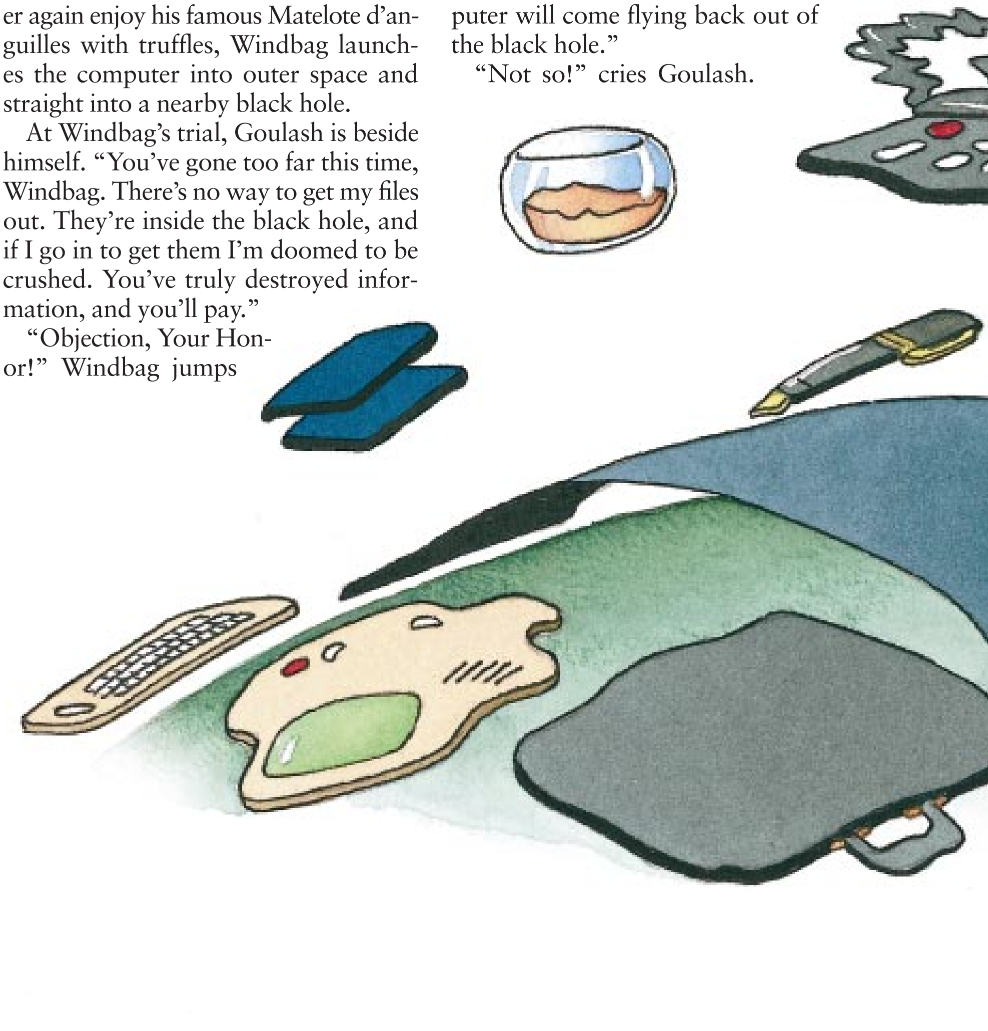
"Nonsense," says an unflustered Goulash. "Information can never be destroyed. It's just your laziness, Windbag. Although it's true that I've scrambled things a bit, all you have to do is go and find each particle in the debris and reverse its motion. The laws of nature are time symmetric, so on reversing everything, your stupid formula will be reassembled. That proves, beyond a shadow of a doubt, that I could never have destroyed your precious information." Goulash wins the case.

Windbag's revenge is equally diabolical. While Goulash is out of town, his computer is burglarized, along with all his files, including his culinary recipes. Just to make sure that Goulash will never again enjoy his famous Matelote d'anguilles with truffles, Windbag launches the computer into outer space and straight into a nearby black hole.

At Windbag's trial, Goulash is beside himself. "You've gone too far this time, Windbag. There's no way to get my files out. They're inside the black hole, and if I go in to get them I'm doomed to be crushed. You've truly destroyed information, and you'll pay."

"Objection, Your Honor!" Windbag jumps up. "Everyone knows that black holes eventually evaporate. Wait long enough, and the black hole will radiate away all its mass and turn into outgoing photons and other particles. True, it may take 10^{70} years, but it's the principle that counts. It's really no different from the bomb. All Goulash has to do is reverse the paths of the debris, and his computer will come flying back out of the black hole."

"Not so!" cries Goulash.



BLACK HOLE'S SURFACE looks to Windbag (in the spaceship) like a spherical membrane, called the horizon. Windbag sees Goulash, who is falling into the black hole, as being slowed down and flattened at the horizon; according to string theory, Goulash also seems to be spread all over it. Thus, Windbag, who represents the outside observer, sees the information contained in everything that falls into the black hole as stopping at the surface. But Goulash finds himself falling right through the horizon to the black hole's center, where he becomes crushed.

"This is different. My recipe was lost behind the black hole's boundary, its horizon. Once something crosses the horizon, it can never get back out without exceeding the speed of light. And Einstein taught us that nothing can ever do that. There is no way the evaporation products, which come from outside the horizon, can contain my lost recipes even in scrambled form. He's guilty, Your Honor."

Her Honor is confused. "We need some expert witnesses. Professor Hawking, what do you say?"

Stephen W. Hawking of the University of Cambridge comes to the stand. "Goulash is right. In most situations, information is scrambled and in a practical sense is lost. For example, if a new deck of cards is tossed in the air, the original order of the cards vanishes. But in principle, if we know the exact details of how the cards are thrown, the original order can be reconstructed. This is called microreversibility. But in my 1976 paper I showed that the principle of microreversibility, which has always held in classical and quantum physics, is violated by black holes. Because information cannot escape from behind the horizon, black holes are a fundamental new source of irreversibility in nature. Windbag really did destroy information."

Her Honor turns to Windbag: "What do you have to say to that?" Windbag calls on Professor Gerard 't Hooft of Utrecht University.

"Hawking is wrong," 't Hooft begins. "I believe black holes must not lead to violation of the usual laws of quantum mechanics. Otherwise the theory would be out of control. You cannot undermine microscopic reversibility without destroying energy conservation. If Hawking were right, the universe would heat up to a temperature of 10^{31} degrees in a tiny fraction of a second. Because this has not happened, there must be some way out of this problem."

Twenty more famous theoretical physicists are called to the stand. All that becomes clear is that they cannot agree.

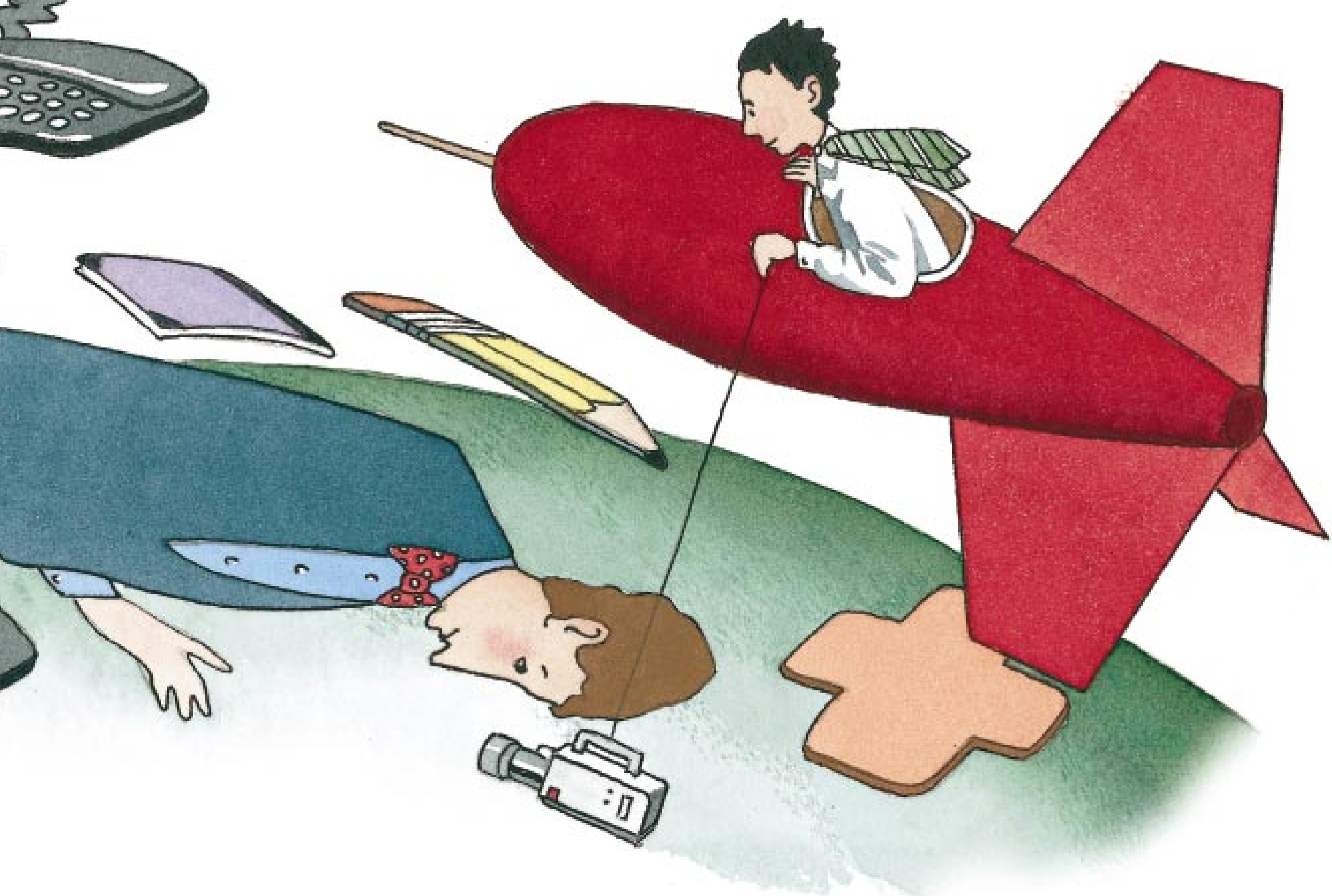
The Information Paradox

Windbag and Goulash are, of course, fictitious. Not so Hawking and 't Hooft, nor the controversy of what happens to information that falls into a black hole. Hawking's claim that a black hole consumes information has drawn attention to a potentially serious conflict between quantum mechanics and the general theory of relativity. The problem is known as the information paradox.

When something falls into a black hole, one cannot expect it ever to come flying back out. The information coded in the properties of its constituent atoms is, according to Hawking, impossible to retrieve. Albert Einstein once rejected quantum mechanics with the protest: "God does not play dice." But Hawking states that "God not only plays dice, He sometimes throws the dice where they cannot be seen"—into a black hole.

The problem, 't Hooft points out, is that if the information is truly lost, quantum mechanics breaks down. Despite its famed indeterminacy, quantum mechanics controls the behavior of particles in a very specific way: it is reversible. When one particle interacts with another, it may be absorbed or reflected or may even break up into other particles. But one can always reconstruct the initial configurations of the particles from the final products.

If this rule is broken by black holes, en-



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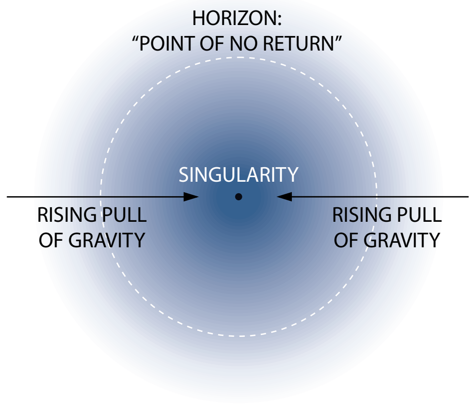
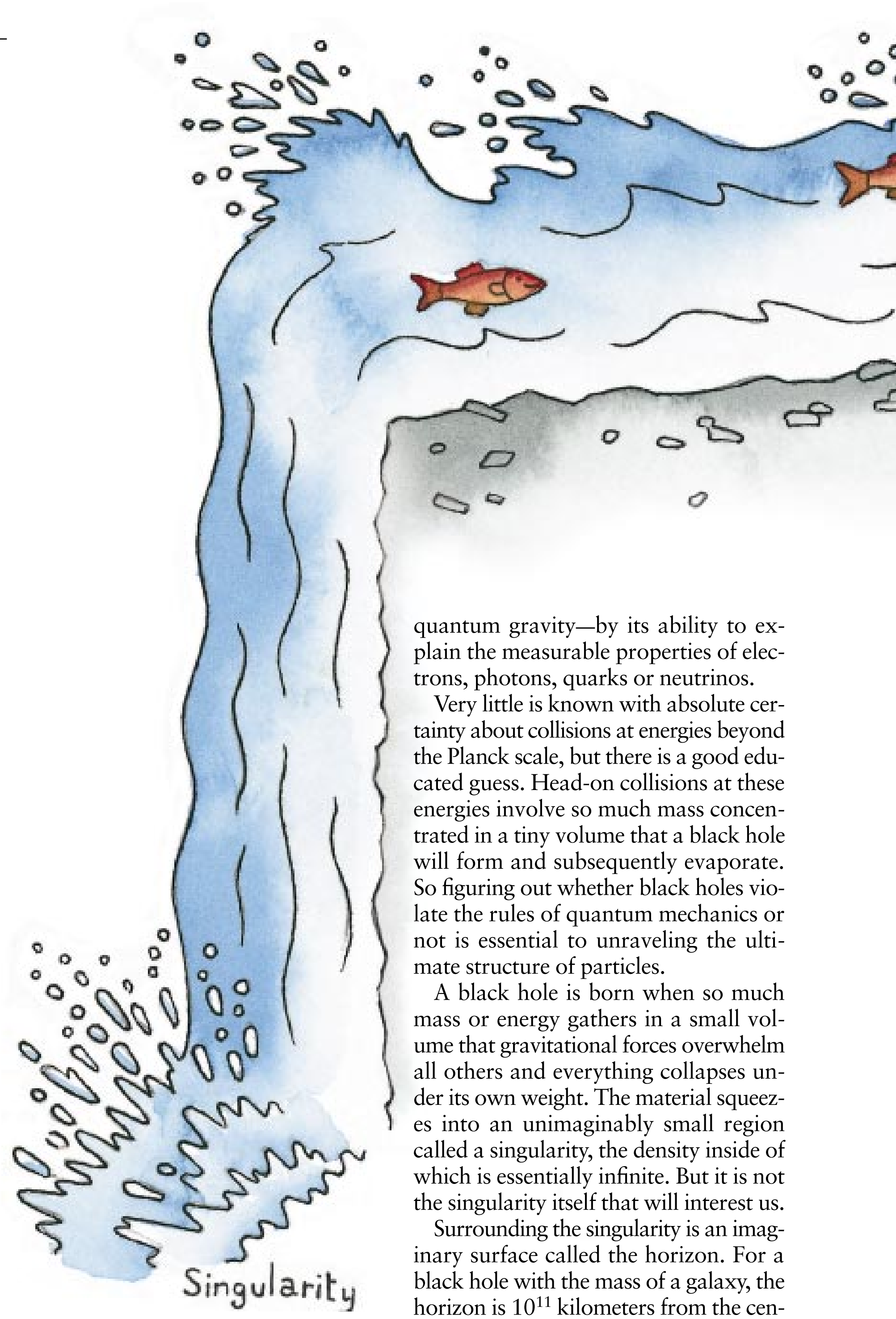


BRYAN CHRISTIE

INVISIBLE HORIZON is represented in this analogy as a line in a river. To the left of it, the water flows faster than a "lightfish" can swim. So if a lightfish happens to drift beyond this line, it can never get back upstream; it is doomed to be crushed in the falls. But the fish notices nothing special at the line. Likewise, a light ray or person who is inside the horizon can never get back out; the object inevitably falls into the singularity at the black hole's center, but without noticing anything special about the horizon.



ergy may be created or destroyed, threatening one of the most essential underpinnings of physics. The conservation of energy is ensured by the mathematical structure of quantum mechanics, which also guarantees reversibility; losing one means losing the other. As Thomas Banks, Michael Peskin and I showed in 1980 at Stanford University, information loss in a black hole leads to enormous amounts of energy being generated. For such reasons, 't Hooft and I believe the information that falls into a black hole must somehow become available to the outside world.

Some physicists feel the question of what happens in a black hole is academic or even theological, like counting angels on pinheads. But it is not so at all: at stake are the future rules of physics. Processes inside a black hole are merely extreme examples of interactions between elementary particles. At the energies that particles can acquire in today's largest accelerators (about 10^{12} electron volts), the gravitational attraction between them is negligible. But if the particles have a "Planck energy" of about 10^{28} electron volts, so much energy—and therefore mass—becomes concentrated in a tiny volume that gravitational forces outweigh all others. The resulting collisions involve quantum mechanics and the general theory of relativity in equal measure.

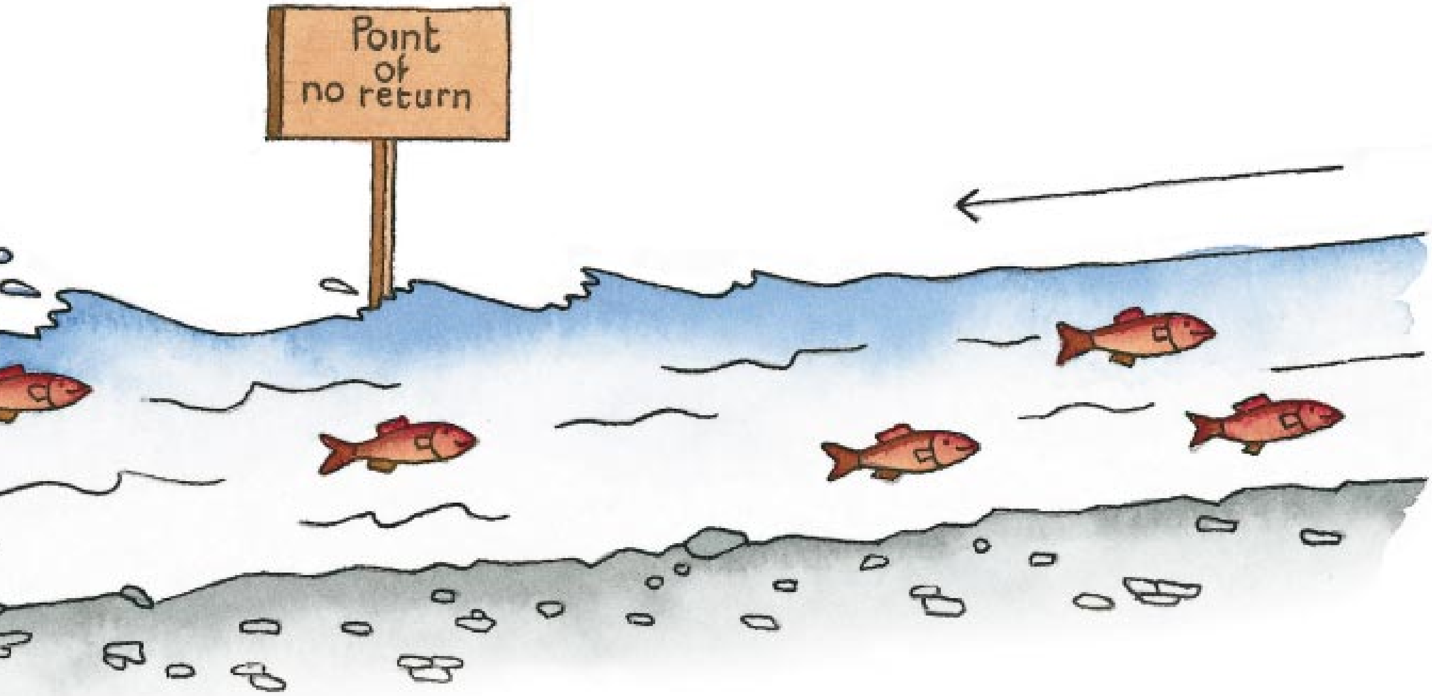
It is to Planckian accelerators that we would nominally look for guidance in building future theories of physics. Alas, Shmuel Nussinov of Tel Aviv University concludes that such an accelerator would have to be at least as big as the entire known universe.

Nevertheless, the physics at Planck energies may be revealed by the known properties of matter. Elementary particles have a variety of attributes that lead physicists to suspect they are not so elementary after all: they must actually have a good deal of undiscovered internal machinery, which is determined by the physics at Planck energies. We will recognize the right confluence of general relativity and quantum physics—or quantum gravity—by its ability to explain the measurable properties of electrons, photons, quarks or neutrinos.

Very little is known with absolute certainty about collisions at energies beyond the Planck scale, but there is a good educated guess. Head-on collisions at these energies involve so much mass concentrated in a tiny volume that a black hole will form and subsequently evaporate. So figuring out whether black holes violate the rules of quantum mechanics or not is essential to unraveling the ultimate structure of particles.

A black hole is born when so much mass or energy gathers in a small volume that gravitational forces overwhelm all others and everything collapses under its own weight. The material squeezes into an unimaginably small region called a singularity, the density inside of which is essentially infinite. But it is not the singularity itself that will interest us.

Surrounding the singularity is an imaginary surface called the horizon. For a black hole with the mass of a galaxy, the horizon is 10^{11} kilometers from the center—as far as the outermost reaches of the solar system are from the sun. For a black hole of solar mass, the horizon is roughly a kilometer away; for a black hole with the mass of a small mountain, the horizon is 10^{-13} centimeter away, roughly the size of a proton.



YAN NASCIMBENE

The horizon separates space into two regions that we can think of as the interior and exterior of the black hole. Suppose that Goulash, who is scouting for his computer near the black hole, shoots a particle away from the center. If he is not too close and the particle has a high velocity, then it may overcome the gravitational pull of the black hole and fly away. It will be most likely to escape if it is shot with the maximum velocity—that of light. If, however, Goulash is too close to the singularity, the gravitational force will be so great that even a light ray will be sucked in. The horizon is the place with the (virtual) warning sign: Point of No Return. No particle or signal of any kind can cross it from the inside to the outside.

At the Horizon

An analogy inspired by William G. Unruh of the University of British Columbia, one of the pioneers in black hole quantum mechanics, helps to explain the relevance of the horizon. Imagine a river that gets swifter downstream. Among the fish that live in it, the fastest swimmers are the "lightfish." But at some point, the river flows at the fish's maximum speed; clearly, any lightfish that drifts past this point can never get back up. It is doomed to be crushed on the rocks below Singularity Falls, located farther downstream. To the unsuspecting lightfish, though, passing the point of no return is a nonevent. No currents or shock waves warn it of the crossing.

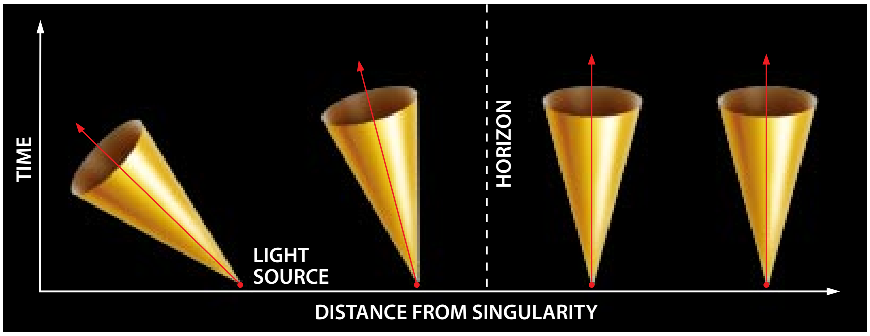
What happens to Goulash, who in a careless moment gets too close to the black hole's horizon? Like the freely drifting fish, he senses nothing special: no great forces, no jerks or flashing lights. He checks his pulse with his wristwatch—normal. His breathing rate—normal. To him the horizon is just like any other place.

But Windbag, watching Goulash from a spaceship safely outside the horizon, sees Goulash acting in a bizarre way. Windbag has lowered to the horizon a cable equipped with a camcorder and other probes, to better keep an eye on Goulash. As Goulash falls toward the black hole, his speed increases until it approaches that of light. Einstein found that if two persons are moving fast relative to each other, each sees the other's clock slow down; in addition, a clock that is near a massive object will run slowly compared with one in empty space. Windbag sees a strangely lethargic Goulash. As he falls, the latter shakes his fist at Windbag. But he appears to be moving ever more slowly; at the horizon, Windbag sees Goulash's motions slow to a halt. Although Goulash falls through the horizon, Windbag never quite sees him get there.

In fact, not only does Goulash seem to slow down, but his body looks as if it is being squashed into a thin layer. Einstein also showed that if two persons move fast with respect to each other, each will see the other as being flattened in the direction of motion. More strangely, Windbag should also see all the material that ever fell into the black hole, including the original matter that made it up—and Goulash's computer—similarly flattened and frozen at the horizon. With respect to an outside observer, all of that matter suffers a relativistic time dilation. To Windbag, the black hole consists of an immense junkyard of flattened matter at its horizon. But Goulash sees nothing unusual until much later, when he reaches the singularity, there to be crushed by ferocious forces.

Black hole theorists have discovered over the years that from the outside, the properties of a black hole can be described in terms of a mathematical membrane above the horizon. This layer has many physical qualities, such as electrical conductivity and viscosity. Perhaps the most surprising of its properties was postulated in the early 1970s by Hawking, Unruh and Jacob D. Bekenstein of the Hebrew University in Israel. They found that as a consequence of quantum mechanics, a black hole—in particular, its horizon—behaves as though it contains heat. The horizon is a layer of hot material of some kind.

The temperature of the horizon depends on just where it is measured. Suppose one of the probes that Windbag has attached to his cable is a thermometer. Far from the horizon he finds that the temperature is inversely proportional to the black hole's mass. For a black hole of solar mass, this "Hawking temperature" is about 10^{-8} degree—far colder than intergalactic space. As Windbag's thermometer approaches the horizon,



LIGHT CONES describe the path of light rays emanating from a point. Outside the horizon the light cones point upward—that is, forward in time. But inside, the light cones tip so that light falls straight into the black hole's center.

however, it registers higher temperatures. At a distance of a centimeter, it measures about a thousandth of a degree; at a nuclear diameter it records 10 billion degrees. The temperature ultimately becomes so high that no imaginable thermometer can measure it.

Hot objects also possess an intrinsic disorder called entropy, which is related to the amount of information a system can hold. Think of a crystal lattice with N sites; each site can house one atom or none at all. Thus, every site holds one "bit" of information, corresponding to whether an atom is there or not; the total lattice has N such bits and can contain N units of information. Because there are two choices for each site and N ways of combining these choices, the total system can be in any one of 2^N states (each of which corresponds to a different pattern of atoms). The entropy (or disorder) is defined as the logarithm of the number of possible states. It is roughly equal to N—the same number that quantifies the capacity of the system for holding information.

Bekenstein found that the entropy of a black hole is proportional to the area of its horizon. The precise formula, derived by Hawking, predicts an entropy of 3.2×10^{64} per square centimeter of horizon area. Whatever physical system carries the bits of information at the horizon must be extremely small and densely distributed: their linear dimensions have to be $1/10^{20}$ the size of a proton's. They must also be very special for Goulash to completely miss them as he passes through.

The discovery of entropy and other thermodynamic properties of black holes led Hawking to a very interesting conclusion. Like other hot bodies, a black hole must radiate energy and particles into the surrounding space. The radiation comes from the region of the horizon and does not violate the rule that nothing can escape from within. But it causes the black hole to lose energy and mass. In the course of time an isolated black hole radiates away all its mass and vanishes.

All of the above, though peculiar, has been known to relativists for some decades. The true controversies arise when, following Hawking, we seek the fate of the information that fell into the black hole during and after its formation. In particular, can it be carried away by the evaporation products—albeit in a very scrambled form—or is it lost forever behind the horizon?

Goulash, who followed his computer into the black hole, would insist that its contents passed behind the horizon, where they were lost to the outside world; this in a nutshell is Hawking's argument. The opposing point of view might be described by Windbag: "I saw the computer fall toward the horizon, but I never saw it fall through. The temperature and radiation grew so intense I lost track of it. I believe the computer was vaporized; later, its energy and mass came back out in the form of thermal radiation. The consistency of quantum mechanics requires that this evaporating energy also carried away all the information in the computer." This is the position that 't Hooft and I take.

Black Hole Complementarity

Is it possible that Goulash and Windbag are in a sense both correct? Can it be that Windbag's observations are indeed consistent with the hypothesis that Goulash and his computer are thermalized and radiated back into space before ever reaching the horizon, even though Goulash discovers nothing unusual until long after, when he encounters the singularity? The idea that these are not contradictory but complementary scenarios was first put forward as the principle of black hole complementarity by Lárus Thorlacius, John Uglum and me at Stanford. Very similar ideas are also found in 't Hooft's work. Black hole complementarity is a new principle of relativity. In the special theory of relativity we find that although different observers disagree about the lengths of time and space intervals, events take place at definite space-time locations. Black hole complementarity does away with even that.

How this principle actually comes into play is clearer when applied to the structure of subatomic particles. Suppose that Windbag, whose cable is also equipped with a powerful microscope, watches an atom fall toward the horizon. At first he sees the atom as a nucleus surrounded by a cloud of negative charge. The electrons in the cloud move so rapidly they form a blur. But as the atom gets closer to the black hole, its internal motions seem to slow down, and the electrons become visible. The protons and neutrons in the nucleus still move so fast that its structure is obscure. But a little later the electrons freeze, and the protons and neutrons start to show up. Later yet, the quarks making up these particles are revealed. (Goulash, who falls with the atom, sees no changes.)

Many physicists believe elementary particles are made of even smaller constituents. Although there is no definitive theory for this machinery, one candidate stands out as being the most promising—namely, string theory. In this theory, an elementary particle does not resemble a point; rather it is like a tiny rubber band that can vibrate in many modes. The fundamental mode has the lowest frequency; then there are higher harmonics, which can be superimposed on top of one another. There are an infinite number of such modes, each of which corresponds to a different elementary particle.

Here another analogy helps. One cannot see the wings of a hovering hummingbird, because its wings flutter too fast. But in a photograph taken with a fast shutter speed, one can see the wings—so the bird looks bigger. If a hummer falls into the black hole, Windbag will see its wings take form as the bird approaches the horizon and the vibrations appear to slow down; it seems to grow. Now suppose that the wings have feathers that flap even faster. Soon these, too, would come into view, adding further to the apparent size of the bird. Windbag sees the hummer enlarge continuously. But Goulash, who falls with the bird, sees no such strange growth.

Like the hummingbird's wings, the string's oscillations are usually too rapid to detect. A string is a minute object, $1/10^{20}$ the size of a proton. But as it falls into a black hole, its vibrations slow down, and more of them become visible. Mathematical studies done at Stanford by Amanda Peet, Thorlacius, Arthur Mezhlumian and me have demonstrated the behavior of a string as its higher modes freeze out. The string spreads and grows, just as if it were being bombarded by particles and radiation in a very hot environment. In a relatively short time the string and all the information that it carries are smeared over the entire horizon.

This picture applies to all the material that ever fell into the black hole—because according to string theory, everything is ultimately made of strings. Each elementary string spreads and overlaps all the others until a dense tangle covers the horizon. Each minute segment of string, measuring 10^{-33} centimeter across, functions as a bit. Thus, strings provide a means for the black hole's surface to hold the immense amount of information that fell in during its birth and thereafter.

CASCADE OF VIBRATIONS on a string slow down and become visible if the string falls into a black hole. Strings are small enough to encode all the information that ever fell into a black hole and offer a way out of the information paradox.

String Theory

It seems, then, that the horizon is made of all the substance in the black hole, resolved into a giant tangle of strings. The information, as far as an outside observer is concerned, never actually fell into the black hole; it stopped at the horizon and was later radiated back out. String theory offers a concrete realization of black hole complementarity and therefore a way out of the information paradox. To outside observers—that is, us—information is never lost. Most important, it appears that the bits at the horizon are minute segments of string.

Tracing the evolution of a black hole from beginning to end is far beyond the current techniques available to string theorists. But some exciting new results are giving quantitative flesh to these ghostly ideas. Mathematically, the most tractable black holes are the "extremal" black holes. Whereas black holes that have no electrical charge evaporate until all their mass is radiated away, black holes with electrical or (in theory) magnetic charge cannot do that; their evaporation ceases when the gravitational attraction equals the electrostatic or magnetostatic repulsion of whatever is inside the black hole. The remaining stable object is called an extremal black hole.

Following earlier suggestions of mine, Ashoke Sen of the Tata Institute of Fundamental Research (TIFR) showed in 1995 that for certain extremal black holes with electrical charge, the number of bits predicted by string theory exactly accounts for the entropy as measured by the area of the horizon. This agreement was the first powerful evidence that black holes are consistent with quantum-mechanical strings.

Sen's black holes were, however, microscopic. More recently, Andrew Strominger of the University of California at Santa Barbara, Cumrun Vafa of Harvard University and, slightly later, Curtis G. Callan and Juan Maldacena of Princeton University extended this analysis to black holes with both electrical and magnetic charge. Unlike Sen's tiny black holes, these new black holes can be large enough to allow Goulash to fall through unharmed. Again, the theorists find complete consistency.

Two groups have done an even more exciting new calculation of Hawking radiation: Sumit R. Das of TIFR, with Samir Mathur of the Massachusetts Institute of Technology; and Avinash Dhar, Gautam Mandal and Spenta R. Wadia, also at TIFR. The researchers studied the process by which an extremal black hole with some excess energy or mass radiates off this flab. String theory fully accounted for the Hawking radiation that was produced. Just as quantum mechanics describes the radiation of an atom by showing how an electron jumps from a high-energy "excited" state to a low-energy "ground" state, quantum strings seem to account for the spectrum of radiation from an excited black hole.

Quantum mechanics, I believe, will in all likelihood turn out to be consistent with the theory of gravitation; these two great streams of physics are merging into a quantum theory of gravity based on string theory. The information paradox, which appears to be well on its way to being resolved, has played an extraordinary role in this ongoing revolution in physics. And although Goulash would never admit it, Windbag will probably turn out to be right: the recipe for Matelote d'anguilles is not forever lost to the world. SA

The Author

LEONARD SUSSKIND is one of the early inventors of string theory. He holds a Ph.D. from Cornell University and has been a professor at Stanford University since 1978. He has made many contributions to elementary particle physics, quantum field theory, cosmology and, most recently, to the theory of black holes. His current studies in gravitation have led him to suggest that information can be compressed into one lower dimension, a concept he calls the holographic universe.

Further Reading

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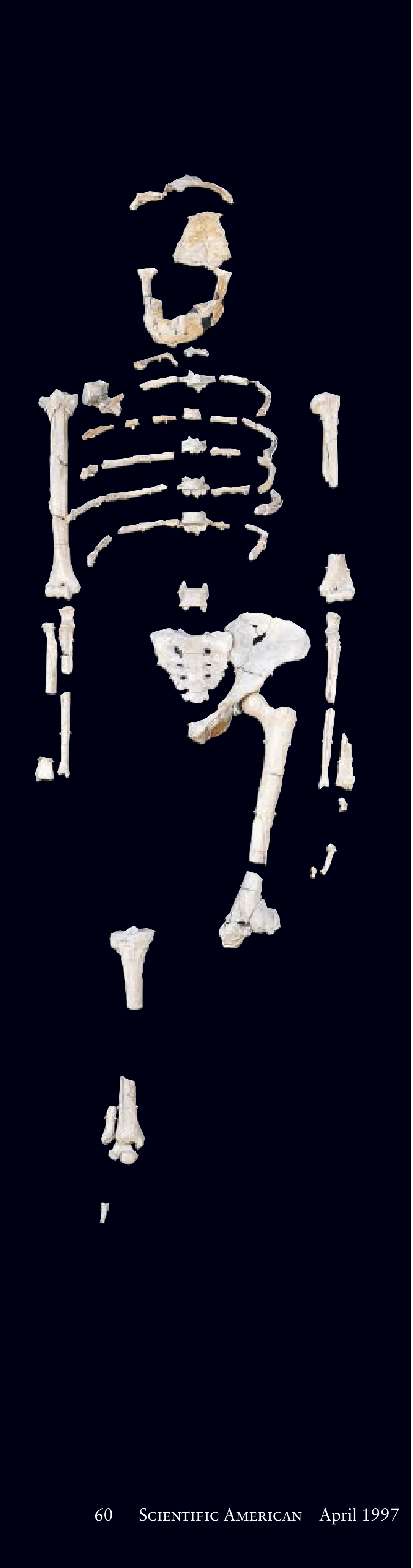


PHOTOGRAPH BY D. FINNIN AND J. BECKETT, FROM CAST ON DISPLAY AT THE AMERICAN MUSEUM OF NATURAL HISTORY

Out of Africa Again…and Again?

Africa is the birthplace of humanity. But how many human species evolved there? And when did they emigrate?

by Ian Tattersall

It all used to seem so simple. The human lineage evolved in Africa. Only at a relatively late date did early humans finally migrate from the continent of their birth, in the guise of the long-known species *Homo erectus*, whose first representatives had arrived in eastern Asia by around one million years ago. All later kinds of humans were the descendants of this species, and almost everyone agreed that all should be classified in our own species, *H. sapiens*. To acknowledge that some of these descendants were strikingly different from ourselves, they were referred to as "archaic *H. sapiens*," but members of our own species they were nonetheless considered to be.

Such beguiling simplicity was, alas, too good to last, and over the past few years it has become evident that the later stages of human evolution have been a great deal more eventful than conventional wisdom for so long had it. This is true for the earlier stages, too, although there is still no reason to believe that humankind's birthplace was elsewhere than in Africa. Indeed, for well over the first half of the documented existence of the hominid family (which includes all upright-walking primates), there is no record at all outside that continent. But recent evidence does seem to indicate that it was not necessarily *H. erectus* who migrated from Africa—and that these peregrinations began earlier than we had thought.

"LUCY" skeleton represents the best-known species of early hominid, or human precursor, *Australopithecus afarensis*, often characterized as a "bipedal chimpanzee." The 3.18-million-year-old skeleton is from the Hadar region of Ethiopia.

A Confused Early History

Recent discoveries in Kenya of fossils attributed to the new species *Australopithecus anamensis* have now pushed back the record of upright-walking hominids to about 4.2 to 3.9 million years (Myr) ago. More dubious finds in Ethiopia, dubbed *Ardipithecus ramidus*, may extend this to 4.4 Myr ago or so. The *A. anamensis* fossils bear a strong resemblance to the later and far better known species *Australopithecus afarensis*, found at sites in Ethiopia and Tanzania in the 3.9- to 3.0-Myr range and most famously represented by the "Lucy" skeleton from Hadar, Ethiopia.

Lucy and her kind were upright walkers, as the structures of their pelvises and knee joints particularly attest, but they retained many ancestral features, notably in their limb proportions and in their hands and feet, that would have made them fairly adept tree climbers. Together with their ape-size brains and large, protruding faces, these characteristics have led many to call such creatures "bipedal chimpanzees." This is probably a fairly accurate characterization, especially given the increasing evidence that early hominids favored quite heavily wooded habitats. Their preferred way of life was evidently a successful one, for although these primates were less adept arborealists than the living apes and less efficient bipeds than later hominids, their basic "eat your cake and have it" adaptation endured for well over two million years, even as species of this general kind came and went in the fossil record.

It is not even clear to what extent lifestyles changed with the invention of stone tools, which inaugurate our archaeological record at about 2.5 Myr ago. No human fossils are associated with the first stone tools known, from sites in Kenya and Ethiopia. Instead there is a motley assortment of hominid fossils from the period following about 2 Myr ago, mostly associated with the stone tools and butchered mammal bones found at Tanzania's Olduvai Gorge and in Kenya's East Turkana region. By one reckoning, at least some of the first stone toolmakers in these areas were hardly bigger or more advanced in their body skeletons than the tiny Lucy; by another, the first tools may have been made by taller, somewhat larger-brained hominids with more modern body structures. Exactly how many species of early hominids there were, which of them made the tools, and how they walked remains one of the major conundrums of human evolution.

Physically, at least, the picture becomes clearer following about 1.9 Myr ago, when the first good evidence occurs in northern Kenya of a species that is recognizably like ourselves. Best exemplified by the astonishingly complete 1.6-Myr-old skeleton known as the Turkana Boy, discovered in 1984, these humans possessed an essentially modern body structure, indicative of modern gait, combined with moderately large-faced skulls that contained brains double the size of those of apes (though not much above half the modern human average). The Boy himself had died as an adolescent, but it is estimated that had he lived to maturity he would have attained a height of six feet, and his limbs were long and slender, like those of people who live today in hot, arid African climates, although this common adaptation does not, of course, indicate any special relationship. Here at last we have early hominids who were clearly at home on the open savanna.

A long-standing paleoanthropological tradition seeks to minimize the number of species in the human fossil record and to trace a linear, progressive pattern of descent among those few that are recognized. In keeping with this practice, the Boy and his relatives were originally assigned to the species *H. erectus*. This species was first described from a skullcap and thighbone found in Java a century ago. Fossils later found in China—notably the now lost 500,000-year-old (500 Kyr old) "Peking Man"—and elsewhere in Java were soon added to the species, and eventually *H. erectus* came to embrace a wide variety of hominid fossils, including a massive braincase from Olduvai Gorge known as OH9. The latter has been redated to about 1.4 Myr, although it was originally thought to have been a lot younger. All these fossil forms possessed brains of moderate size (about 900 to 1,200 milliliters in volume, compared with an average of around 1,400 milliliters for modern humans and about 400 milliliters for apes), housed in long, low skull vaults with sharp angles at the back and heavy brow ridges in front. The few limb bones known were robust but essentially like our own.

Whether *H. erectus* had ever occupied Europe was vigorously debated, the alternative being to view all early human fossils from that region (the earliest of them being no more than about 500 Kyr old) as representatives of archaic *H. sapiens*. Given that the Javan fossils were conventionally dated in the range of 1 Myr to 700 Kyr and younger and that the earliest Chinese fossils were reckoned to be no more than 1 Myr old, the conclusion appeared clear: *H. erectus* (as exemplified by OH9 and also by the earlier Turkana Boy and associated fossils) had evolved in Africa and had exited that continent not much more than 1 Myr ago, rapidly spreading to eastern Asia and spawning all subsequent developments in human evolution, including those in Europe.

Yet on closer examination the specimens from Kenya turned out to be distinctively different in braincase construction from those of classic eastern Asian *H. erectus*. In particular, certain anatomical features that appear specialized in the eastern Asian *H. erectus* look ancestral in the African fossils of comparable age. Many researchers began to realize that we are dealing with two kinds of early human here, and the earlier Kenyan form is now increasingly placed in its own species, *H. ergaster*. This species makes a plausible ancestor for all subsequent humans, whereas the cranial specializations of *H. erectus* suggest that

PHOTOGRAPH BY D. FINNIN AND J. BECKETT, FROM CAST ON DISPLAY AT THE AMERICAN MUSEUM OF NATURAL HISTORY

"TURKANA BOY," an adolescent *Homo ergaster* dated to about 1.6 million years ago, is representative of the first hominids with an effectively modern body skeleton.

PHOTOGRAPH BY ROBERT CAMPBELL; COURTESY OF MEAVE LEAKEY

NEWLY DISCOVERED SPECIES *Australopithecus anamensis* is the earliest well-documented hominid. This lower jaw from Kanapoi, Kenya, seen as it was found in the field, has been dated to around four million years ago. *A. anamensis* closely resembles *A. afarensis* in dental details, and a partial tibia (shinbone) indicates that it walked upright.

this species, for so long regarded as the standard-issue hominid of the 1- to 0.5-Myr period, was in fact a local (and, as I shall explain below, ultimately terminal) eastern Asian development.

An Eastern Asian Cul-de-Sac

The plot thickened in early 1994, when Carl C. Swisher of the Berkeley Geochronology Center and his colleagues applied the newish argon/argon dating method to volcanic rock samples taken from two hominid sites in Java. The results were 1.81 and 1.66 Myr: far older than anyone had really expected, although the earlier date did confirm one made many years before. Unfortunately, the fossils from these two sites are rather undiagnostic as to species: the first is a braincase of an infant (juveniles never show all the adult characteristics on which species are defined), and the second is a horrendously crushed and distorted cranium that has never been satisfactorily reconstructed. Both specimens have been regarded by most as *H. erectus,* but more for reasons of convenience than anything else. Over the decades, sporadic debate has continued regarding whether the Javan record contains one or more species of early hominid. Further, major doubt has recently been cast on whether the samples that yielded the older date were actually obtained from the same spot as the infant specimen. Still, these dates do fit with other evidence pointing to the probability that hominids of some kind were around in eastern Asia much earlier than anyone had thought.

Independent corroboration of this scenario comes, for instance, from the site of Dmanisi in the former Soviet republic of Georgia, where in 1991 a hominid lower jaw was found that its describers allocated to *H. erectus.* Three different methods suggested that this jaw was as old as 1.8 Myr; although not everyone has been happy with this dating, taken together the Georgian and new Javan dates imply an unexpectedly early hominid exodus from Africa. And the most parsimonious reading of the admittedly imperfect record suggests that these pioneering emigrants must have been *H. ergaster* or something very much like it.

A very early hominid departure from Africa has the advantage of explaining an apparent anomaly in the archaeological record. The stone tools found in sediments coeval with the earliest *H. ergaster* (just under 2 Myr ago) are effectively identical with those made by the first stone toolmakers many hundreds of thousands of years before. These crude tools consisted principally of sharp flakes struck with a stone "hammer" from small cobbles. Effective cutting tools though these may have been (experimental archaeologists have shown that even elephants can be quite efficiently butchered using them), they were not made to a standard form but were apparently produced simply to obtain a sharp cutting edge. Following about 1.4 Myr ago, however, standardized stone tools began to be made in Africa, typified by the hand axes and cleavers of the Acheulean industry (first identified in

PHOTOGRAPH BY CRAIG CHESEK, FROM A CAST AT THE AMERICAN MUSEUM OF NATURAL HISTORY

"PEKING MAN" is the name given to this skull of a male *H. erectus* from Zhoukoudian, near Beijing. The skull was reconstructed from fragments of various individuals, all probably around 500,000 years old.

REPLICA OF OLDOWAN BASALT CORE illustrates how sharp flakes were struck from the core to provide cutting implements. Tools of this kind were first made around 2.5 million years ago.

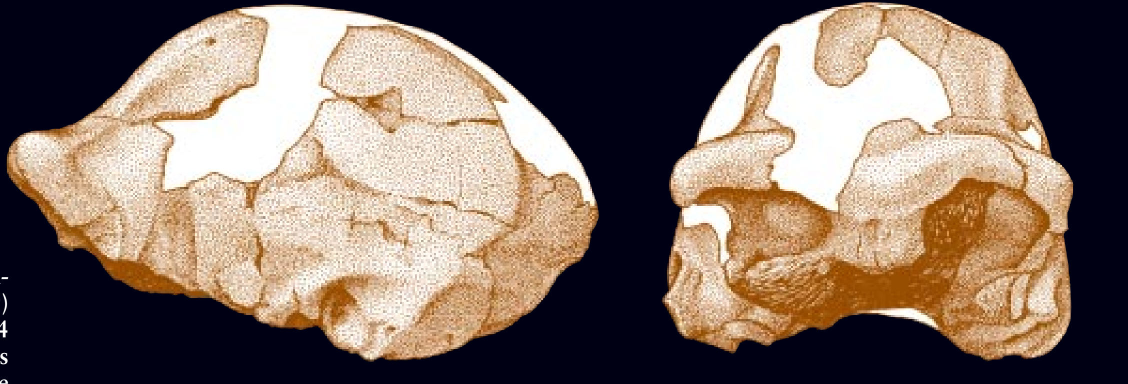
TWO ACHEULEAN TOOLS, from St. Acheul, France, are probably around 300,000 years old, but implements of this kind began to be made in Africa as many as 1.5 million years ago. On the left is a pointed hand ax, and on the right a blunt-ended cleaver.

PHOTOGRAPHS BY WILLARD WHITSON

the mid-19th century from St. Acheul in France). These were larger implements, carefully shaped on both sides to a teardrop form. Oddly, stone tool industries in eastern Asia lacked such utensils, which led many to wonder why the first human immigrants to the region had not brought this technology with them, if their ancestors had already wielded it for half a million years. The new dates suggest, however, that the first emigrants had left Africa before the invention of the Acheulean technology, in which case there is no reason why we should expect to find this technology in eastern Asia. Interestingly, a few years ago the archaeologist Robin W. Dennell caused quite a stir by reporting very crude stone tools from Riwat in Pakistan that are older than 1.6 Myr. Their great age is now looking decreasingly anomalous.

Of course, every discovery raises new questions, and in this case the problem is to explain what it was that enabled human populations to expand beyond Africa for the first time. Most scholars had felt it was technological advances that allowed the penetration of the cooler continental areas to the north. If, however, the first emigrants left Africa equipped with only the crudest of stoneworking technologies, we have to look to something other than technological prowess for the magic ingredient. And because the first human diaspora apparently followed hard on the heels of the acquisition of more or less modern body form, it seems reasonable to conclude that the typically human wanderlust emerged in concert with the emancipation of hominids from the forest edges that had been their preferred habitat. Of course, the fact that the Turkana Boy and his kin were adapted in their body proportions to hot, dry environments does nothing to explain why *H. ergaster* was able to spread rapidly into the cooler temperate zones beyond the Mediterranean; evidently the new body form that made possible remarkable endurance in open habitats was in itself enough to make the difference.

The failure of the Acheulean ever to diffuse as far as eastern Asia reinforces the notion, consistent with the cranial specializations of *H. erectus,* that this part of the world was a kind of paleoanthropological cul-de-sac. In this region ancient human populations largely followed their own course, independent of what was going on elsewhere in the world. Further datings tend to confirm this view. Thus, Swisher and his colleagues have very recently reported dates for the Ngandong *H. erectus* site in Java that center on only about 40 Kyr ago. These dates, though very carefully obtained, have aroused considerable skepticism; but, if accurate, they have considerable implications for the overall pattern of human evolution. For they are so recent as to suggest that the long-lived *H. erectus* might even have suffered a fate similar to that experienced by the Neanderthals in Europe: extinction at the hands of late-arriving *H. sapiens.* Here we find reinforcement of the gradually emerging picture of human evolution as one of repeated experimentation, with regionally differentiated species, in this case on opposite sides of



SKULLCAP known as Olduvai Hominid 9 (OH9) was recently dated to 1.4 million years old; it was originally believed to have been much younger. Its affinities are still debated.

DRAWINGS BY DON MCGRANAGHAN

SUCCESSIVE WAVES of early humans exited from Africa to all parts of the Old World. The record of these emigrations is incomplete, but it is evident that this history is much longer and more complex than has traditionally been believed.

LAURIE GRACE/JANA BRENNING

the Eurasian continent, being ultimately replaced by other hominid lineages that had evolved elsewhere.

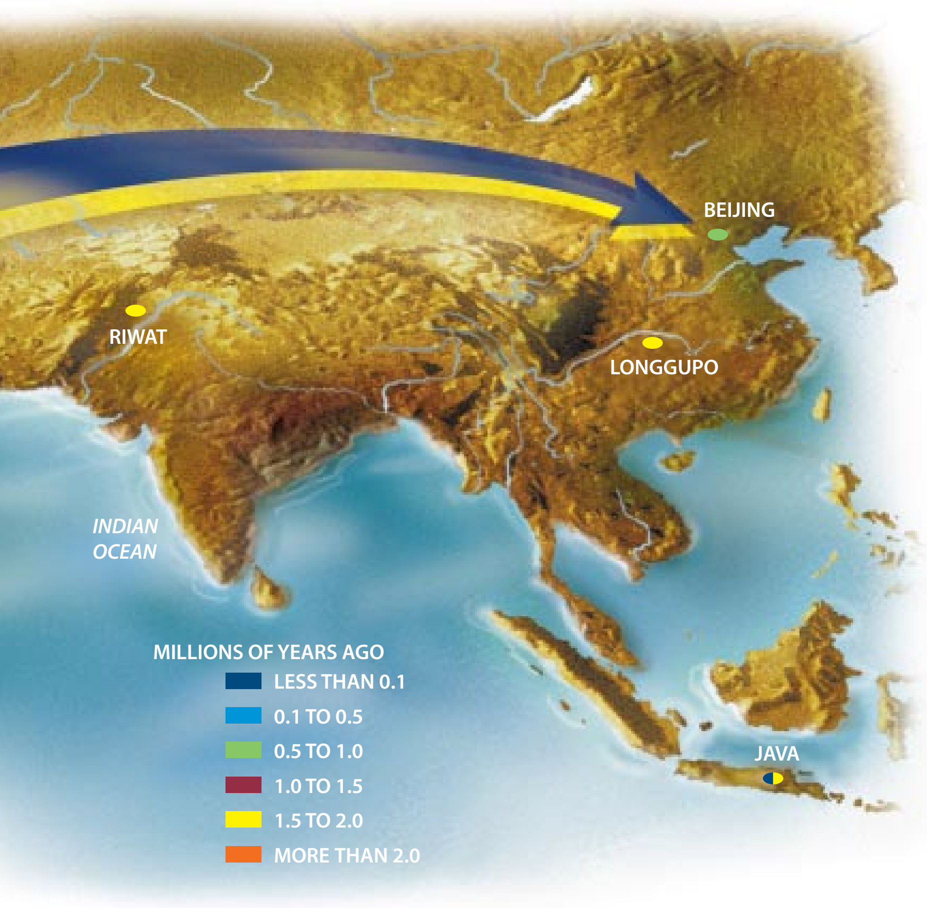
At the other end of the scale, an international group led by Huang Wanpo of Beijing's Academia Sinica last year reported a remarkably ancient date for Longgupo Cave in China's Sichuan Province. This site had previously yielded an incisor tooth and a tiny lower jaw fragment with two teeth that were initially attributed to *H. erectus,* plus a few very crude stone artifacts. Huang and his colleagues concluded that the fossils and tools might be as much as 1.9 Myr old, and their reanalysis of the fossils suggested to them a closer resemblance to earliest African *Homo* species than to *H. erectus.*

This latter claim has not gone unexamined. As my colleague Jeffrey H. Schwartz of the University of Pittsburgh and I pointed out, for instance, the teeth in the jaw fragment resemble African *Homo* in primitive features rather than in the specialized ones that indicate a special relationship. What is more, they bear a striking resemblance to the teeth of an orangutan-related hominoid known from a much later site in Vietnam. And although the incisor appears hominid, it is fairly generic, and there is nothing about it that aligns it with any particular human species. Future fossil finds from Longgupo will, with luck, clarify the situation; meanwhile the incisor and stone tools are clear evidence of the presence of humans in China at what may be a very early date indeed. These ancient eastern Asians were the descendants of the first emigrants from Africa, and, whatever the hominids of Longgupo eventually turn out to have been, it is a good bet that Huang and his colleagues are right in guessing that they represent a precursor form to *H. erectus* rather than that species itself.

COURTESY OF RUSSELL CIOCHON *University of Iowa*

COURTESY OF RUSSELL CIOCHON *University of Iowa*

FOSSILS FROM LONGGUPO, such as the lower jaw fragment (*side and top views at left*), together with crude stone tools (*right*), may indicate the presence of hominids in China as much as 1.9 million years ago.



All this makes sense, but one anomaly remains. If *H. erectus* was an indigenous eastern Asian development, then we have to consider whether we have correctly identified the Olduvai OH9 braincase as belonging to this species. If we have, then *H. erectus* evolved in eastern Asia at quite an early date (remember, OH9 is now thought to be almost 1.4 Myr old), and one branch of the species migrated back to Olduvai in Africa. But if these new Asian dates are accurate, it seems more probable that as we come to know more about OH9 and its kind we will find that they belonged to a different species of hominid altogether.

The opposite end of the Eurasian continent was, as I have hinted, also isolated from the human evolutionary mainstream. As we saw, humans seem to have arrived in Europe fairly late. In this region, the first convincing archaeological sites, with rather crude tools, show up at about 800 Kyr ago or thereabouts (although in the Levant, within hailing distance of Africa, the site of 'Ubeidiya has yielded Acheulean tools dated to around 1.4 Myr ago, just about as early as any found to the south). The problem has been that there has been no sign of the toolmakers themselves.

This gap has now begun to be filled by finds made by Eudald Carbonell of the University of Tarragona in Spain and his co-workers at the Gran Dolina cave site in the Atapuerca Hills of northern Spain. In 1994 excavations there produced numerous rather simple stone tools, plus a number of human fossil fragments, the most complete of which is a partial upper face of an immature individual. All came from a level that was dated to more than 780 Kyr ago. No traces of Acheulean technology were found among the tools, and the investigators noted various primitive traits in the fossils, which they provisionally attributed to *H. heidelbergensis*. This is the species into which specimens formerly classified as archaic *H. sapiens* are increasingly being placed. Carbonell and his colleagues see their fossils as the starting point of an indigenous European lineage that gradually evolved into

COURTESY OF RUSSELL CIOCHON *University of Iowa*

PARTIAL MANDIBLE (*top and side views*) from Dmanisi, in former Soviet Georgia, may be as much as 1.8 million years old. Initially assigned to *H. erectus*, its species is still uncertain.

COURTESY OF ERIC DELSON

JAVIER TRUEBA *Madrid Scientific Films*

GRAN DOLINA CAVE in the Atapuerca Hills of northern Spain has produced the earliest human fossils yet found in Europe. These fossils, dated to about 780,000 years ago and initially attributed to *H. heidelbergensis*, may in fact represent a distinct form. The juvenile frontal and mandible fragment (*right*) is one of the Gran Dolina fossils. The mature cranium (*below*) is from Sima de los Huesos, about one kilometer from Gran Dolina, where a huge trove of mostly fragmentary but exquisitely preserved human fossils is dated to about 300,000 years ago.

PHOTOGRAPH BY JAVIER TRUEBA; COURTESY OF JUAN-LUIS ARSUAGA

JAVIER TRUEBA *Madrid Scientific Films*

the Neanderthals. These latter, large-brained hominids are known only from Europe and western Asia, where they flourished in the period between about 200 Kyr and 30 Kyr ago, when they were extinguished in some way by invading *H. sapiens*.

This is not the only possibility, however. With only a preliminary description of the very fragmentary Gran Dolina fossils available, it is hard to be sure, but it seems at least equally possible that they are the remains of hominids who made an initial foray out of Africa into Europe but failed to establish themselves there over the long term. Representatives of *H. heidelbergensis* are known in Africa as well, as long ago as 600 Kyr, and this species quite likely recolonized Europe later on. There it would have given rise to the Neanderthals, whereas a less specialized African population founded the lineage that ultimately produced *H. sapiens*.

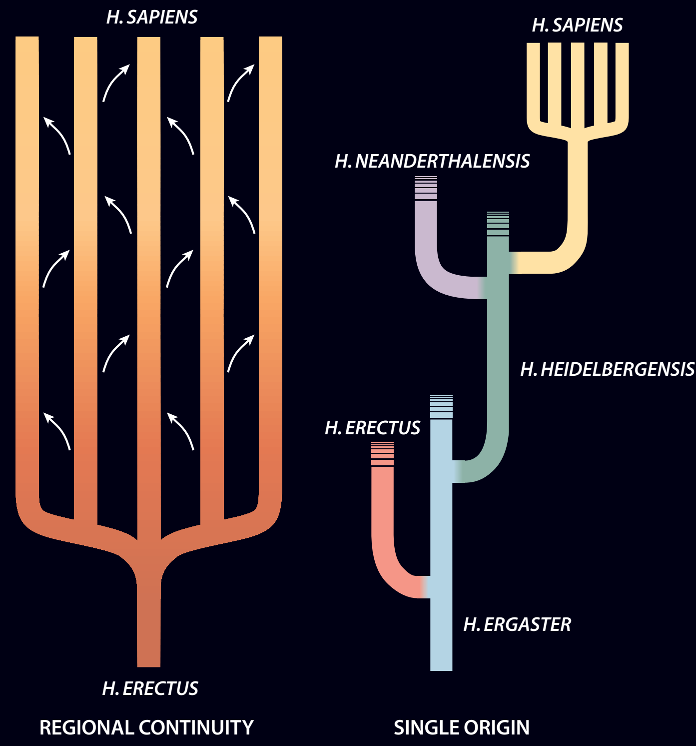
At another site, only a kilometer from Gran Dolina, Juan-Luis Arsuaga of Universidad Complutense de Madrid and his colleagues have discovered a huge cache of exquisitely preserved human fossils, about 300 Kyr old. These are said to anticipate the Neanderthals in certain respects, but they are not fully Neanderthal by any means. And although they emphasize that the Neanderthals (and possibly other related species) were an indigenous European development, these fossils from Sima de los Huesos ("Pit of the Bones") do not establish an unequivocal backward connection to the Gran Dolina neighbors.

Born in Africa

Every longtime reader of *Scientific American* will be familiar with the competing models of "regional continuity" and "single African origin" for the emergence of our own species, *H. sapiens* [see "The Multiregional Evolution of Humans," by Alan G. Thorne and Milford H. Wolpoff, and "The Recent African Genesis of Humans," by Allan C. Wilson and Rebecca L. Cann; April 1992]. The first of these models holds that the highly archaic *H. erectus* (including *H. ergaster*) is nothing more than an ancient variant of *H. sapiens* and that for the past two million years the history of our lineage has been one of a braided stream of evolving populations of this species in all areas of the Old World, each adapting to local conditions, yet all consistently linked by gene exchange. The variation we see today among the major geographic populations of humans is, by this reckoning, simply the latest permutation of this lengthy process.

The other notion, which happens to coincide much better with what we know of evolutionary processes in general, proposes that all modern human populations are descended from a single ancestral population that emerged in one place at some time between about 150 Kyr and 100 Kyr ago. The fossil evidence, thin as it is, suggests that this place of origin was somewhere in Africa (although the neighboring Levant is an alternative possibility); proponents of this scenario point to the support afforded by comparative molecular studies for the notion that all living humans are descended from an African population.

THE LEADING THEORIES of the origins of modern humans are contrasted in these diagrams. According to the notion of "regional continuity," all modern human populations trace their beginnings to *H. erectus,* but each regional population evolved along its own distinctive lines, exchanging enough genes with its neighbors (*arrows represent gene exchange*) to remain part of the same species; all eventually became *H. sapiens*. The "single origin" theory holds that *H. sapiens* descended from a single ancestral population that emerged in one place, probably Africa.



LAURIE GRACE; SOURCE: *The Last Neanderthal,* by Ian Tattersall (Macmillan, 1995)

In view of what I have already said about the peripheral roles played in human evolution by early populations both in eastern Asia and Europe, it should come as no surprise that between these two possibilities my strong preference is for a single and comparatively recent origin for *H. sapiens,* very likely in Africa—the continent that, from the very beginning, has been the engine of mainstream innovation in human evolution. The rise of modern humans is a recent drama that played out against a long and complex backdrop of evolutionary diversification among the hominids, but the fossil record shows that from the earliest times Africa was consistently the center from which new lineages of hominids sprang. Clearly, interesting evolutionary developments occurred in both Europe and eastern Asia, but they involved populations that were not only derived from but also eventually supplanted by emigrants from Africa. In Africa our lineage was born, and ever since its hominids were first emancipated from the forest edges, that continent has pumped out successive waves of emigrants to all parts of the Old World. What we see in the human fossil record as it stands today is without doubt a shadowy reflection at best of what must have been a very complex sequence of events.

Most important, the new dates from eastern Asia show that human population mobility dates right back to the very origins of effectively modern bodily form. Those from Europe demonstrate that although distinctive regional variants evolved there, the history of occupation of that region may itself not have been at all a simple one. As ever, though, new evidence of the remote human past has served principally to underline the complexity of events in our evolution. We can only hope that an improving fossil record will flesh out the details of what was evidently a richly intricate process of hominid speciation and population movement over the past two million years. SA

The Author

IAN TATTERSALL was born in England and raised in East Africa. He is chairman of the department of anthropology at the American Museum of Natural History in New York City. His latest books include *The Fossil Trail: How We Know What We Think We Know about Human Evolution* (Oxford University Press, 1995) and *The Last Neanderthal: The Rise, Success, and Mysterious Extinction of Our Closest Human Relatives* (Macmillan, 1995). His *Becoming Human: Evolution and Human Uniqueness* will be published by G. P. Putnam's Sons next year.

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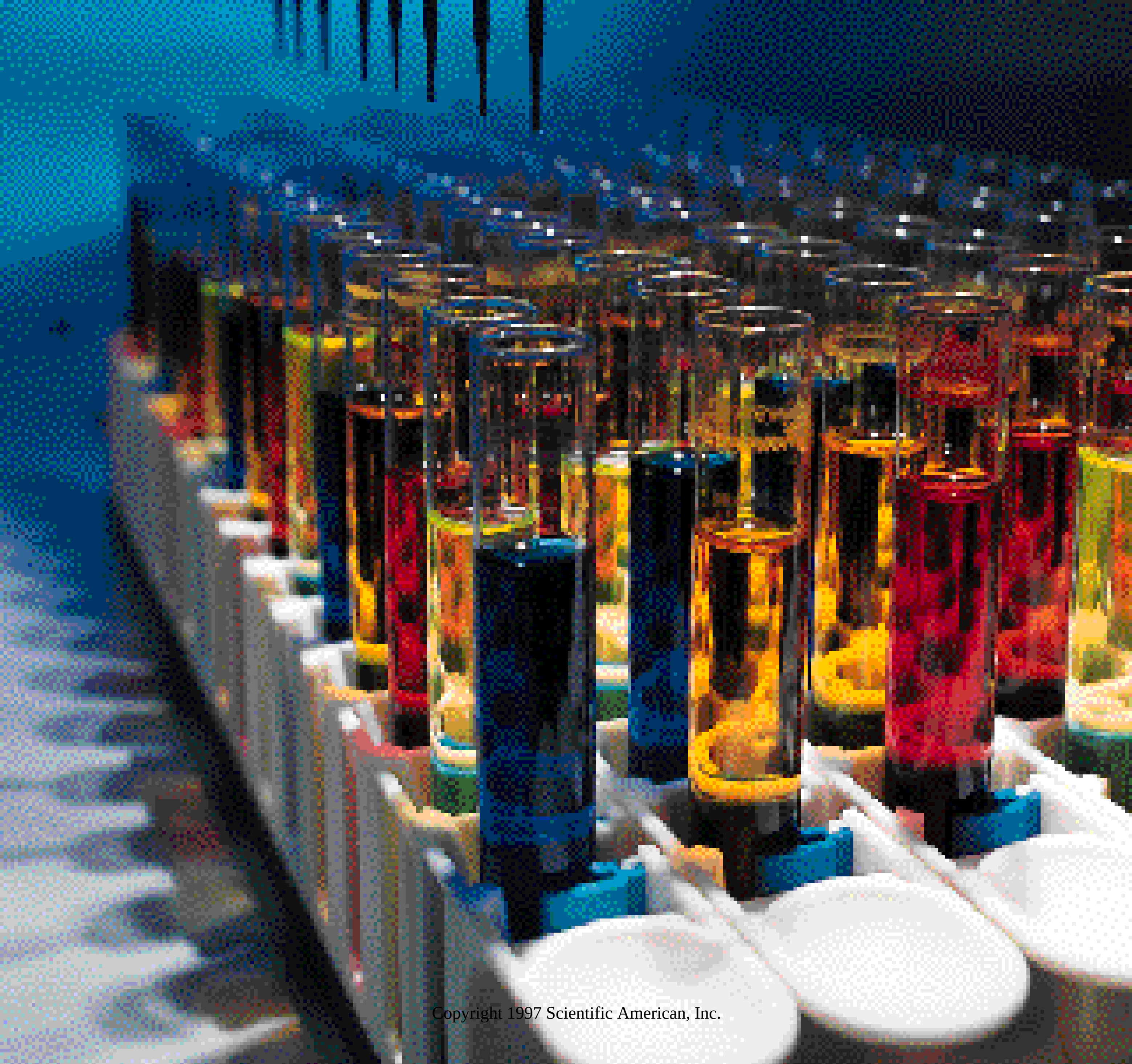
Combinatorial Chemistry and New Drugs

An innovative technique that quickly produces large numbers of structurally related compounds is changing the way drugs are discovered

by Matthew J. Plunkett and Jonathan A. Ellman



To fight disease, the immune system generates proteins known as antibodies that bind to invading organisms. The body can make about a trillion different antibodies, produced by shuffling and reshuffling their constituent parts. But the immune system is not equipped to craft a specialized antibody each time it is faced with a new pathogen. Instead the body selectively deploys only those existing antibodies that will work most effectively against a particular foe. The immune system does this, in effect, by mass screening of its antibody repertoire, identifying the ones that work best and making more of those. In the past few years, we and other chemists have begun to follow nature's example in order to develop new drugs. In a process called combinatorial chemistry, we generate a large number of related compounds and then screen the collection for the ones that could have medicinal value.

This approach differs from the most common way pharmaceutical makers discover new drugs. They typically begin by looking for signs of a desired activity in almost anything they can find, such as diverse collections of synthetic compounds or of chemicals derived from bacteria, plants or other natural sources. Once they identify a promising substance (known in the field as a lead compound), they laboriously make many one-at-a-time modifications to the structure, testing after each step to determine how the changes affected the compound's chemical and biological properties.

Often these procedures yield a compound having acceptable potency and safety. For every new drug that makes it to market in this way, however, researchers quite likely tinkered with and abandoned thousands of other compounds en route. The entire procedure is time-consuming and expensive: it takes many years and hundreds of millions of dollars to move from a lead compound in the laboratory to a bottle of medicine on the shelf of your local pharmacy.

The classical approach has been improved by screening tests that work more rapidly and reliably than in the past and by burgeoning knowledge about how various modifications are likely to change a molecule's biological activity. But as medical science has advanced, demand for drugs that can intervene in disease processes has escalated. To find those drugs, researchers need many more compounds to screen as well as a way to find lead compounds that require less modification.

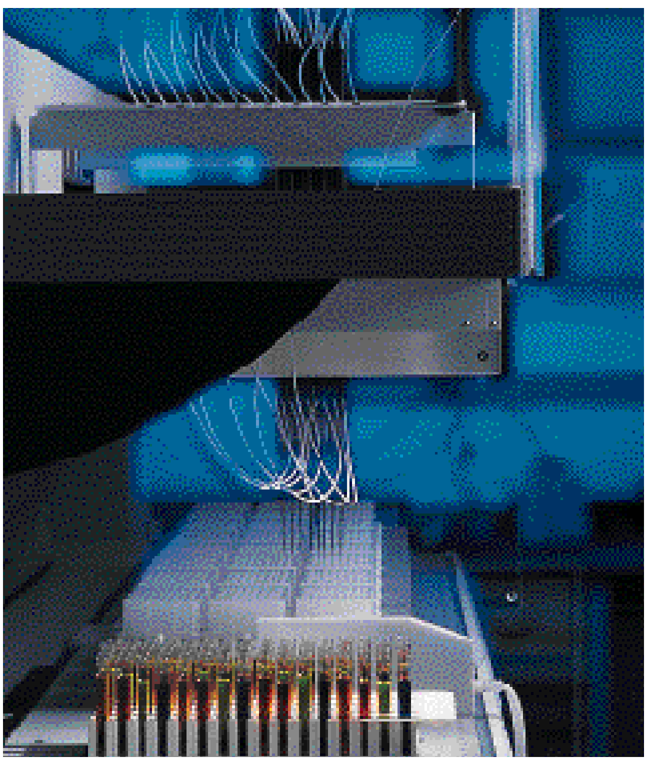
Finding the Right Combination

Combinatorial chemistry responds to that need. It enables drug researchers to generate quickly as many as several million structurally related molecules. Moreover, these are not just any molecules, but ones that a chemist, knowing the attributes of the starting materials, expects will have a desired property. Screening of the resulting pool of compounds reveals the most potent varieties. Combinatorial chemistry can thus offer drug candidates that are ready for clinical testing faster and at a lower cost than ever before.

Chemists make combinatorial collections, or libraries, of screenable compounds in a rather simple way. We rely on standard chemical reactions to assemble selected sets of building blocks into a huge variety of larger structures. As a simplified example, consider four molecules: A1, A2, B1 and B2. The molecules A1 and A2 are structurally related and are thus said to belong to the same class of compounds; B1 and B2 belong to a second class. Suppose that these two classes of compounds can react to form molecules, some variant of which we suspect could produce a potent drug. The techniques of combinatorial chemistry allow us to construct easily all the possible combinations: A1-B1, A1-B2, A2-B1 and A2-B2.

Of course, in the real world, scientists typically work with much larger numbers of molecules. For instance, we might select 30 structurally related compounds that all share, say, an amine group ($-NH_2$). Next, we might choose a second set of 30 compounds that all contain a carboxylic acid ($-CO_2H$). Then, under appropriate conditions, we would mix and match every amine with every carboxylic acid to form new molecules called amides (–CONH–). The reaction of each of the 30 amines with each of the 30 carboxylic acids gives a total of 30 × 30, or 900, different combinations. If we were to add a third set of 30 building blocks, the total number of final structures would be 27,000 (30 × 30 × 30). And if we used more than 30 molecules in each set, the number of final combinations would rise rapidly.

Drugmakers have two basic combinatorial techniques at their disposal. The first, known as parallel synthesis, was invented in the mid-1980s by H. Mario Geysen, now at Glaxo Wellcome. He initially used parallel synthesis as a quick way to identify which small segment of any given large protein bound to an antibody. Geysen generated a variety of short protein fragments, or peptides, by combining multiple amino acids (the building blocks of peptides and proteins) in different permutations. By performing dozens or sometimes hundreds of reactions at the same time and then testing



CHARLES O'REAR

MIXING AND MATCHING of molecular building blocks in the technique known as combinatorial chemistry allows researchers to generate huge numbers of structures quickly. A robot (*above*) delivers the reactive chemicals used to assemble a large collection of compounds (*opposite page*).

CHARLES O'REAR

to see whether the resulting peptides would bind to the particular antibody of interest, he rapidly found the active peptides from a large universe of possible molecules.

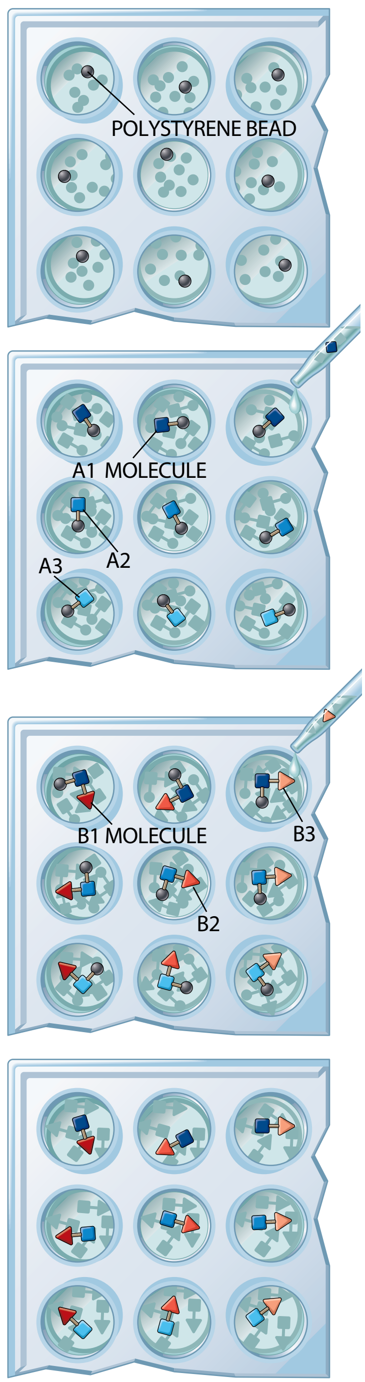
In a parallel synthesis, all the products are assembled separately in their own reaction vessels. To carry out the procedure, chemists often use a so-called microtitre plate—a sheet of molded plastic that typically contains eight rows and 12 columns of tiny wells, each of which holds a few milliliters of the liquid in which the reactions will occur. The array of rows and columns enables workers to organize the building blocks they want to combine and provides a ready means to identify the compound in a particular well.

For instance, if researchers wanted to produce a series of amides by combining eight different amines and 12 carboxylic acids using the reactions we described earlier, they would place a solution containing the first amine in the wells across the first row, the second amine across the second row, and so on. They would then add each of the carboxylic acids to the wells sequentially, supplying a different version to each column. From only 20 different building blocks, investigators can obtain a library of 96 different compounds.

Chemists often start a combinatorial synthesis by attaching the first set of building blocks to inert, microscopic beads made of polystyrene (often referred to as solid support). After each reaction, researchers wash away any unreacted material, leaving behind only the desired products, which are still tethered to the beads. Although the chemical reactions required to link compounds to the beads and later to detach them introduce complications to the synthesis process, the ease of purification can outweigh these problems.

In many laboratories today, robots assist with the routine work of parallel synthesis, such as delivering small amounts of reactive molecules into the appropriate wells. In this way, the process becomes more accurate and less tedious. Scientists at Parke-Davis constructed the first automated method for parallel synthesis—a robotic device that can generate 40 compounds at a time. And investigators at Ontogen have developed a robot that can make up to 1,000 compounds a day. In general, the time needed to complete a parallel synthesis depends on how many compounds are being produced: when making thousands of compounds, doubling the number of products requires nearly twice as much time. Such practical considerations restrict parallel synthesis to producing libraries containing tens of thousands of compounds rather than many more.

Parallel Synthesis



STEP 1
Start with a molded plastic sheet of wells (called a microtitre plate) that have been partly filled with a solution containing inert polystyrene beads (*gray circles*). Typical microtitre plates have eight rows and 12 columns, for a total of 96 wells; this example illustrates only the upper left corner of the plate.

STEP 2
Add the first set of molecules—the A class (*squares*)—to the beads, putting the A1 molecules into the wells of the first row, the A2 molecules into the wells of the second row, and so on. After one set of molecules has been added, filter the material in every well to eliminate unreacted chemicals (those unattached to beads).

STEP 3
Add the second set of molecules—the B class (*triangles*)—down the columns, with B1 in the first column, B2 in the second, et cetera. Filter away unreacted chemicals as in step 2.

STEP 4
Once the 96-member library has been produced, detach the final structures from the beads so that the compounds can be screened for biological activity.

JARED SCHNEIDMAN DESIGN

Split and Mix

The second technique for generating a combinatorial library, known as a split-and-mix synthesis, was pioneered in the late 1980s by Árpád Furka, now at Advanced ChemTech in Louisville, Ky. In contrast to parallel synthesis, in which each compound remains in its own container, a split-and-mix synthesis produces a mixture of related compounds in the same reaction vessel. This method substantially reduces the number of containers required and raises the number of compounds that can be made into the millions. The trade-off, however, is that keeping track of such large numbers of compounds and then testing them for biological activity can become quite complicated.

A simple example can explain this approach. Imagine that researchers have three sets of molecules (call them A, B and C), each set having three members (A1, A2, A3; B1, B2, B3; and so on). Inside one container, they attach the A1 molecules to polystyrene beads; in a second container A2 molecules, and in a third A3 molecules. Then the workers place all the bead-bound A molecules into one reaction vessel, mix them well and split them again into three equal portions, so that each vial holds a mixture of the three compounds. The researchers then add B1 molecules to the first container, B2 to the second, and B3 to the third. One more round of additions to introduce the C molecules produces a total of 27 different compounds.

To isolate the most potent of these structures, scientists first screen the final mixtures of compounds and determine the average activity of each batch. Then, using a variety of techniques, they can deduce which of the combinations in the most reactive batch has the desired biological activity.

A number of pharmaceutical companies have also automated the split-and-mix procedure. One of the earliest announcements came from a group at Chiron. Chemists there developed a robotic system that can make millions of compounds in a few weeks using this approach. The robot delivers chemicals and performs the mixing and partitioning of the solid support.

As we mentioned earlier, one of the problems with a split-and-mix synthesis is identifying the composition of a reactive compound within a large mixture. Kit Lam of the University of Arizona has developed a way to overcome this obstacle. He noted that at the end of a split-and-mix synthesis, all the molecules attached to a single bead are of the same structure. Scientists can pull out from the mixture the beads that bear biologically active molecules and then, using sensitive detection techniques, determine the molecular makeup of the compound attached. Unfortunately, this technique will work only for certain compounds, such as peptides or small segments of DNA.

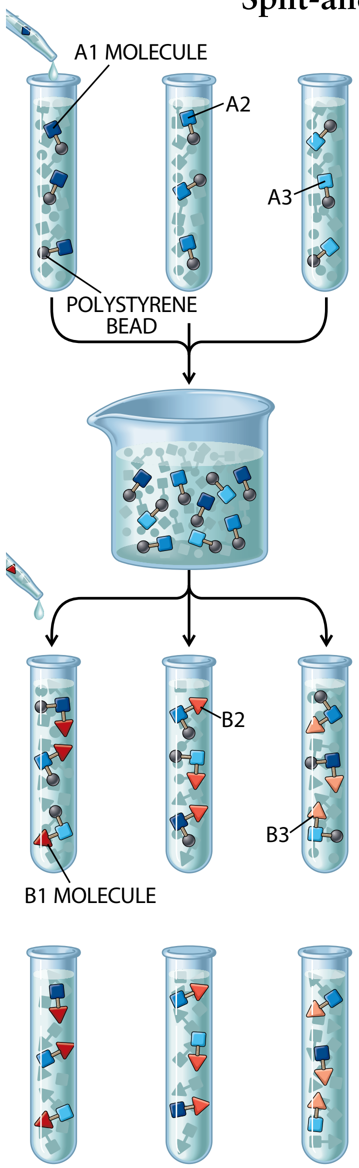
Other investigators have developed methods to add to each bead a chemical label essentially listing the order in which specific building blocks have been added to the structure—in other words, the chemical equivalent of a UPC bar code. Reading the collection of these so-called tags on a particular bead gives a unique signature and hence the identity of the compound on that bead. Researchers at the biotechnology company Pharmacopeia, drawing on techniques introduced by W. Clark Still of Columbia University, have been very successful in applying powerful tagging techniques to their combinatorial libraries.

Nevertheless, because of the difficulties of identifying compounds made in a split-and-mix synthesis, most pharmaceutical companies today continue to rely on parallel synthesis.

Drug Libraries

Both the parallel and the split-and-mix techniques of combinatorial chemistry began as ways to make peptides. Although these molecules are important in biological systems, peptides have limited utility as drugs because they degrade in the gut, they cannot be absorbed well through the stomach and

Split-and-Mix Synthesis



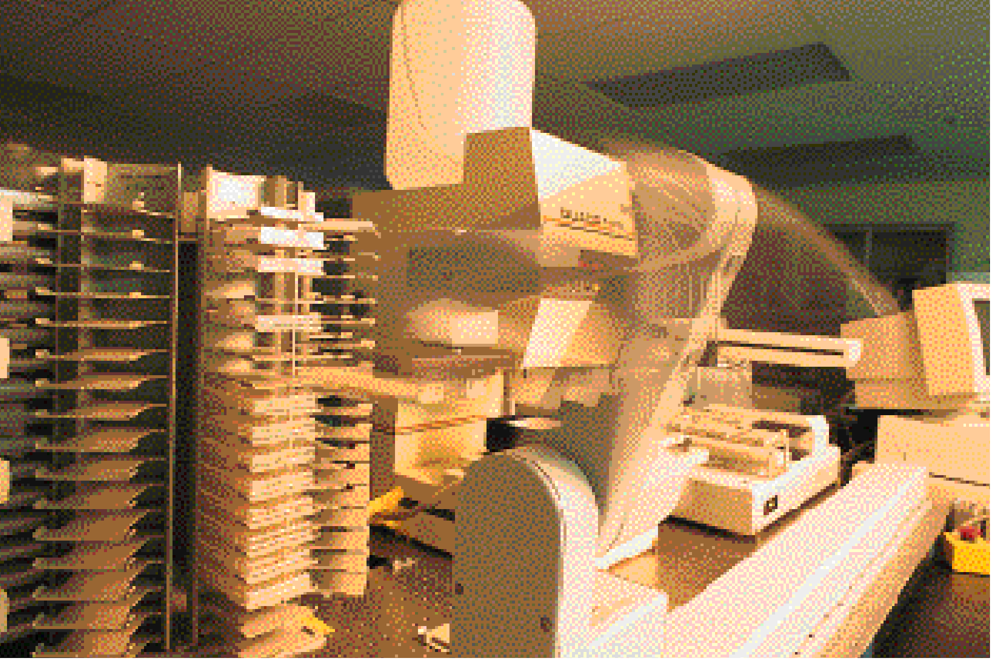
STEP 1
Start with test tubes holding a solution containing inert polystyrene beads (*gray circles*). For simplicity, this example shows only three containers, but dozens might be used. Add the first set of molecules—the A class (*squares*)—to the test tubes, putting A1 molecules into the first container, A2 molecules into the second, and so on.

STEP 2
Mix the contents of all the test tubes.

STEP 3
Split the mixture into equivalent portions. Then add the second set of molecules—the B class (*triangles*)—placing B1 molecules into the first test tube, B2 into the second, et cetera. (Repeat steps 2 and 3 as many times as needed, depending on the number of sets of building blocks to be added.)

STEP 4
Separate the beads from any unreacted chemicals and detach the final structures. Researchers often screen the contents of each test tube to determine the mixture's average biological activity. Because each mixture shares the same final component, workers can determine which variant scores best—say, B2 might be most potent. They repeat the synthesis, adding only B2 to the A compounds to find which of the A-B2 combinations are the most biologically active.

JARED SCHNEIDMAN DESIGN



SCREENING ROBOT at Arris Pharmaceutical automatically shuttles microtitre plates bearing combinatorial libraries to the equipment that tests for biological activity.

they are rapidly cleared from the bloodstream. The pharmaceutical industry began to pursue combinatorial methods more aggressively after realizing that these techniques could also be applied to druglike compounds, such as the class of molecules known as benzodiazepines.

Benzodiazepines are one of the most widely prescribed classes of medicines. The best-known representative is diazepam, or Valium, but the class includes a number of other derivatives with important biological activity: anticonvulsant and antihypnotic agents, antagonists of platelet-activating factor (a substance important in blood clotting), inhibitors of the enzyme reverse transcriptase in HIV, and inhibitors of Ras farnesyl transferase (an enzyme involved in cancer). Because of the broad activity of this class, benzodiazepines were the first compounds to be studied in a combinatorial synthesis seeking new drugs. In 1992 one of us (Ellman), working with Barry Bunin, also at the University of California at Berkeley, described a way to synthesize benzodiazepines on a solid support, making possible the synthesis of libraries containing thousands of benzodiazepine derivatives.

More recently, the two of us (Plunkett and Ellman) worked out a better approach for making benzodiazepines on a solid support; our new synthesis provides easy access to much larger numbers of compounds. The most challenging aspect of any combinatorial synthesis is determining the experimental conditions that will minimize side reactions giving rise to impurities. We spent more than a year fine-tuning the reaction conditions for our new benzodiazepine synthesis, but after determining the optimal procedure, we, along with Bunin, generated 11,200 compounds in two months using a parallel synthesis.

Promising Leads

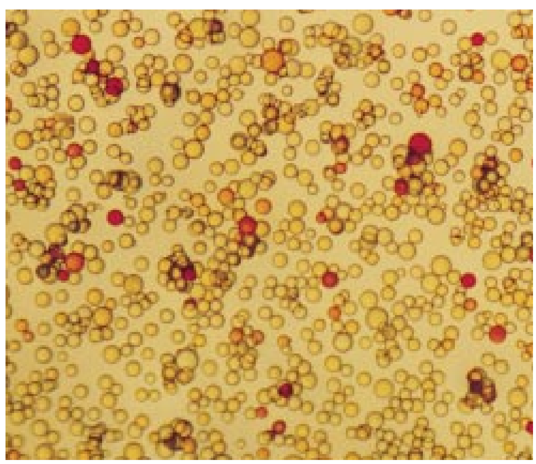
From our benzodiazepine libraries, we have identified several compounds with promising biological activity. In a project with Victor Levin and Raymond Budde of the University of Texas M. D. Anderson Cancer Center in Houston, we have identified a benzodiazepine derivative that inhibits an enzyme implicated in colon cancer and osteoporosis. And in collaboration with Gary Glick and his colleagues at the University of Michigan, we discovered another benzodiazepine that inhibits the interaction of antibodies with single-strand DNA—a process that may be involved in systemic lupus erythematosus. These compounds are still in the very early stages of laboratory testing.

Once we and others demonstrated that combinatorial chemistry could be used to assemble druglike molecules, the pharmaceutical industry began pursuing more projects in this area. In the past five years, dozens of small companies devoted entirely to combinatorial chemistry have begun operation. Nearly all the major pharmaceutical companies now have their own combinatorial chemistry departments or have entered a partnership with a smaller, specialized company that does.

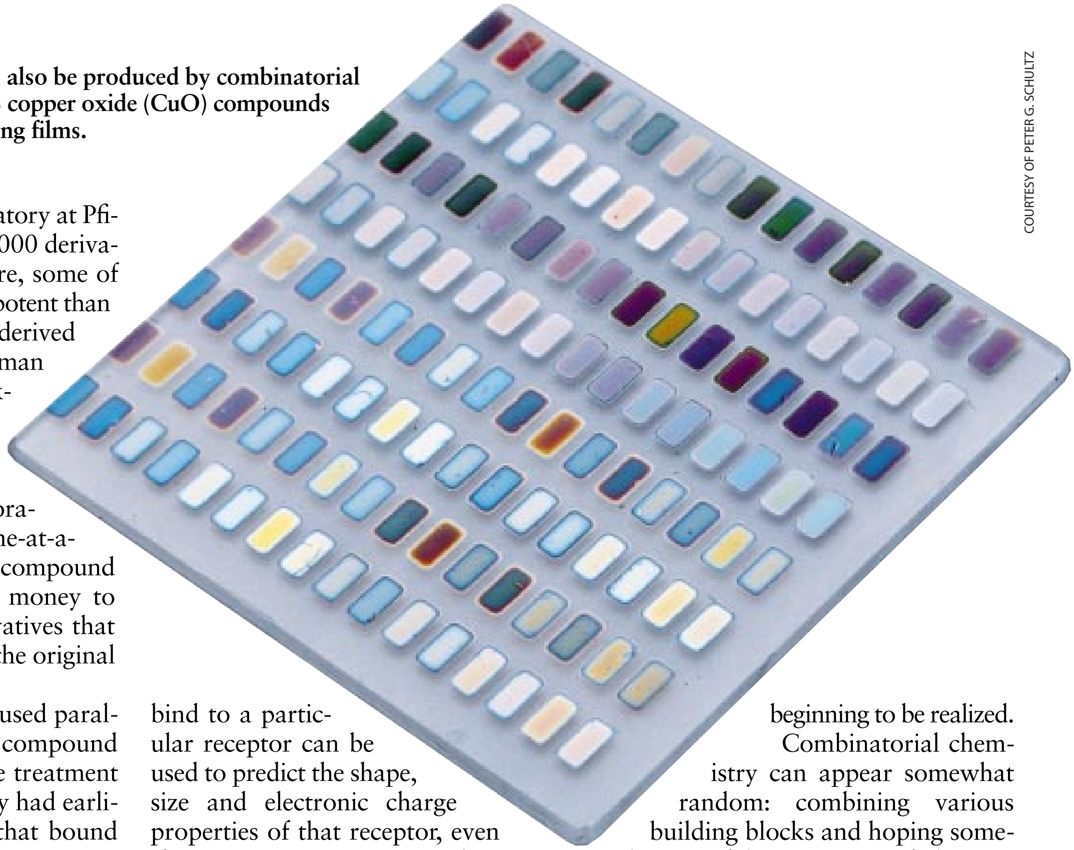
As might be expected, researchers have branched out beyond benzodiazepines, routinely applying combinatorial techniques to a wide array of starting materials. In general, chemists use combinatorial libraries of small organic molecules as sources of promising lead compounds or to optimize the activity of a known lead. When searching for a new lead structure, researchers often generate large libraries, with tens of thousands or even millions of final products. In contrast, a library designed to improve the potency and safety of an existing lead is typically much smaller, with only a few hundred compounds.

Several pharmaceutical companies are now conducting human clinical trials of drug candidates discovered through combinatorial chemistry. Because such programs are relatively new, none of these candidates has yet been studied long enough to receive approval from the U.S. Food and Drug Administration. But it is only a matter of time before a medicine developed with assistance from combinatorial methods reaches the market.

Pfizer has one example in its pipeline. Using standard methods in 1993, the company discovered a lead compound that appeared to have potential for preventing atherosclerosis, or hardening of the arteries. In less than a year, using



POLYSTYRENE BEADS (magnified roughly 100 times) are often used in combinatorial chemistry so that the products, which are attached to the beads, will be easy to separate from unreacted material. Beads that tested positive in a screening assay for artificial steroid receptors turned red.



SUPERCONDUCTORS can also be produced by combinatorial chemistry. This library of 128 copper oxide (CuO) compounds yielded several superconducting films.

COURTESY OF PETER G. SCHULTZ

parallel synthesis, one laboratory at Pfizer generated in excess of 1,000 derivatives of the original structure, some of which were 100 times more potent than the lead compound. A drug derived from this series is now in human clinical trials. Notably, workers made more than 900 molecules before they noticed any improvement in biological activity. Few laboratories making standard one-at-a-time modifications to a lead compound could afford the time and money to generate nearly 1,000 derivatives that showed no advantage over the original substance.

Chemists at Eli Lilly also used parallel synthesis to develop a compound now in clinical trials for the treatment of migraine headaches. They had earlier found a lead substance that bound effectively to a desired drug target, or receptor. But the lead also had a high affinity for other, related receptors, behavior that could produce unwanted side effects. Researchers used parallel synthesis to make approximately 500 derivatives of that lead before arriving at the one currently being evaluated.

Researchers will inevitably find ways to generate combinatorial libraries even faster and at a lower cost. Already they are working out clever reaction methods that will enhance the final yield of products or replace the need for adding and later removing polystyrene beads. The future will also see changes in how information about the activity of tested compounds is gathered and analyzed in the pharmaceutical industry. For example, data on how thousands of compounds in one combinatorial library bind to a particular receptor can be used to predict the shape, size and electronic charge properties of that receptor, even if its exact structure is unknown. Such information can guide chemists in modifying existing leads or in choosing starting materials for constructing new combinatorial libraries.

Although the focus here has been the discovery of drugs, the power of combinatorial chemistry has begun to influence other fields as well, such as materials science. Peter G. Schultz and his colleagues at the University of California at Berkeley have used combinatorial methods to identify high-temperature superconductors. Other researchers have applied combinatorial techniques to liquid crystals for flat-panel displays and materials for constructing thin-film batteries. Scientists working on these projects hope to produce new materials quickly and cheaply. Clearly, the full potential of this powerful approach is only beginning to be realized.

Combinatorial chemistry can appear somewhat random: combining various building blocks and hoping something useful comes out of the mix may seem to be the triumph of blind luck over knowledge and careful prediction. Yet this impression is far from the truth. A good library is the result of extensive development and planning. Chemists must decide what building blocks to combine and determine how to test the resulting structures for biological activity. Combinatorial chemistry allows researchers to gather, organize and analyze large amounts of data in a variety of new and exciting ways. The principle of selecting the most effective compounds from a collection of related ones—the guiding axiom of the immune system—is changing the way chemists discover new drugs. It is a pleasant irony that this lesson gleaned from our natural defenses can be helpful when those defenses fail. SA

The Authors

MATTHEW J. PLUNKETT and JONATHAN A. ELLMAN worked together at the University of California, Berkeley, on combinatorial techniques for use with druglike molecules. After receiving his Ph.D. from Berkeley in 1996, Plunkett moved to Arris Pharmaceutical, where he specializes in making combinatorial libraries for random screening and protease inhibition. Ellman joined the faculty of Berkeley in 1992. His laboratory is currently engaged in the development of new chemistry for the synthesis of organic compound libraries and in the application of the library approach to different problems in chemistry and biology.

Further Reading

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How Erosion Builds Mountains

An understanding of how tectonic, erosional and climatic forces interact to shape mountains permits clearer insights into the earth's history

Nicholas Pinter and Mark T. Brandon

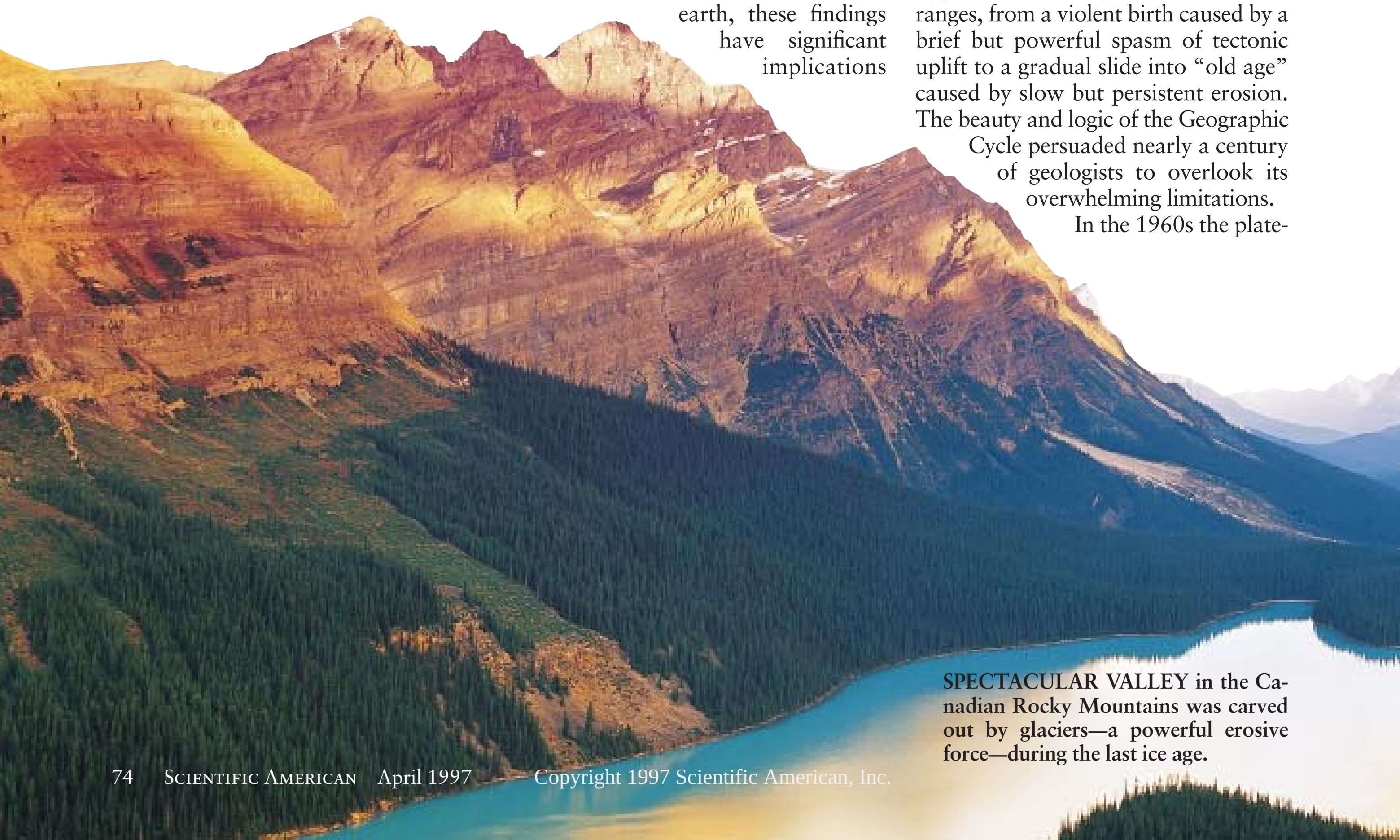
Mountains are far more massive than all human structures combined and are sculpted in greater detail than a Baroque palace. The world's tallest pinnacle—Mount Everest in the Himalayas—reaches 8,848 meters, or about 15 times higher than anything people have ever built. Not surprisingly, such spectacular topography has evoked awe and inspired artists and adventurers throughout human existence.

Recent research has led to important new insights into how this most magnificent of the earth's relief comes to be. Mountains are created and shaped, it appears, not only by the movements of the vast tectonic plates that make up the earth's exterior but also by climate and erosion. In particular, the interactions between tectonic, climatic and erosional processes exert strong control over the shape and maximum height of mountains as well as the amount of time necessary to build—or destroy—a mountain range. Paradoxically, the shaping of mountains seems to depend as much on the destructive forces of erosion as on the constructive power of tectonics. In fact, after 100 years of viewing erosion as the weak sister of tectonics, many geologists now believe erosion actually may be the head of the family. In the words of one research group, "Savor the irony should mountains owe their [muscles] to the drumbeat of tiny raindrops."

Because of the importance of mountain building in the evolution of the earth, these findings have significant implications for earth science. To a geologist, the earth's plains, canyons and, especially, mountains reveal the outline of the planet's development over hundreds of millions of years. In this sprawling history, mountains indicate where events in or just below the earth's crust, such as the collisions of the tectonic plates, have thrust this surface layer skyward. Thus, mountains are the most visible manifestation of the powerful tectonic forces at work and the vast time spans over which those forces have operated.

The recent model builds on a lengthy history. One of the first comprehensive models of how mountains evolve over time was the Geographic Cycle, published in 1899. This model proposed a hypothetical life cycle for mountain ranges, from a violent birth caused by a brief but powerful spasm of tectonic uplift to a gradual slide into "old age" caused by slow but persistent erosion. The beauty and logic of the Geographic Cycle persuaded nearly a century of geologists to overlook its overwhelming limitations.

In the 1960s the plate-



SPECTACULAR VALLEY in the Canadian Rocky Mountains was carved out by glaciers—a powerful erosive force—during the last ice age.

tectonics revolution explained how mountain building is driven by the horizontal movements of vast blocks of the lithosphere—the relatively cool and brittle part of the earth's exterior. According to this broad framework, internal heat energy shapes the planet's surface by compressing, heating and breaking the lithosphere, which varies in thickness from 100 kilometers or less below the oceans to 200 or more below the continents. The lithosphere is not a solid shell but rather is subdivided into dozens of plates. Driven by heat from below, these plates move with respect to one another, accounting for most of our world's familiar surface features and phenomena, such as earthquakes, ocean basins and mountains.

Earth scientists have not by any means discarded plate tectonics as a force in mountain building. Over the past couple of decades, however, they have come to the conclusion that mountains are best described not as the result of tectonics alone but rather as the products of a system that encompasses erosional and climatic processes in addition to tectonic ones and that has many complex linkages and feedbacks among those three components.

Plate tectonics still provides the basic framework that accounts for the distribution of mountains across the earth's surface. Mountain building is still explained as the addition of mass, heat or some combination of the two to an area of the earth's crust (the crust is the upper part of the lithosphere). Thicker or hotter crust rises upward, forming mountains, because the crust is essentially floating on the mantle under it, and crust that is either thicker or hotter (less dense) floats higher. Plate tectonics contributes to the thickening of the crust by either lateral convergence between adjacent plates or through the upward flow of heat and magma (molten rock).

Subduction or Collision

Convergence of tectonic plates generally occurs in one of two ways. One plate may slide down, or subduct, below the other, into the mantle. At a subduction-zone boundary, the upper plate is thickened as a result of the compression and from magma being added by the melting of the descending plate. Many mountains, including almost all the ranges that surround the Pacific Ocean in a geologically active area known as the ring of fire, formed by subduction. With continental collision, on the other hand, neither plate subducts into the mantle, and therefore all the mass added as a result of the collision contributes to the building of mountains. Such collisions have created some spectacular topography, such as the Tibetan Plateau and the Himalayas, which include all 10 of the world's highest peaks.

The flow of magma and heat to the earth's crust, for example, during volcanic activity, can also drive mountain building. The earth's longest mountain chains—the mid-ocean ridges—are the result of magma welling up as adjacent plates move apart, forming new crust under the ocean. These ridges run through the Atlantic, eastern Pacific and Indian oceans like the seam on a baseball; the Mid-Atlantic Ridge alone is more than 15,000 kilometers long, rising as much as 4,000 meters above the surrounding abyssal plains of the ocean floor. On land, heat associated with the flow of magma can also help uplift large areas by making the crust less dense and more buoyant on the underlying mantle.

The emerging, system-oriented view of mountain building adds to those tectonic phenomena the often closely intertwined effects of erosion and climate. Erosion includes the disaggregation of bedrock, the stripping away of sediment from slopes and the transport of the sediment by rivers. The mix of erosional agents active on a particular landscape—gravity, water, wind and glacial ice—depends on the local climate, the steepness of the topography and the types of rock at or near the surface.

Climate is inextricably linked with erosion because it affects the average rate of material loss across a landscape. In general, wetter conditions favor faster rates of erosion; however, more moisture also promotes the growth of vegetation, which helps to "armor" the surface. Mountains in polar latitudes are the least vulnerable to erosion, partly because of the aridity of cold climates and partly because continental ice sheets such as those on Greenland and Antarctica commonly are frozen to the underlying rock and cause little erosion. In contrast, mountain glaciers such as those of the European Alps and the Sierra Nevada in California aggressively attack the subsurface rock, so that this type of glacier may be the earth's most potent erosional agent.

There are many other links among erosion, climate and topography. For example, mountains lift the winds that

RICHARD SISK *Panoramic Images*

THE GEOSPHERE PROJECT/TOM VAN SANT, INC.

HIMALAYAS and Tibetan Plateau are clearly visible in this satellite image as a mostly white area north and east of India. The ridges along the southern boundary of this area are the Himalayas, which are the stunning manifestation of an ongoing collision that began 50 million years ago, when the Indian tectonic plate began plowing into the Asian one.

flow over them, causing increased precipitation on the range's windward slopes, intensifying erosion as a result. Known as orography, this effect is also responsible for the "rain shadow" that creates deserts on the leeward sides of many mountain ranges [*see photograph on opposite page*]. Elevation can also affect erosion, because average temperature decreases with altitude, so that higher peaks are less likely to be protected by vegetation and more likely to be eroded by glaciers. In temperate regions the rate of erosion is proportional to the average steepness of the topography, apparently because gravity- and water-driven processes are stronger on steeper slopes. Taken together, all these facts suggest that mountains evolve their own climates as they grow—becoming typically wetter, colder and characterized by more intense erosion.

The links described above demonstrate that mountain ranges are best viewed as a system. To understand the behavior of any such system, it is necessary to identify both its components and the interactions among those components. Because these interactions are so important, simple system inputs can lead to surprisingly complex outputs. Such complexities include feedback—stabilizing or destabilizing links between component processes. In the simple example we have outlined, the output of the system is the height of the mountain range, whereas one of the inputs is erosion rate. As the mountains grow taller, erosion increases, reducing the growth rate. Because this feedback tends to lessen the input—thereby moderating the output as well—it is known as negative feedback. In contrast, positive feedback has the opposite effect, accelerating any change in a system. The creation of a rain shadow is an example of positive feedback; erosion is inhibited, allowing a mountain range to continue its rapid growth. The rain shadow north of the Himalayas has contributed to the formation of the high-standing Tibetan Plateau [*see box on pages 78 and 79*].

The concept of feedback is at the heart of the new understanding of how mountains are built—and even how mountain building affects the earth system as a whole. Numerous different types of feedback have been recognized or postulated. Among the most unexpected insights that have accrued from these discoveries is the realization that several important feedbacks enable surface processes, such as climate and erosion, to influence profoundly tectonic processes deep below the surface (and vice versa).

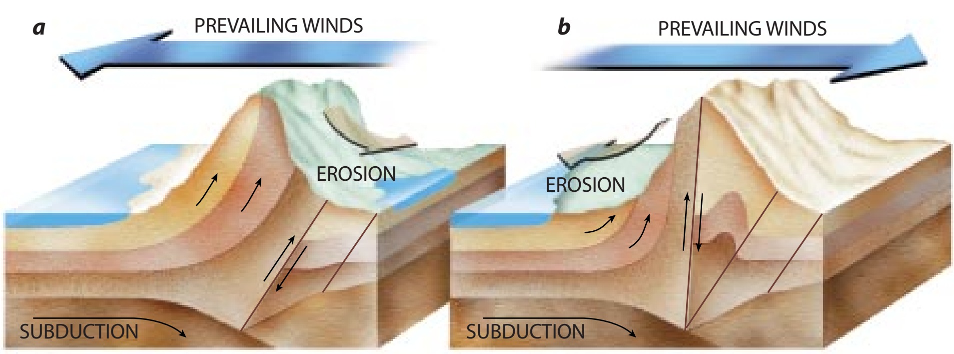
Isostasy Is Key

One important feedback occurs through the phenomenon known as isostasy, which refers to the buoyancy of the earth's crust as it floats on the denser, fluidlike mantle below it. A mountain range, like any physical structure, must be supported, and it turns out that this support comes mainly from the strength of the crust and from isostasy. Under the soaring peaks of every mountain range is a buoyant "root" of crust that penetrates into the mantle. Icebergs offer a useful analogy: because ice is about 90 percent as dense as water, a given mass of ice above the water is supported by nine times that mass underneath the waterline. Continental crust is about 80 to 85 percent as dense as the mantle beneath, enabling crustal roots tens of kilometers deep to support mountains several kilometers high.

Isostasy is the key mechanism that links a mountain's tectonic, or internal, evolution to its geomorphic, or external, development. When erosion at the surface removes mass, isostasy responds by lifting the entire mountain range up to replace about 80 percent of the mass removed. This uplift explains a number of phenomena that were puzzling before researchers fully appreciated the role of feedback in mountain building.

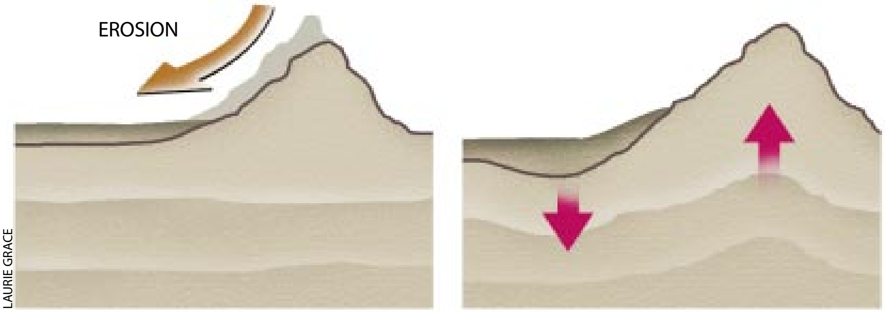
For example, high-precision surveys along the U.S. Atlantic Coast have revealed that the land is rising at rates of a few millimeters to a few centimeters a century. This was puzzling because the Appalachian Mountains lie in the interior of the North American plate, where there is no convergent plate boundary to account for the uplift. Some geologists suggested that the survey results must therefore be in error. Given our new understanding, however, some or all of the measured uplift may be the isostatic response to erosion, especially in the high-relief areas of the Appalachians. Erosion that is concentrated at the bottom of river valleys may be especially significant because it can lift mountain peaks to elevations *higher* than the elevations before erosion started. This is possible because the removal of mass is localized (in the valleys), but the isostatic response lifts the entire mountain block, including both valleys and peaks.

Although isostasy can prop them up for many millions of years, landscapes



LAURIE GRACE; SOURCE: Sean Willett, Christopher Beaumont and Philippe Fullsack, *Geology*, Vol. 21, No. 4, April 1993

OROGRAPHY refers to the phenomenon in which mountains lift the air currents flowing over them, increasing precipitation over the crest and windward slopes of the range. In a mountain range near an ocean, for example, when the prevailing winds blow offshore, opposite to the direction of subduction (*a*), erosion is concentrated on the inland side of the range, without tectonic uplift do eventually succumb to erosion. Several studies have suggested that large areas of Australia are good examples of very old, decaying landscapes. These areas, which have not experienced tectonic uplift for hundreds of millions of years, are at most a few hundred meters above sea level. Their rates of surface uplift seem to be consistent with only isostatic response to erosion. In such tectonically active mountains as the Himalayas and the European Alps, measured uplift reflects a combination of tectonic driving forces and erosionally driven isostatic uplift. Given the rates at which mountains grow and then decay, we can infer that dozens of major mountain ranges may have come and gone on the earth throughout its history.



LAURIE GRACE

ISOSTATIC UPLIFT occurs as a result of the buoyancy of a mountain on the more dense, fluidlike mantle (*not shown*) on which it "floats." Erosion causes the crust to rise up, whereas deposition of the resulting sediment weighs the crust downward.

Unusual Tectonic Times?

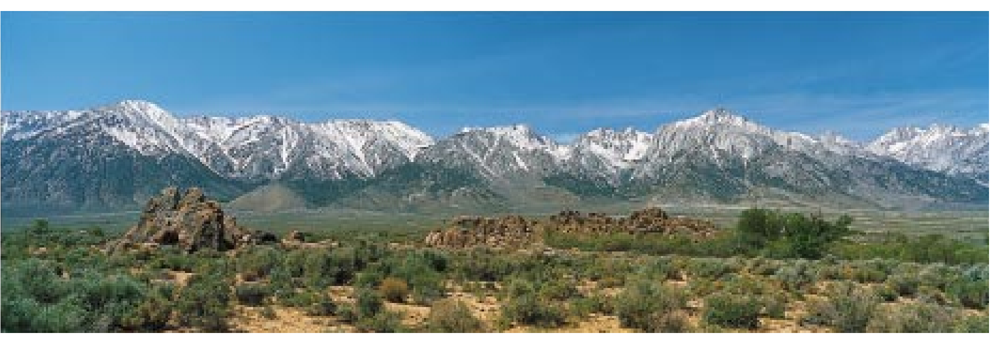
The construction of mountains, including ancient mountains that were built and eroded away in the distant past, can leave a variety of marks in the geologic record, such as those from lava flows, intrusion of magma, the exposure of once deeply buried rocks, as well as copious sediment deposited in lowland basins and the fossils of plants known to thrive only at high altitudes. By studying such indicators from many different periods, geologists can make inferences about the extent of mountain building on the earth at different times, thereby gaining insights into the planet's development.

Various geologists have looked at the relative abundance of sediment, magmatic activity and other potential indicators of mountain building and concluded that the past 40 million years represents an anomalous surge of tectonic activity and mountain building. This same geologic period, however, also saw a major climate shift on the earth, a global cooling that transformed Greenland and Antarctica from temperate, vegetated lands to permanent ice sheets and that culminated in the glaciers that covered North America and Europe during the past two million years. Thus, at present there are two opposing theories about mountain building and climate over the past 40 million years: either the surge of mountain building caused the global climate shift, or the climate shift caused the surge of mountain building.

The first of these two theories asserts that powerful and widespread mountain building cooled the earth as a result of the feedback between mountains and climate. For example, glaciers tend to be self-perpetuating: once established, they increase the reflectivity, or albedo, of the surface, thus lowering temperatures and allowing more ice to form. Widespread uplift of large mountain masses in the past 40 million years could have increased the area of the earth covered by mountain glaciers, which would have increased the albedo of the planet. Atmospheric carbon dioxide may have been another important feedback agent. One interpretation states that mountain building can alter the global distribution of rain and snowfall, increasing the pace at which rock is broken down by dissolution and chemical reactions. According to this hypothesis, accelerated chemical weathering removed carbon dioxide from the atmosphere, reducing the greenhouse effect and thereby leading to a cooler global climate.

But perhaps climate change was the more powerful, independent change during the past 40 million years. This theory suggests that climate change produced geologic evidence that has been falsely interpreted as accelerated mountain growth. Many climate scientists believe global cooling was driven by continental drift, which changed the distribution of land and ocean area with respect to latitude as well as the pattern of ocean currents, which are major mechanisms by which the earth equilibrates the heat imbalance between the equator and the poles [see "Chaotic Climate," by Wallace S. Broecker; Scientific American, November 1995]. How could these climate changes mimic mountain building? Through isostatic uplift. According to this interpretation, global cooling intensified erosion in many mountain ranges. Stepped-up erosion, particularly in the bottom of river and glacial valleys, resulted in increased uplift of mountain summits as isostasy compensated for the erosion.

The cause-and-effect ambiguity between global climate and mountain building has been billed as a geologic paradox to rival the "chicken and egg" question, but such circularity is common in feedback-rich systems. Geologists may not currently know what initiated the changes in climate and topography that occurred in the past 40 million years, but they now understand that the many kinds of feedback in this system



GERALD FRENCH *Panoramic Images*

exposing the deepest, most deformed rocks in that area. When the wind is in the same direction as subduction (*b*), erosion denudes the coastal side of the range, literally pulling buried rocks toward the surface. In this case, the inland side of the mountain range lies in an arid "rain shadow," such as the desert east of the Sierra Nevada (*photograph*).

The Himalayas and the Appalachians

The Himalayas and the Appalachians are two of the earth's grandest mountain ranges. Both were built by continental collisions, but the two ranges are about as different as mountains can be. Their comparison illustrates well the key principles of the new, system-oriented view of mountain building.

Stretching 2,500 kilometers across northern India and southern Tibet, the Himalayas are the king of mountain ranges. In this range stand many of the world's highest peaks, including Mount Everest, the tallest at 8,848 meters. Together with the Tibetan Plateau, to the north of the range in southwest China, the Himalayas contain the globe's greatest total mountain mass. It has even been suggested that this mountain belt is the largest high-elevation mass that the earth has seen in the past billion years. The plateau, on the other hand, gives the impression of a low desert plain—except that its altitude can take one's breath away. The plateau is the earth's largest expanse of land above 5,000 meters—a region approximately half the area of the continental U.S., most of it at least 600 meters higher than Mount Whitney, the highest single point in the continental U.S.

All this dramatic and varied topography developed during the past 50 million years, as a result of the collision between the Indian and the Asian tectonic plates. The collision began to squeeze both India and Tibet, activating a series of crustal-scale contractional faults that thrust part of the Indian continent underneath southern Asia. The northward velocity of India before the collision was 15 to 20 centimeters a year, and the velocity afterward was about five. Such deceleration of an entire continent is less surprising than the fact that India has continued to plow into and through southern Asia at about five centimeters a year for the past 40 to 50 million years. India has advanced 2,000 kilometers into the Asian plate, give or take 800 kilometers, roughly doubling the thickness of the crust, uplifting the Himalayas and the Tibetan Plateau and pressing huge areas of Indochina and eastern China out to the east and southeast.

Construction of the Himalayas and the Tibetan Plateau illustrates many of the principles of feedback-rich mountain building. For example, uplift of the plateau apparently triggered a climatic change


CLYDE H. SMITH *Peter Arnold, Inc.*

APPALACHIANS AND HIMALAYAS were formed by the same set of geologic processes, but roughly 250 million years apart. Many more years of erosion have given the older Appalachians (*left*) a less

are capable of amplifying any change and that tectonics, climate and erosion must have acted together in creating the geologic evidence that we find today.

Erosion's Pull

The recognition of the many types of feedback in the mountain-building system reveals that erosion not only participates in shaping mountains but also guides tectonic processes deep within the crust. The ultimate limiting force to mountain growth is gravity. Thus, erosion, by reducing the weight of the mountain range, actually accelerates tectonic processes beneath the mountains. For this reason, erosional processes can be viewed as "sucking" crust into mountain ranges and up toward the surface. And in this manner, erosion leaves a distinct fingerprint on the rocks and on the pattern of crustal deformation in and under mountains.

The type of rock at the surface of a mountain is determined, in part, by the local climate and by the rate and pattern of erosion. In this way, erosion influences both the topography and also the composition and structure of mountains. Metamorphism of rocks (changes as a result of heating and pressure) and the creation of many rock-forming minerals are governed by the pressure and temperature profile within the crust. Seemingly small details of climate and erosion, such as wind speed and direction or minor differences in latitude, can profoundly influence the temperature history, and therefore the type of rock created, as a mountain range evolves.

Recently computer models have examined the effects of prevailing wind direction and orography on the distribution of different metamorphic zones in mountain ranges. For mountains formed by subduction, prevailing winds in the same direction as subduction cause most of the precipitation to fall on the seaward side of the mountain range, which faces the subducting plate.

This phenomenon intensifies deformation and exhumation of rocks from deep in the crust. If, on the other hand, the prevailing winds are in the opposite direction as subduction, erosion is concentrated on the landward side of the mountain range, so that deformation is relatively uniform throughout the range, and deep exhumation is limited to the interior, or continental, side of the range. One study of the eroded cores of several ancient mountain ranges revealed that the fingerprint of orography and wind direction remains clear, in the distribution of rocks sucked into the range by climatically driven erosion, up to two billion years after the ranges had become tectonically inactive.

With growing evidence that tectonic uplift and erosion can occur over similar timescales and at similar rates, many researchers have concluded that some mountain ranges have achieved a steady-state topography. In this state, the size and basic shape of the mountains can remain stable for hundreds of thousands to millions of years, undergoing little or no change, because the rate of erosion matches the rate of uplift.

Three Stages

Although relatively few of the earth's mountains are now believed to be in perfect equilibrium, many of them may have achieved such a balance at some time in their history. Mountain ranges, it appears, often go through three distinct phases. The first, formative stage begins with the converging of plates or some other tectonic event that thickens crust and causes topography to rise. During this stage, rates of uplift exceed those of erosion. Erosion rates increase dramatically, however, as elevations and

GALEN ROWELL *Mountain Light*

rugged appearance than the Himalayas (*right*), which are still being uplifted by strong tectonic forces. The Himalayas may be the largest high-elevation mass to arise on the earth in the past billion years.

around eight million years ago, which dramatically strengthened the Asian monsoon, the pattern of intense seasonal rainfall across southern Asia. The monsoon pattern sharply intensified erosion in the Himalayas, increasing the flux of sediment from the Indus and Bengal rivers by factors as high as 13. The strengthening of the Asian monsoon apparently caused a surge of uplift in the Himalayas, as the isostasy (buoyancy) of the crust responded to the intensified erosion in the region. Meanwhile the interior of the Tibetan Plateau evolved much more slowly because it lies in the rain shadow of the Himalayas and because the major rivers have not yet eroded their way into it.

Although the present-day Appalachians are less spectacular than the Himalayas, they were created by the same tectonic processes and are now being shaped by the same system feedback. The primary difference is age: the Himalayas are about 50 million years old, whereas the main uplift of the Appalachians culminated 250 to 350 million years ago.

Geologically, the eastern coast of North America is the quiet side of the continent today. Before 200 million years ago, however, it was a hotbed of mountain building. During the previous several hundred million years, the predecessor to the Atlantic Ocean (called the Iapetus Ocean) was subducting underneath eastern North America. As the Iapetus gradually closed, at least three smaller landmasses, probably island arcs analogous to present-day Japan, slammed into the continent. Later, the mountain-building process culminated with the collision of Africa and the eastern U.S. The early Appalachians that resulted from these collisions are estimated to have been 250 to 350 kilometers wide, with average elevations of 3,500 to 4,500 meters and isolated peaks perhaps much higher. One study suggests that during the past 270 million years, erosion has stripped between 4,500 and 7,500 meters of material from the surface of the Appalachians. (This fact does not mean that the mountains were once 4,500 to 7,500 meters higher; isostatic uplift, it should be recalled, would continually prop the mountains up in response to erosion.) Over the past 200 million years, as North America rifted away from Africa and the Atlantic Ocean began to open, secondary events may have triggered minor episodes of uplift, but erosion has been the dominant process shaping the mountain range. *—N.P. and M.T.B.*

relief increase. Depending on the size of the range and the local climate, uplift may persist until erosion rates or the strength of the crust limits the average elevation of the range from increasing any more. This is the second stage, a steady state that continues as long as the rates of uplift and erosion remain equal. When uplift diminishes, erosion begins to dominate and the final stage begins. The average elevation of the mountain range begins a long, slow decline. The cycle may be interrupted or complicated at any stage by tectonic or climatic events, and the feedback among those processes and erosion.

The new model of how mountains develop promises to be as revolutionary as was plate tectonics some three decades ago. Just as plate tectonics managed to explain the worldwide distribution of earthquakes, volcanoes, fossils and many different rocks and minerals, the new understanding of mountain building shows how tectonic forces, the earth's climate and topography interact to create some of the earth's most spectacular landscapes. Like plate tectonics, the new model also illuminates phenomena that had long puzzled geologists. Computer simulations incorporating many of the model's principal precepts, for example, have proved very successful in mimicking the effects of complex tectonic histories, climatic variability and different geologic settings. Continuing research will provide even more details of how the earth's magnificent mountain ranges grow, evolve and decline, as well as details concerning the importance of mountains in shaping the climate and tectonics of our planet. SA

The Authors

NICHOLAS PINTER and MARK T. BRANDON began their collaboration at Yale University in the emerging field of active tectonics—which emphasizes the interactions between tectonic deformation and the earth's topography. Pinter carried out postdoctoral research there and is now an assistant professor at Southern Illinois University at Carbondale. His research focuses on the topographic expression of tectonic processes, especially related to fault activity and earthquake hazard. Brandon is an associate professor of structural geology and tectonics at Yale. His research in Washington State, Kamchatka and New Zealand is focused on understanding the interrelation between tectonic uplift and erosion at subduction zones and collisional mountain ranges.

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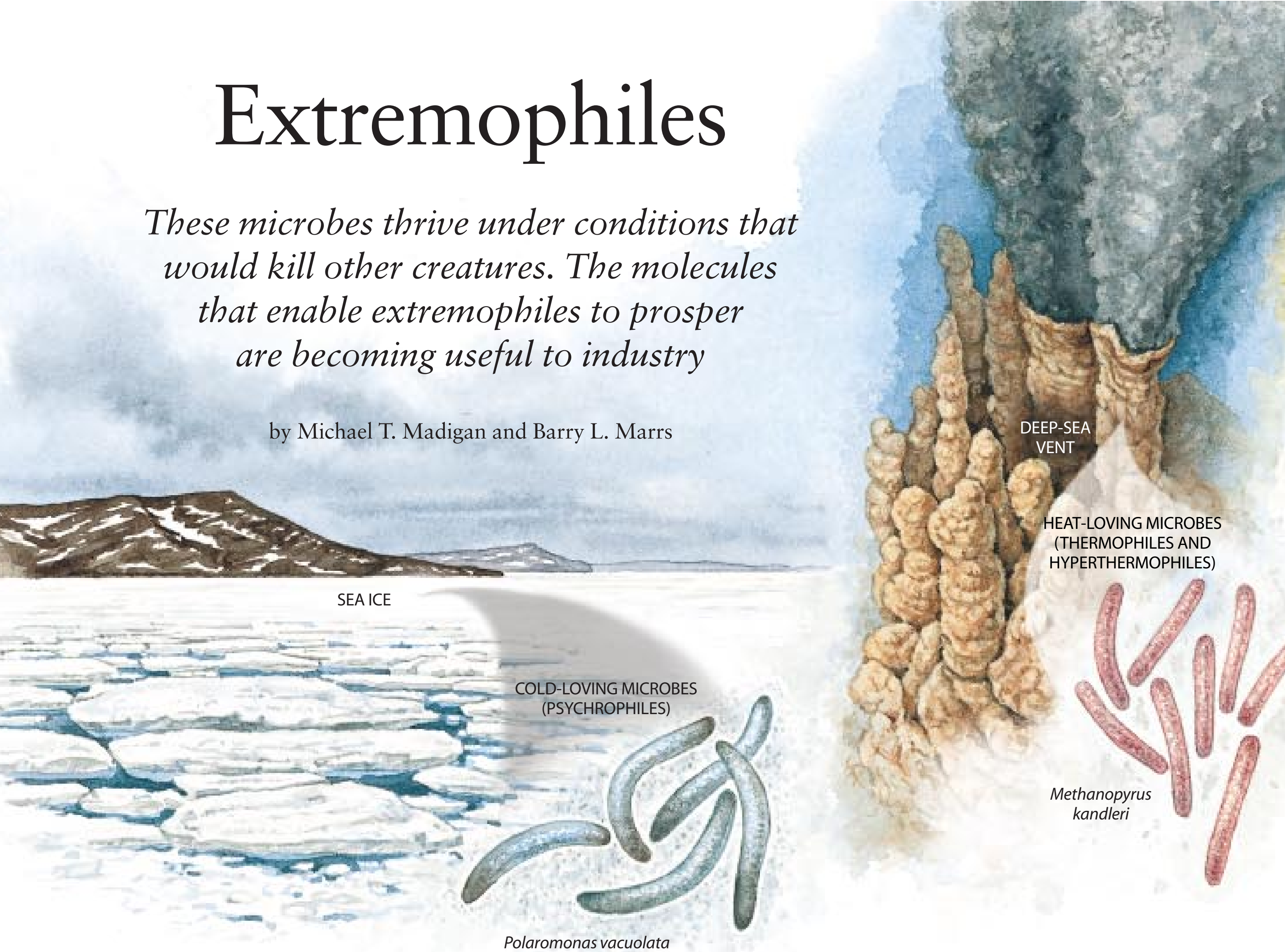
Extremophiles

These microbes thrive under conditions that would kill other creatures. The molecules that enable extremophiles to prosper are becoming useful to industry

by Michael T. Madigan and Barry L. Marrs



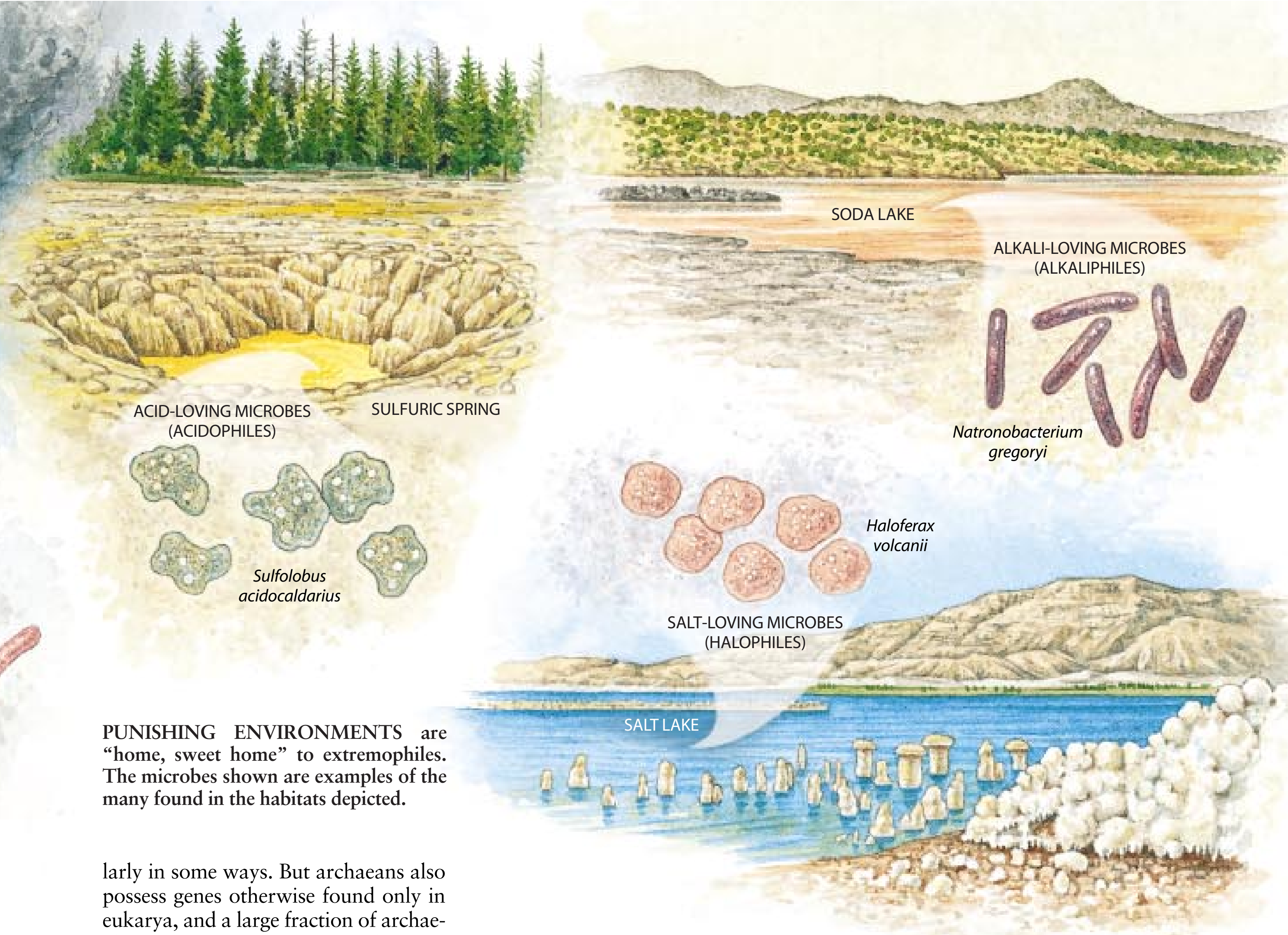
Imagine diving into a refreshingly cool swimming pool. Now, think instead of plowing into water that is boiling or near freezing. Or consider jumping into vinegar, household ammonia or concentrated brine. The leap would be disastrous for a person. Yet many microorganisms make their home in such forbidding environments. These microbes are called extremophiles because they thrive under conditions that, from the human vantage, are clearly extreme. Amazingly, the organisms do not merely tolerate their lot; they do best in their punishing habitats and, in many cases, require one or more extremes in order to reproduce at all.

Some extremophiles have been known for more than 40 years. But the search for them has intensified recently, as scientists have recognized that places once assumed to be sterile abound with microbial life. The hunt has also been fueled in the past several years by industry's realization that the "survival kits" possessed by extremophiles can potentially serve in an array of applications.

Of particular interest are the enzymes (biological catalysts) that help extremophiles to function in brutal circumstances. Like synthetic catalysts, enzymes, which are proteins, speed up chemical reactions without being altered themselves. Last year the biomedical field and other industries worldwide spent more than $2.5 billion on enzymes for applications ranging from the production of sweeteners and "stonewashed" jeans to the genetic identification of criminals and the diagnosis of infectious and genetic diseases. Yet standard enzymes stop working when exposed to heat or other extremes, and so manufacturers that rely on them must often take special steps to protect the proteins during reactions or storage. By remaining active when other enzymes would fail, enzymes from extremophiles—dubbed "extremozymes"—can potentially eliminate the need for those added steps, thereby increasing efficiency and reducing costs. They can also form the basis of entirely new enzyme-based processes.

Perhaps 20 research groups in the U.S., Japan, Germany and elsewhere are now actively searching for extremophiles and their enzymes. Although only a few extremozymes have made their way into use thus far, others are sure to follow. As is true of standard enzymes, transforming a newly isolated extremozyme into a viable product for industry can take several years.

Studies of extremophiles have also helped redraw the evolutionary tree of life. At one time, dogma held that living creatures could be grouped into two basic domains: bacteria, whose simple cells lack a nucleus, and eukarya, whose cells are more complex. The new work lends strong support to the once heretical proposal that yet a third group, the archaea, exists. Anatomically, archaeans lack a nucleus and closely resemble bacteria in other ways. And certain archaeal genes have similar counterparts in bacteria, a sign that the two groups function simi-



PUNISHING ENVIRONMENTS are "home, sweet home" to extremophiles. The microbes shown are examples of the many found in the habitats depicted.

ROBERTO OSTI

larly in some ways. But archaeans also possess genes otherwise found only in eukarya, and a large fraction of archaeal genes appear to be unique. These unshared genes establish archaea's separate identity. They may also provide new clues to the evolution of early life on the earth [*see box on pages 86 and 87*].

Some Need It Hot

Heat-loving microbes, or thermophiles, are among the best studied of the extremophiles. Thermophiles reproduce, or grow, readily in temperatures greater than 45 degrees Celsius (113 degrees Fahrenheit), and some of them, referred to as hyperthermophiles, favor temperatures above 80 degrees C (176 degrees F). Some hyperthermophiles even thrive in environments hotter than 100 degrees C (212 degrees F), the boiling point of water at sea level. In comparison, most garden-variety bacteria grow fastest in temperatures between 25 and 40 degrees C (77 and 104 degrees F). Further, no multicellular animals or plants have been found to tolerate temperatures above about 50 degrees C (122 degrees F), and no microbial eukarya yet discovered can tolerate long-term exposure to temperatures higher than about 60 degrees C (140 degrees F).

Thermophiles that are content at temperatures up to 60 degrees C have been known for a long time, but true extremophiles—those able to flourish in greater heat—were first discovered only about 30 years ago. Thomas D. Brock, now retired from the University of Wisconsin–Madison, and his colleagues uncovered the earliest specimens during a long-term study of microbial life in hot springs and other waters of Yellowstone National Park in Wyoming.

The investigators found, to their astonishment, that even the hottest springs supported life. In the late 1960s they identified the first extremophile capable of growth at temperatures greater than 70 degrees C. It was a bacterium, now called *Thermus aquaticus,* that would later make possible the widespread use of a revolutionary technology—the polymerase chain reaction (PCR). About this same time, the team found the first hyperthermophile in an extremely hot and acidic spring. This organism, the archaean *Sulfolobus acidocaldarius,* grows prolifically at temperatures as high as 85 degrees C. They also showed that microbes can be present in boiling water.

Brock concluded from the collective studies that bacteria can function at higher temperatures than eukarya, and he predicted that microorganisms would likely be found wherever liquid water existed. Other work, including research that since the late 1970s has taken scientists to more hot springs and to environments around deep-sea hydrothermal vents, has lent strong support to these ideas. Hydrothermal vents, sometimes called smokers, are essentially natural undersea rock chimneys through which erupts superheated, mineral-rich fluid as hot as 350 degrees C.

To date, more than 50 species of hyperthermophiles have been isolated, many by Karl O. Stetter and his colleagues at the University of Regensburg in Germany. The most heat-resistant of these microbes, *Pyrolobus fumarii,* grows in the walls of smokers. It reproduces best in an environment of about 105 degrees C and can multiply in temperatures of up to 113 degrees C. Remarkably, it stops growing at temperatures below 90 degrees C (194 degrees F). It gets too cold! Another hyperthermophile that lives in deep-sea chimneys, the methane-producing archaean *Methanopyrus,* is now drawing much attention because it lies near the root in the tree of life; analysis of its genes and activities is expected to help clarify how the world's earliest cells survived.

THOMAS D. BROCK

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

THOMAS D. BROCK

EXTREME ENVIRONMENTS can also be extremely colorful. Halophiles account for the redness in salt collection ponds near San Francisco Bay in California (*left*), and thermophiles brighten a hot spring in Yellowstone National Park in Wyoming (*right*). A glass slide dipped directly into one of Yellowstone's boiling springs soon revealed the presence of abundant microbial life (*top*).

What is the upper temperature limit for life? Do "super-hyperthermophiles" capable of growth at 200 or 300 degrees C exist? No one knows, although current understanding suggests the limit will be about 150 degrees C. Above this temperature, probably no life-forms could prevent dissolution of the chemical bonds that maintain the integrity of DNA and other essential molecules.

Not Too Hot to Handle

Researchers interested in how the structure of a molecule influences its activity are trying to understand how molecules in heat-loving microbes and other extremophiles remain functional under conditions that destroy related molecules in organisms adapted to more temperate climes. That work is still under way, although it seems that the structural differences need not be dramatic. For instance, several heat-loving extremozymes resemble their heat-intolerant counterparts in structure but appear to contain more of the ionic bonds and other internal forces that help to stabilize all enzymes.

Whatever the reason for their greater activity in extreme conditions, enzymes derived from thermophilic microbes have begun to make impressive inroads in industry. The most spectacular example is *Taq* polymerase, which derives from *T. aquaticus* and is employed widely in PCR. Invented in the mid-1980s by Kary B. Mullis, then at Cetus Corporation, PCR is today the basis for the forensic "DNA fingerprinting" that received so much attention during the recent O. J. Simpson trials. It is also used extensively in modern biological research, in medical diagnosis (such as for HIV infection) and, increasingly, in screening for genetic susceptibility to various diseases, including specific forms of cancer.

In PCR, an enzyme known as a DNA polymerase copies repeatedly a snippet of DNA, producing an enormous supply. The process requires the reaction mixture to be alternately cycled between low and high temperatures. When Mullis first invented the technique, the polymerases came from microbes that were not thermophilic and so stopped working in the hot part of the procedure. Technicians had to replenish the enzymes manually after each cycle.

To solve the problem, in the late 1980s scientists at Cetus plucked *T. aquaticus* from a clearinghouse where Brock had deposited samples roughly 20 years earlier. The investigators then isolated the microbe's DNA polymerase (*Taq* polymerase). Its high tolerance for heat led to the development of totally automated PCR technology. More recently, some users of PCR have replaced the *Taq* polymerase with *Pfu* polymerase. This enzyme, isolated from the hyperthermophile *Pyrococcus furiosus* ("flaming fireball"), works best at 100 degrees C.

A different heat-loving extremozyme in commercial use has increased the efficiency with which compounds called cyclodextrins are produced from cornstarch. Cyclodextrins help to stabilize volatile substances (such as flavorings in foods), to improve the uptake of medicines by the body, and to reduce bitterness and mask unpleasant odors in foods and medicines.

Others Like It Cold, Acidic, Alkaline

Cold environments are actually more common than hot ones. The oceans, which maintain an average temperature of one to three degrees C (34 to 38 degrees F), make up over half the earth's surface. And vast land areas of the Arctic and Antarctic are permanently frozen or are unfrozen for only a few weeks in summer. Surprisingly, the most frigid places, like the hottest, support life, this time in the form of psychrophiles (cold lovers).

James T. Staley and his colleagues at the University of Washington have shown, for example, that microbial communities populate Antarctic sea ice—ocean water that remains frozen for much of the year. These communities include photosynthetic eukarya, notably algae and diatoms, as well as a variety of bacteria. One bacterium obtained by Staley's group, *Polaromonas vacuolata,* is a prime representative of a psychrophile: its optimal temperature for growth is four degrees C, and it finds temperatures above 12 degrees C too warm for reproduction. Cold-loving organisms have started to interest manufacturers who need enzymes that work at refrigerator temperatures—such as food processors (whose products often require cold temperatures to avoid spoilage), makers of fragrances (which evaporate at high temperatures) and producers of cold-wash laundry detergents.

Among the other extremophiles now under increasing scrutiny are those that prefer highly acidic or basic conditions (acidophiles and alkaliphiles). Most natural environments on the earth are essentially neutral, having pH values between five and nine. Acidophiles thrive in the rare habitats having a pH below five, and alkaliphiles favor habitats with a pH above nine.

Highly acidic environments can result naturally from geochemical activities (such as the production of sulfurous gases in hydrothermal vents and some hot springs) and from the metabolic activities of certain acidophiles themselves. Acidophiles are also found in the debris left over from coal mining. Interestingly, acid-loving extremophiles cannot tolerate great acidity inside their cells, where it would destroy such important molecules as DNA. They survive by keeping the acid out. But the defensive molecules that provide this protection, as well as others that come into contact with the environment, must be able to operate in extreme acidity. Indeed, extremozymes that are able to work at a pH below one—more acidic than even vinegar or stomach fluids—have been isolated from the cell wall and underlying cell membrane of some acidophiles.

Potential applications of acid-tolerant extremozymes range from catalysts for the synthesis of compounds in acidic solution to additives for animal feed, which are intended to work in the stomachs of animals. The use of enzymes in feed is already quite popular. The enzymes that are selected are ones that microbes normally secrete into the environment to break food into pieces suitable for ingestion. When added to feed, the enzymes improve the digestibility of inexpensive grains, thereby avoiding the need for more expensive food.


MICHAEL MILSTEIN


COURTESY OF JAMES T. STALEY *University of Washington (photograph and inset)*

EXTREMOPHILE PROSPECTORS Karl O. Stetter (*left*) of the University of Regensburg in Germany and James T. Staley (*right*) of the University of Washington brave the elements to find extremophiles in a Yellowstone hot spring and in Antarctic sea ice, respectively. The psychrophiles in one ice core are evident as a dark band in the inset.

Alkaliphiles live in soils laden with carbonate and in so-called soda lakes, such as those found in Egypt, the Rift Valley of Africa and the western U.S. Above a pH of eight or so, certain molecules, notably those made of RNA, break down. Consequently, alkaliphiles, like acidophiles, maintain neutrality in their interior, and their extremozymes are located on or near the cell surface and in external secretions. Detergent makers in the U.S. and abroad are particularly excited by alkaliphilic enzymes. In Japan, where industry has embraced extremozymes with enthusiasm, much of the research into alkaliphilic extremozymes has been spearheaded by Koki Horikoshi of the Japan Marine Science and Technology Center in Yokosuka.

To work effectively, detergents must be able to cope with stains from food and other sources of grease—jobs best accomplished by such enzymes as proteases (protein degraders) and lipases (grease degraders). Yet laundry detergents tend to be highly alkaline and thus destructive to standard proteases and lipases. Alkaliphilic versions of those enzymes can solve the problem, and several that can operate efficiently in heat or cold are now in use or being developed. Alkaliphilic extremozymes are also poised to replace standard enzymes wielded to produce the stonewashed look in denim fabric. As if they were rocks pounding on denim, certain enzymes soften and fade fabric by degrading cellulose and releasing dyes.

A Briny Existence

The list of extremophiles does not end there. Another remarkable group—the halophiles—makes its home in intensely saline environments, especially natural salt lakes and solar salt evaporation ponds. The latter are human-made pools where seawater collects and evaporates, leaving behind dense concentrations of salt that can be harvested for such purposes as melting ice. Some saline environments are also extremely alkaline because weathering of sodium carbonate and certain other salts can release ions that produce alkalinity. Not surprisingly, microbes in those environments are adapted to both high alkalinity and high salinity.

Halophiles are able to live in salty conditions through a fascinating adaptation. Because water tends to flow from areas of high solute concentration to areas of lower concentration, a cell suspended in a very salty solution will lose water and become dehydrated unless its cytoplasm contains a higher concentration of salt (or some other solute) than its environment. Halophiles contend with this problem by producing large amounts of an internal solute or by retaining a solute extracted from outside. For instance, an archaean known as *Halobacterium salinarum* concentrates potassium chloride in its interior. As might be expected, the enzymes in its cytoplasm will function only if a high concentration of potassium chloride is present. But proteins in *H. salinarum* cell structures that are in contact with the environment require a high concentration of sodium chloride.

The potential applications for salt-tolerant enzymes do not leap to mind as readily as those for certain other extremozymes. Nevertheless, at least one intriguing application is under consideration. Investigators are exploring incorporating halophilic extremozymes into procedures used to increase the amount of crude extracted from oil wells.

To create passages through which trapped oil can flow into an active well, workers pump a mixture of viscous guar gum and sand down the well hole.

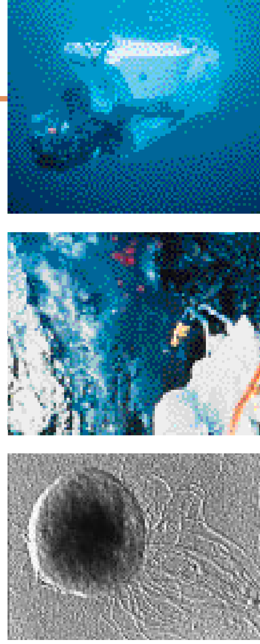
Archaea Makes Three

In the summer of 1996 a large collaboration of scientists deciphered the full sequence of units, or nucleotides, in every gene of *Methanococcus jannaschii*—a methane-producing extremophile that thrives at temperatures near 85 degrees Celsius. The results strikingly confirmed the once ridiculed proposal that life consists of three major evolutionary lineages, not the two that have been routinely described in textbooks.

The recognized lineages were the bacteria (with their simple cells that lack a true nucleus) and the eukarya (plants, humans and other animals having cells that contain a nucleus). By comparing molecules known as ribosomal RNA in many different organisms, Carl R. Woese and his collaborators at the University of Illinois had concluded in 1977 that a group of microbes once classified as bacteria and called archaebacteria belonged, in fact, to a separate lineage: the archaea. *M. jannaschii* is the first of the archaeans to have had its genes sequenced in full.

The sequencing made it possible to compare *M. jannaschii*'s total complement of genes with the many genes that have so far been sequenced in other organisms. Forty-four percent of *M. jannaschii*'s genes resemble those in bacteria or eukarya, or both. And consistent with Woese's scheme, fully 56 percent are completely different from any genes yet described.

That *M. jannaschii* has characteristics of bacteria and eukarya but also has marked differences suggests that archaea and the other two lineages have a common distant ancestor. Partly because many archaea and some bacteria are adapted to the conditions widely believed to have existed on the early earth—especially high heat and little or no oxygen—a majority of investigators suspect that those two groups appeared first, diverging from a common ancestor relatively soon after life began. Later, the eukarya split off from the ar-



ALVIN (*top*), a scientific submarine, reaches out an arm (*middle*) to snag material around a deep-sea vent. *Methanococcus jannaschii*, a spherical cell with many flagella, was among its finds in 1982. The diagram on the opposite page depicts the three major evolutionary lineages of life.

ROD CATANACH *Woods Hole Oceanographic Institution (top)*; WOODS HOLE OCEANOGRAPHIC INSTITUTION *(middle)*; KARL O. STETTER *University of Regensburg, Germany (bottom)*

Then they set off an explosive to fracture surrounding rock and to force the mixture into the newly formed crevices. The guar facilitates the sand's dispersion into the cracks, and the sand props open the crevices. Before the oil can pass through the crevices, however, the gum must be eliminated. If an enzyme that degrades guar gum is added just before the mixture is injected into the wellhead, the guar retains its viscosity long enough to carry the sand into the crevices but is then broken down.

At least, that is what happens in the ideal case. But oil wells are hot and often salty places, and so ordinary enzymes often stop working prematurely. An extremozyme that functioned optimally in high heat and salt would presumably remain inactive at the relatively cool, relatively salt-free surface of the well. It would then become active gradually as it traveled down the hole, where temperature rises steadily with increasing depth. The delayed activity would provide more time for the sand mixture to spread through the oil-bearing strata, and the tolerance of heat and salt would enable the enzyme to function longer for breaking down the guar. Preliminary laboratory tests of this prospect, by Robert M. Kelly of North Carolina State University, have been encouraging.

If the only sources of extremozymes were large-scale cultures of extremophiles, widespread industrial applications of these proteins would be impractical. Scientists rarely find large quantities of a single species of microbe in nature. A desired organism must be purified, usually by isolating single cells, and then grown in laboratory culture. For organisms with extreme lifestyles, isolation and large-scale production can prove both difficult and expensive.

Harvesting Extremozymes

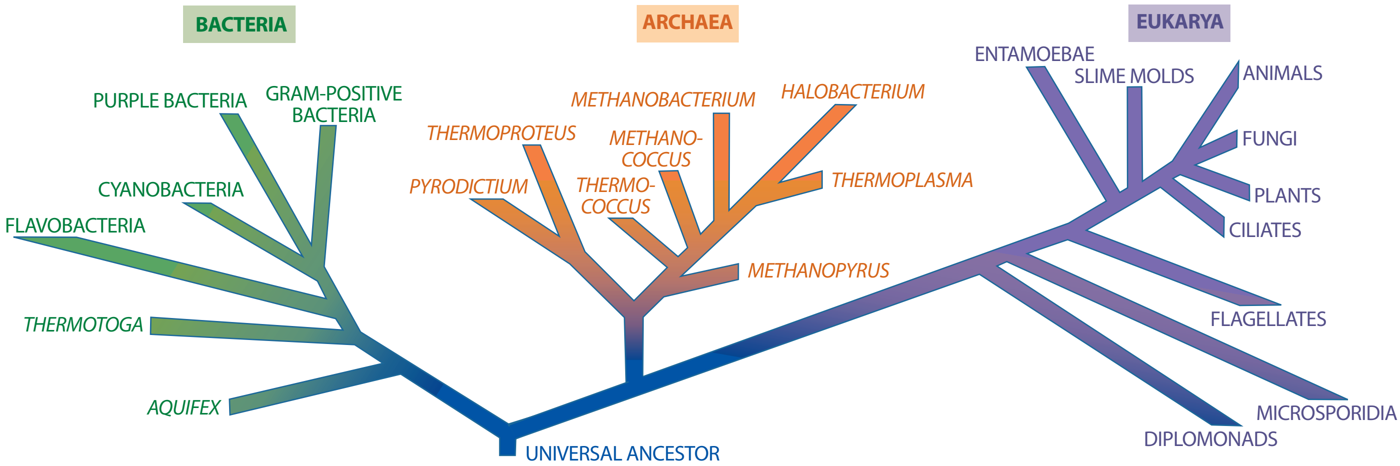
Fortunately, extremozymes can be produced through recombinant DNA technology without massive culturing of the source extremophiles. Genes, which consist of DNA, specify the composition of the enzymes and other proteins made by cells; these proteins carry out most cellular activities. As long as microbial prospectors can obtain sample genes from extremophiles in nature or from small laboratory cultures, they can generally clone those genes and use them to make the corresponding proteins. That is, by using the recombinant DNA technologies, they can insert the genes into ordinary, or "domesticated," microbes, which will often use the genes to produce unlimited, pure supplies of the enzymes.

Two approaches have been exploited to identify potentially valuable extremozymes. The more traditional route requires scientists to grow at least small cultures of an extremophile obtained from an interesting environment. If the scientists are looking for, say, protein-degrading enzymes, they test to see whether extracts of the cultured cells break down selected proteins. If such activity is detected, the researchers turn to standard biochemical methods to isolate the enzymes responsible for the activity and to isolate the genes encoding the enzymes. They then must hope that the genes can be induced to give rise to their corresponding proteins in a domesticated host.

In the other approach, investigators bypass the need to grow any cultures of extremophiles. They isolate the DNA from all living things in a sample of water, soil or other material from an extreme environment. Then, using recombinant DNA technology once again, they deliver random stretches of DNA into a domesticated host—ideally one insert per host cell—without knowing the identities of the genes in those fragments. Finally, they screen the colonies that grow out, looking for evidence of activity by novel enzymes. If they find such evidence, they know that an inserted gene is responsible and that it will work in the domesticated host. This method thus avoids many bottlenecks in the traditional process. It turns up only enzymes that can be manufactured readily in tried-and-true hosts. And investigators can mine the genes for the enzymes from mixed populations of microbes without needing to culture extremophiles that might have trouble growing outside their native milieu.

chaea. Further support for this scenario can be seen in the evolutionary tree itself: hyperthermophilic, oxygen-sensitive organisms, such as *Methanopyrus* (archaea) and *Aquifex* (bacteria), branch off close to the root.

Scientists are eager to learn the nature of the genes that are unique to archaea. Genes are the blueprints from which enzymes and other proteins important to cell structure and function are made. Many of the unique archaeal genes undoubtedly encode novel proteins that may provide insights into how ancient cells survived. And certain of these unusual proteins can probably be enlisted for developing innovative medicines or to perform new tricks in industry. *—M.T.M. and B.L.M.*



JENNIFER C. CHRISTIANSEN; SOURCE: *Brock Biology of Microorganisms (Prentice Hall, 1997)*

Although the microbes of the world are incredibly diverse, scientists rarely find in them the perfect enzyme for a given task. Therefore, microbiologists at the cutting edge of industrial enzyme technology have begun to modify extremozymes, tailoring them to meet specific demands. For instance, after finding an extremozyme that degrades proteins fairly efficiently at high temperatures, investigators might alter the enzyme so that it functions across a broader range of acidity and salinity.

Biologists today generally achieve such modifications in either of two ways. Practitioners of the "rational design" approach first discern the structural basis of the property of interest. Next, they alter an enzyme's gene to guarantee that the resulting catalytic protein will gain that property. Devotees of the other approach, known as directed evolution, make more or less random variations in the gene encoding a selected enzyme and, from those genes, generate thousands of different versions of the enzyme. Then they screen the collection to see whether any of the variations has gained the hoped-for feature. This last strategy is also said to be Edisonian, because when Thomas Edison sought a material to serve as a filament for the lightbulb, he tried everything available, from bamboo splints to silk threads, and chose the one that worked best.

So far most extremozymes in commercial use are little altered from their original state. But rational design and Edisonian approaches promise to enhance extremozymes. They may also help to convert enzymes from ordinary microbes into artificial extremozymes.

Discovery of extremophiles opens new opportunities for the development of enzymes having extraordinary catalytic capabilities. Yet for any new enzyme to gain commercial acceptance, its makers will have to keep down the costs of production, for example, by ensuring that the domesticated microbes used as the extremozyme-producing factory will reliably generate large quantities of the protein. The difficulties of perfecting manufacturing techniques, and the reluctance of industries to change systems that already work reasonably well, could slow the entry of new extremozymes into commerce. It seems inevitable, however, that their many advantages will eventually prove irresistible. SA

The Authors

MICHAEL T. MADIGAN and BARRY L. MARRS share a particular interest in photosynthetic bacteria. Madigan received his Ph.D. in bacteriology in 1976 under Thomas D. Brock at the University of Wisconsin–Madison. He is now professor of microbiology at Southern Illinois University at Carbondale. Madigan's studies focus on the biodiversity and metabolic characteristics of photosynthetic bacteria, especially in extreme environments. Marrs received his Ph.D. in biology from Case Western Reserve University in 1968. He then spent several years in academics and industry, recently as the founding chief executive officer of Recombinant Biocatalysis, which is commercializing enzymes from extremophiles. He is currently founder and head of a new company, Photosynthetic Harvest, which plans to make use of the chemicals in green plants.

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The Science of Murphy's Law

Life's little annoyances are not as random as they seem: the awful truth is that the universe is against you

by Robert A. J. Matthews

Late for work, you paw frantically through your sock drawer, unable to find a matching pair in its jumbled disarray. In the kitchen, your toast slides off the plate and lands on the floor—butter-side down, of course. Finally out of the house, you reach the train station and join a line for a ticket—and then find yourself watching the lines on either side shoot ahead, while you remain stuck behind someone arranging a world tour.

Is it all just chance misfortune—and no more likely, probabilistically speaking, than happier outcomes? Or is there something about the way the universe works that favors this kind of aggravation? Alas, a strong case can be made for the latter explanation. Indeed, there is evidence that the universe is against you.

Of course, this idea has for many years been a part of popular wisdom; there is even a name for it: Murphy's Law. "If something can go wrong, it will" is how the law is usually expressed. But though most nonscientists have never doubted the validity of Murphy's Law, scientists typically dismiss it as nothing more than a product of our selective memory for those times when things don't go well.

In this case, however, the scientists appear to have dismissed popular wisdom too hastily. Using a wide range of mathematics and science, from probability theory to rigid-body dynamics, I have been investigating Murphy's Law.

JASON GOLTZ (*photograph*); TOMO NARASHIMA (*drawing*); SLIM FILMS (*computer montage*)

BAD DAY might feature some improbable misfortunes as well as some that are not so improbable—such as taking along an umbrella that turns out to be unneeded or being unable to find a matching pair of socks.

And the awful truth is that many of the most famous manifestations of Murphy's Law actually do have a basis in fact.

The familiar version of Murphy's Law is not quite 50 years old, but the essential idea behind it has been around for centuries. In 1786 the Scottish poet Robert Burns observed that

> The best laid schemes o' mice an' men
> Gang aft agley ("Are prone to go awry").

In 1884 the Victorian satirist James Payn described perhaps the most famous example of Murphy's Law:

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

The modern version of Murphy's Law has its roots in U.S. Air Force studies performed in 1949 on the effects of rapid deceleration on pilots. Volunteers were strapped on a rocket-propelled sled, and their condition was monitored as the sled was brought to an abrupt halt. The monitoring was done by electrodes fitted to a harness designed by Captain Edward A. Murphy.

After what had seemed to be a flawless test run one day, the harness's failure to record any data puzzled technicians. Murphy discovered that every one of its electrodes had been wired incorrectly, prompting him to declare: "If there are two or more ways of doing something, and one of them can lead to catastrophe, then someone will do it."

At a subsequent press conference, Murphy's rueful observation was presented by the project engineers as an excellent working assumption in safety-critical engineering. But before long—and to Murphy's chagrin—his principle had been transformed into an apparently flippant statement about the cussedness of everyday events. Ironically, by losing control over his original meaning, Murphy thus became the first victim of his eponymous law.

I became intrigued by Murphy's Law in 1994, after reading a letter in a magazine describing what happens when a paperback book slides off a desk. The writer claimed that a book initially with its front cover uppermost almost always lands face down. Did this, he asked, have any bearing on the notorious buttered-toast phenomenon?

My first reaction was perhaps typical of most scientists: I thought that the book was as likely to land face up as face down and that the reader hadn't repeated the experiment often enough. Yet when I tried it, it became clear that the behavior of a tumbling book was far from random. Its final state was clearly dictated by its rate of spin, which was typically too low to allow the book to make a complete revolution and come face up again by the time it hit the floor. The torque induced by gravity as the book—or piece of toast, for that matter—goes over the edge simply does not lead to a sufficiently fast spin rate.

Straightforward measurements and dynamical calculations approximating the book (or toast) as a rigid, rough, thin plate confirmed that the motion has nothing to do with aerodynamic effects, which are negligible. The presence of the thin layer of butter is also irrelevant: the butter-down landings are primarily the result of gravity and surface friction.

I later learned that others had published similar analyses of the tumbling toast phenomenon years earlier. It was when I began to dig deeper into its causes that I uncovered something truly surprising: a connection between the dynamics of tumbling toast and the fundamental constants of nature.

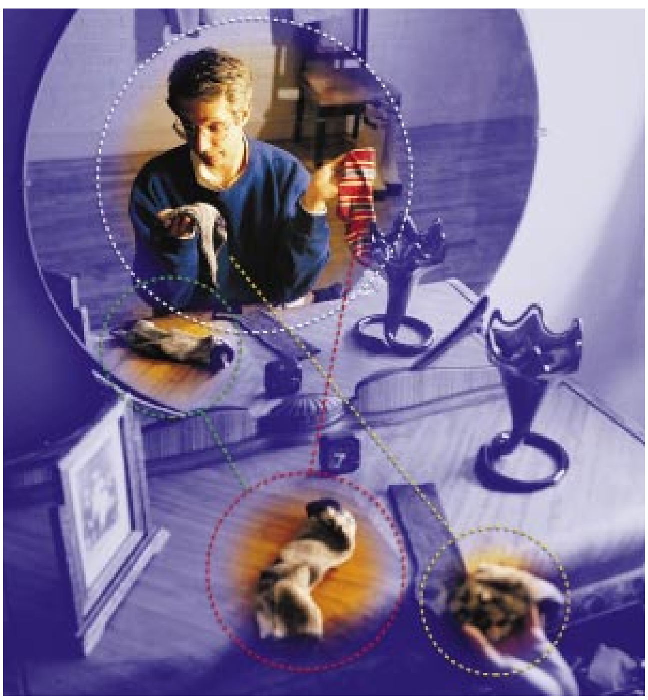
Clearly, toast would land butter-side up if it fell from sufficiently tall tables. So why are tables the height they are? Because they must be convenient for human beings. So why are humans the height they are? Some years ago William H. Press, a professor of astrophysics at Harvard University, pointed out that as bipedal, essentially columnar animals we humans are relatively unstable against toppling. If we were a lot taller, he further reasoned, we would be in danger of severely injuring our head every time we fell over. At a more fundamental level, this likelihood of injury means there is a limit on human height set by the relative strengths of the chemical bonds making up our skull and by the strength of gravity pulling us over.

Cosmic Constants

The strengths of these two forces are in turn dictated by various fundamental constants—such as the charge on the electron—whose values were fixed in the cosmic big bang some 15 billion years ago. Using an argument similar to that of Press, I found that the values of these constants lead to a maximum height for human beings of around three meters, which is still below that needed to avoid butter-down landings of toast [see "The Anthropomurphic Principle," by Ian Stewart; Scientific American, December 1995]. It seems that toast tends to land butter-side down because the universe is designed that way.

The publication of this result in the *European Journal of Physics* in 1995 generated an astonishing amount of popular interest. I soon found myself being asked to explain other examples of Murphy's Law: Why is the weather always worse during weekends, say, or why do cars break down on the way to important meetings?

The trouble with many such examples is that either they are not true or they are entirely anecdotal and thus beyond the reach of analysis. For some, like car break-



JASON GOLTZ; SLIM FILMS

ODD SOCKS are likely to accumulate as a result of random and repeated sock loss, combinatoric analysis shows.

downs, the standard scientific explanation of "selective memory" seems reasonable. Nevertheless, I have found some well-known manifestations of Murphy's Law that are amenable to analysis. And again, the results tend to support popular belief in the law's validity.

Lost on the Fringes

One manifestation of the Murphy principle that is rather easy to explain is Murphy's Law of Maps, which might be expressed as, "If a place you're looking for can lie on the inconvenient parts of the map, it will." The reason turns out to involve an interesting combination of probability and optical illusion. Suppose that the map is square; the "Murphy Zone" consists then of those parts of the map close to its edges and down the central crease, where following roads to their destination is most awkward.

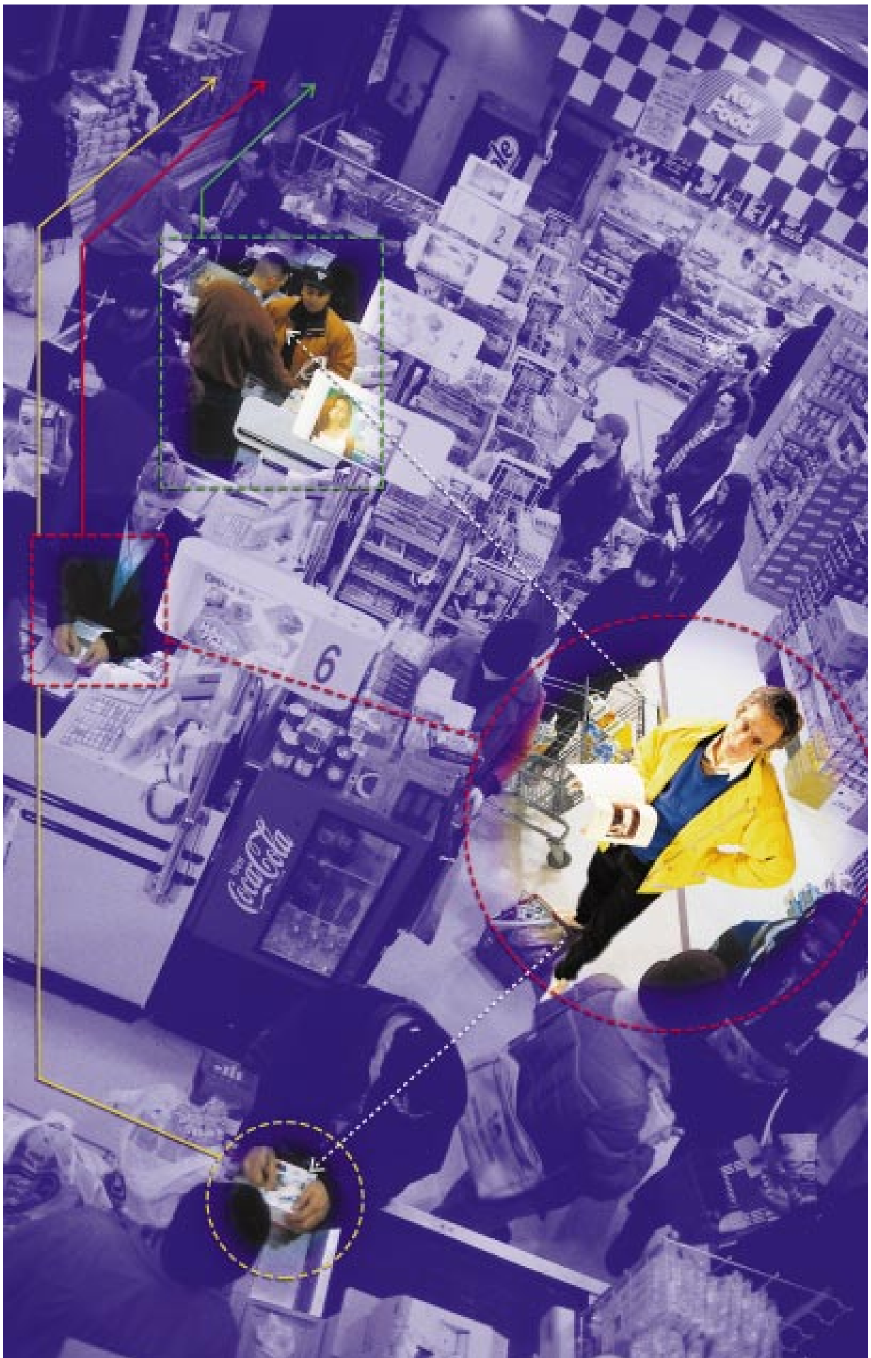
Simple geometry shows that if the width of the Murphy Zone makes up just one tenth of the width of the entire map, it nonetheless accounts for more than *half* the area of the map. Hence, a point picked at random on a map has a better than 50–50 chance of falling into the Murphy Zone. This surprising result stems from the fact that although the Murphy Zone looks rather narrow, its perimeter tracks the largest dimension of the map, so the total area of this zone is deceptively large.

Another example of Murphy's Law that is relatively easily explained is Murphy's Law of Queues: "The line next to you will usually finish first." Of course, if you stand in line behind a family of 12 shopping for the winter, it is hardly surprising if all the other queues finish before yours does. But what if your line is identical in length and makeup to all the others? Surely then you'll be safe from Murphy's Law?

Sorry, but the answer is no. It is true that, on average, all the queues will move at more or less the same rate—each being equally likely to suffer from the kind of random delays that occur when, for example, the cashier has to change the cash-register tape or a customer wants to use a personal check drawn on an obscure bank to pay for a pack of chewing gum. But during any one trip to the supermarket, we don't care about averages: we just want our line to finish first on that particular visit. And in that case, the chances that we've picked the queue that will turn out to be the one least plagued by random delays is just 1/*N*, where *N* is the total number of queues in the supermarket.

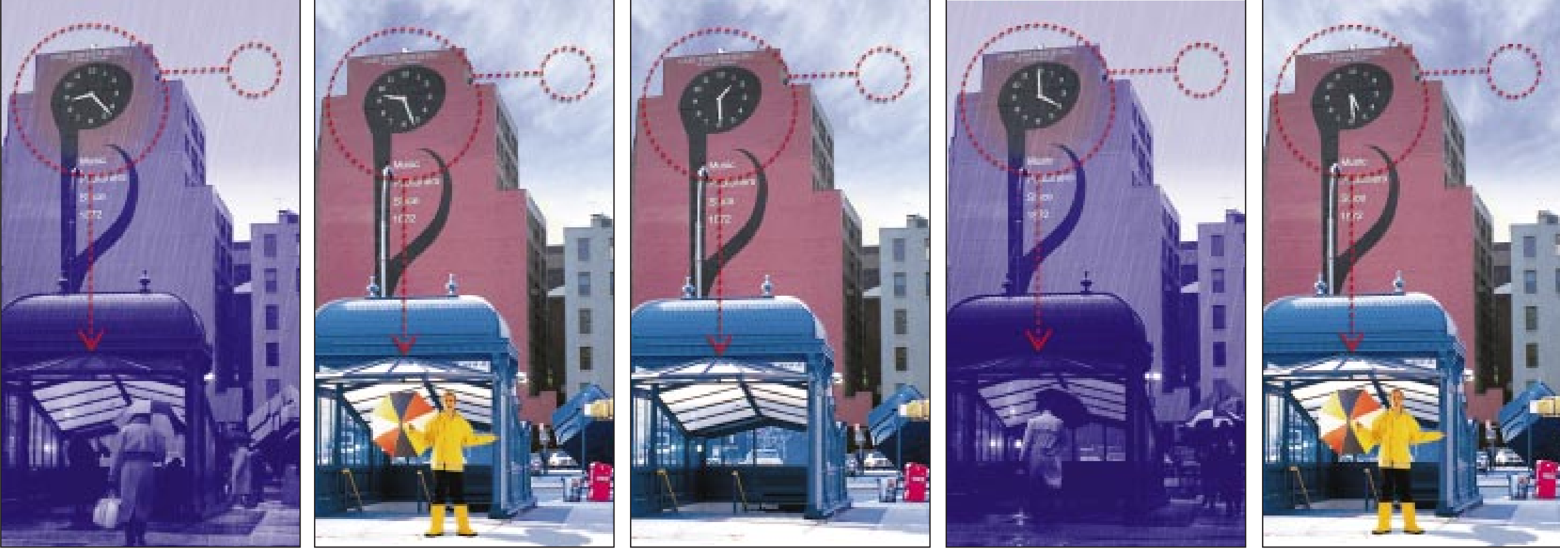
Even if we are concerned only about beating the queues on either side of ours, the chances we'll do so are only one in three. In other words, two thirds of the time, either the line to the left or the one on the right will beat ours.

Probability theory and combinatorics, the mathematical study of arrangements, hold the key to another notorious example of Murphy's Law: "If odd socks can be created, they will be." Anyone who has hunted through a drawer looking for a matching pair will have been struck by the ubiquity of odd socks. Popular folklore has blamed everything from gremlins to quantum black holes. Yet it is possible to probe the mystery



JASON GOLTZ; SLIM FILMS

WHICH LINE will move fastest? Each is likely to be held up by the kind of random delays that occur when, for example, customers pay by check, but simple probability confirms that it is quite likely that the fastest line will be one you are not in.



RAIN GEAR often goes unneeded because the base rate of rain—the probability that rain will fall during the typically brief time when a person is outside—is low throughout much of the world. Rare weather events cannot be predicted reliably.

JASON GOLTZ; SLIM FILMS

of odd socks without knowing anything about where they go.

To see how, imagine you have a drawer containing only complete pairs of socks. Now suppose one goes missing; don't worry about where or how. Instantly you have an odd sock left behind in the drawer. Now a second sock goes missing. This can be either that odd sock just created or—far more likely—it will be a sock from an as yet unbroken complete pair, creating yet another odd sock in the drawer.

Already one can see signs of a natural propensity that can be confirmed by combinatoric analysis. Random sock loss is always more likely to create the maximum possible number of odd socks than to leave us free of the things. For example, if we started with 10 complete pairs, by the time half our socks have gone missing, it is four times more likely that we will be left with a drawerful of odd socks, rather than one containing only complete pairs. And the most likely outcome will be just two complete pairs lost among six odd socks. No wonder matching pairs can be so difficult to find in the morning.

Probability theory also casts light on Murphy's Law of Umbrellas: "Carrying an umbrella when rain is forecast makes rain less likely to fall." With meteorologists now claiming rain-forecast accuracy rates of more than 80 percent, it seems obvious that taking an umbrella on their advice will prove correct four times out of five. This reasoning, however, fails to take into account the so-called base rate of rain. If rain is pretty infrequent, then most of the correct forecasts that resulted in that impressive 80 percent accuracy figure were predictions of no rain. This is hardly impressive (especially in, say, Phoenix or San Diego).

Don't Take the Umbrella

Thus, when deciding whether to take an umbrella, you need to take into account the probability of rain falling during the hour or so you are on your walk, which is usually pretty low throughout much of the world. For example, suppose that the hourly base rate of rain is 0.1, meaning that it is 10 times more likely not to rain during your hour-long stroll. Probability theory then shows that even an 80 percent accurate forecast of rain is twice as likely to prove wrong as right during your walk—and you'll end up taking an umbrella unnecessarily. The fact is that even today's apparently highly accurate forecasts are still not good enough to predict rare events reliably.

Captain Murphy was perhaps justifiably irritated by what in his view was the trivialization of his worthy principle for safety-critical engineering. Nevertheless, I believe the popular version of his law is not without merits.

That many of the manifestations of Murphy's Law do have some basis in fact suggests that perhaps scientists should not be so hasty to explain away the experience of millions as mere delusion. And with many of the explanations based on disciplines ranging from rigid-body dynamics to probability theory, analysis of various manifestations of Murphy's Law may also help motivate students to study otherwise dry topics.

But perhaps the most important lesson behind Murphy's Law is its lighthearted demonstration that apparently trivial phenomena do not always have trivial explanations. On the whole, that is not such a bad legacy. SA

To obtain high-quality reprints of this article, please see page 39.

The Author

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LOCKE AND WHITFIELD

Jules Verne, Misunderstood Visionary

Discovery of a long-lost novel reveals that, from the start, the father of science fiction was gravely concerned with the dangers of technology

by Arthur B. Evans and Ron Miller

Almost a century after his death, the well-known French author Jules Verne has once again managed to fire the imagination of people around the world, this time with a hitherto unpublished novel, *Paris in the 20th Century.* The manuscript, completed in 1863 but long locked away in a safe, was uncovered only in 1989 by Verne's great-grandson, and it appeared in English translation just a few months ago. This 19th-century vision of the future describes life among skyscrapers of glass and steel, high-speed trains, gas-powered automobiles, calculators, fax machines and a global communications network. The prescience of these forecasts matches what one would have expected from the author who introduced countless readers of his age to a host of technological marvels, from submarines to helicopters and spacecraft.

But, strangely, this newly published work belies the commonly held image of Verne as an apostle of scientific progress. In fact, *Paris in the 20th Century* is a tragedy. It portrays the life of an idealistic young man who struggles to find happiness in the fiercely materialistic dystopia that Paris has become by 1960. Like George Orwell's *1984,* Verne's novel is a grim and troubling commentary on the human costs of technological progress.

That such a message should come from Jules Verne proves surprising to many. Most people—particularly in America—assume that Verne wrote about the wonders of technology because he was himself an optimistic scientist. Many also believe Verne wrote primarily for children, crafting novels that were invariably exciting but intellectually shallow. These misconceptions show how Verne's current status has completely eclipsed the reality of his life and writings. They are part of the continuing misunderstanding of this author, a result of some severely abridged translations and simplified adaptations for Hollywood cinema.

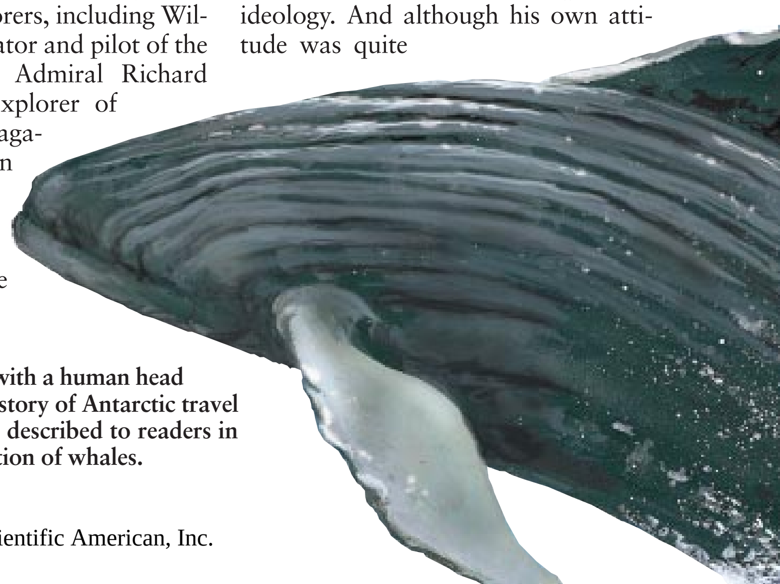
> But let the Americans be forewarned against this excessive slaughter! Little by little, whales will become rare on these southern seas, and it will become necessary to hunt them beyond the ice floes of Antarctica!
>
> ***The Ice Sphinx***

In truth, Verne was neither a scientist nor an engineer: he was simply a writer—and a very prolific one. (Over his lifetime, Verne produced more than 60 novels.) Yet his works were meticulously grounded in fact, and his books inspired many leading scientists, engineers, inventors and explorers, including William Beebe (the creator and pilot of the first bathysphere), Admiral Richard Byrd (a pioneer explorer of Antarctica), Yuri Gagarin (the first human to fly in space) and Neil Armstrong (the first astronaut to walk on the moon). Verne's novels were thus profoundly influential, and perhaps uniquely so.

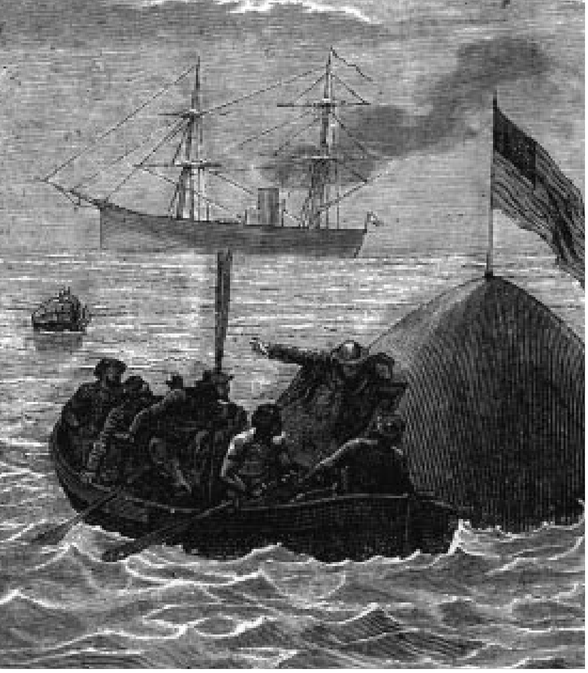
Although novels with scientific underpinnings had been written before, Verne raised the technique of scientific verisimilitude to a fine art. And this type of science fiction, based on scrupulously accurate descriptions of science and technology, has tended to dominate the genre ever since. But Verne's devotion to technical detail does not reflect an innate confidence in the virtues of science. Indeed, his earliest writings—a mixture of plays, essays and short stories—were distinctly critical of science and technology.

It was only the strict tutelage of his publisher, Pierre-Jules Hetzel, that steered Verne toward the narrative recipe that would eventually make him famous: fast-paced adventure tales heavily flavored with scientific lessons and an optimistic ideology. And although his own attitude was quite

RON MILLER



SCULPTURED ROCK FORMATION resembling a resting lion with a human head looms over the tumultuous sea in Jules Verne's *The Ice Sphinx,* a story of Antarctic travel based on an uncompleted work by Edgar Allan Poe. In it, Verne described to readers in 1897 how excessive hunting threatened to bring about the extinction of whales.



SPLASHDOWN, as described in Verne's *From the Earth to the Moon* and *Around the Moon* (*left*), closely matches events that actually transpired during recovery of the astronauts of *Apollo 11* (*right*) after their return from the surface of the moon in 1969.

different, Verne offered little resistance to Hetzel. After the release of his initial book in 1863, the first in a series of novels published under the banner "Extraordinary Voyages: Voyages in Known and Unknown Worlds," Verne explained to his friends at the Paris stock market (where he had been working part-time to make ends meet) about his accomplishment. "My friends, I bid you adieu.... I've just written a novel in a new style.... If it succeeds, it will be a gold mine." He was right.

Under Hetzel's continual guidance, Verne created one lucrative novel after another, each fundamentally of this same type. But most of the works published after Hetzel's death in 1886 show Verne reverting to his original themes—championing environmentalism, anticapitalism and social responsibility while questioning the benefits that science and technology could bring to an imperfect world. To understand how Verne's later writings could differ so completely from popular perceptions of him as an unswerving proponent of science requires a closer understanding of the man and his times.

Literary Ambitions

Jules Gabriel Verne was born on February 8, 1828, in the prosperous seaport city of Nantes, France. When he reached the age of 20, his family sent him to college in Paris to follow in his father's footsteps and become a lawyer. But young Jules had other ideas. Although he dutifully completed his law studies, Verne found himself drawn into the Parisian literary world. Encouraged by a friend and mentor, the elder Alexandre Dumas (author of *The Three Musketeers*), Verne dreamed of someday becoming a celebrated writer himself. He ultimately decided to forgo a career as an attorney and began to compose poetry and plays.

As an aspiring young dramatist working at the Théâtre Lyrique, Verne earned extra money by penning short articles on scientific and historical topics for a popular French magazine. He culled the facts he needed for these reports from long sessions in the library, poring over reference books, scientific journals and newspapers. Soon Verne began to consider the possibility of incorporating such technical documentation into a novel—a "novel of science" as he came to call it—that would mix fiction with fact, adventure with scientific principles. Verne imagined this innovative literary form as a blend of fiction of the kind written by James Fenimore Cooper, Sir Walter Scott and Edgar Allan Poe, with the newest discoveries, explorations and experiments of his age.

Such stories would take full advantage of the unprecedented public enthusiasm for science, engineering and exploration that then prevailed in France. During this period of rapid industrialization and technological growth, scientists and engineers were becoming popular heroes. This trend, coupled with a long-standing lack of science instruction in France's public schools (a consequence of their control by the Roman Catholic Church), created great demand for educational novels about science.

The genesis of Verne's first book, *Five Weeks in a Balloon,* reflects the pattern he followed in composing many of his subsequent works. Although Verne derived much source material from his own research, he also discussed his writing plans with various friends and relatives. In particular, he consulted his cousin Henri Garcet (a mathematician), Jacques Arago (explorer and brother to the respected physicist and astronomer François Arago) and Félix Tournachon, known to most Parisians by the pseudonym "Nadar."

Widely recognized as a pioneer photographer, daredevil balloonist and champion of the Society for the Encouragement of Air Travel via Heavier than Air Vehicles, Nadar bolstered Verne's interest in flight. Nadar also introduced Verne into his own circle of friends, including such noted engineers and scientists as Jacques Babinet, inventor of the first instrument for measuring humidity, and Gabriel La Landelle, whose helicopter design later provided the model for one of Verne's fictional machines. Discussions with Nadar and his associates helped Verne to amass the technical knowledge that enabled him to draft his first novel.

Another fount of ideas came from current events. Stories about balloon travel, both real and fictional, had become increasingly popular in France during the late 1850s and early 1860s. Daily newspaper accounts of strange and exotic discoveries in Africa also generated a large following of avid French readers, who closely monitored the adventures of various intrepid explorers as they trekked across that vast and then mysterious continent. There is no doubt that Verne saw in these popular travelogues the ideal scenario for his first scientific adventure novel.

Soon after completing the manuscript in 1862, Verne chanced to meet the noted Parisian publisher Pierre-Jules Hetzel. Verne promptly asked Hetzel if he would consider a story tentatively entitled "An Air Voyage" (a work that the distraught author had very nearly destroyed after another publishing house rejected it). Hetzel agreed to the request, and a few weeks later, Verne and Hetzel began what would prove to be a highly prosperous collaboration, lasting for a quarter of a century. Verne's novels initially appeared in Hetzel's new journal, *Magazine of Education and Recreation*.

Seeking to re-create the commercial windfall of Hetzel's widely read French publication, a similar periodical in Great Britain, called *The Boy's Own Paper*, published the first English translations of Verne's works. Although these narratives had instant and lasting appeal among youthful English readers, this popularity proved a mixed blessing. The hurried translations were often crude bowdlerizations: they omitted most of the science and emphasized only the most sensational parts of the original texts. Unfortunately, it was primarily through these slapdash translations that Verne became known to the English-speaking world, and these same versions—most of which are still the standard translations today—established and maintained Verne's reputation in both Great Britain and America.

A Well-Known Author

In 1864, two years after he met Hetzel, Verne wrote *Journey to the Center of the Earth*, a story that would prove to be one of his most enduring. His inspiration for this story undoubtedly came from the growing public interest in geology, paleontology and rival theories of evolution. Narrated in the first person by the young protagonist Axel, *Journey to the Center of the Earth* manages to maintain an even balance between the detailed scientific observations of his uncle, Professor Lidenbrock, and Axel's own poetic reveries as they descend into the earth and discover a subterranean, prehistoric world. Such intertwining of fact with fantasy constitutes the core of Verne's narrative strategy.

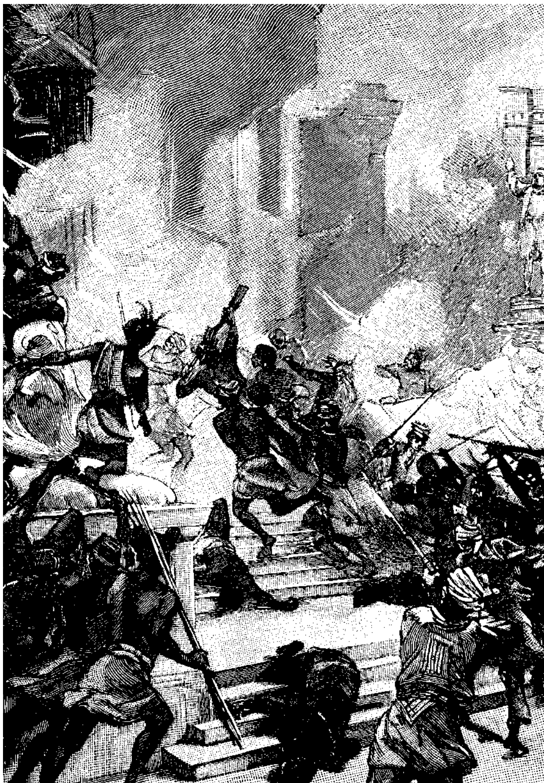
The next year Verne published *From the Earth to the Moon*. Breaking with literary tradition, which called for recounting such a voyage only as an imaginary undertaking, Verne based his account on an extrapolation of contemporary scientific principles. The resulting prophetic qualities of this novel are uncanny. For instance, Verne chose a launch site not far from Cape Canaveral in Florida; he also gave his readers the initial velocity required for escaping the earth's gravitation. In the sequel, *Around the Moon*, Verne correctly described the effects of weightlessness, and he even pictured the spacecraft's fiery reentry and splashdown in the Pacific Ocean—amazingly, at a site just three miles from where *Apollo 11* landed on its return from the moon in 1969.

As was probably often the case, some of the forecasts in these two novels may have been self-fulfilling, because so many of the scientists and engineers who pioneered spaceflight (such as Hermann Oberth and Konstantin Tsiolkovski) had read Verne's works. It might not be unreasonable to suggest that modern astronautics would have had a major setback had Verne not written about the subject. With his close attention to scientific principles, Verne encountered the same technical problems astronautical engineers were to face in the next century. That Verne's carefully constructed answers were similar to the modern solutions should not be at all surprising.

But there would also prove to be scientific mistakes embedded in Verne's writing. His greatest error in *From the Earth to the Moon* was to launch his spacecraft using a gigantic cannon instead of booster rockets. Yet that choice may have been a purposeful departure from reasoned thinking. The inclusion of much skeptical questioning in the novel indicates that Verne knew quite well his giant cannon would not work. But given the primitive state of rocketry, he also knew that his readers would be more willing to accept the notion of a giant moon gun (although Verne did call on rockets to maneuver the vehicle in space). And he probably could not resist the opportunity to poke fun at the fierce competition among American artillery makers after the Civil War—a humorous thread that runs through both *From the Earth to the Moon* and *Around the Moon*. Verne's fiction was indeed quite sensitive to the world around him.

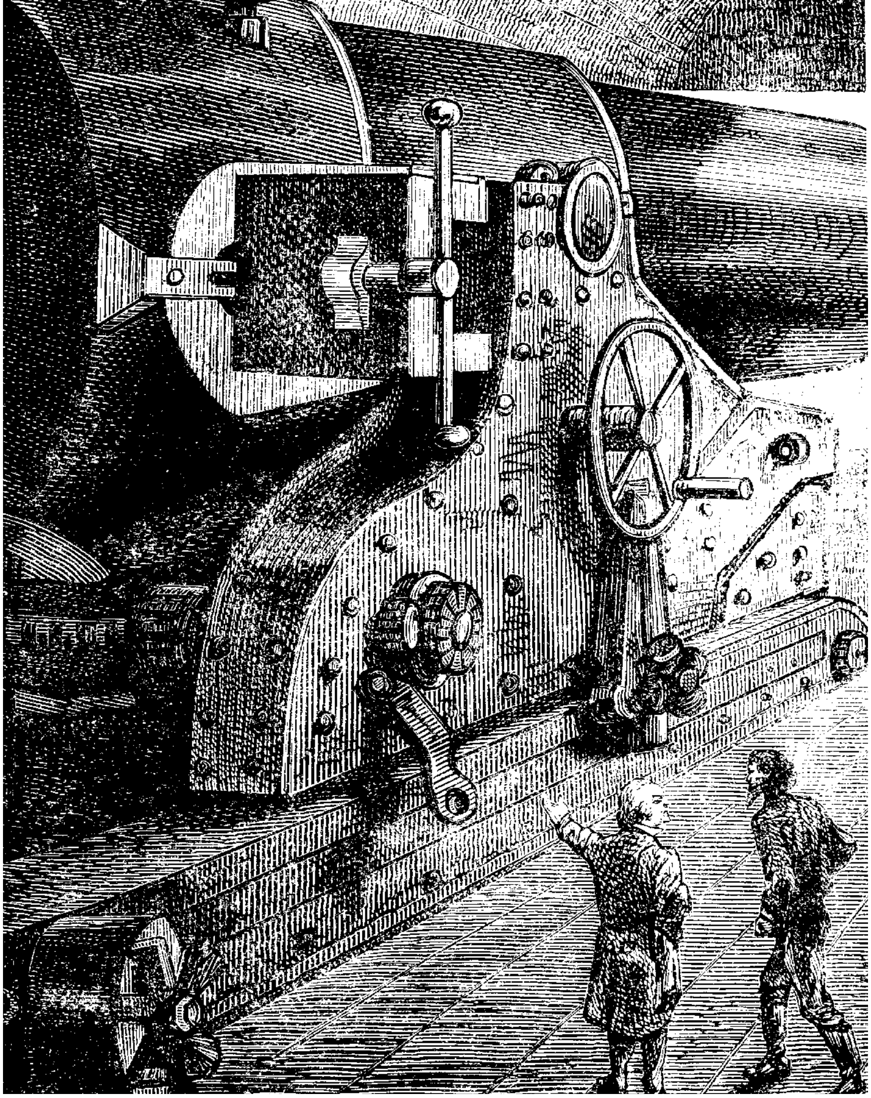
It is fitting that he began his first nautical novel while comfortably ensconced on a yacht he had purchased in 1868 to cruise the Somme River and the French coast. One year later Verne put the finishing touches on the world's first novel of oceanography, *Twenty Thousand Leagues under the Sea*. The sheer imaginative power of this underwater saga, which featured, among numerous colorful characters, the *Nautilus* (named after the submarine Robert Fulton had constructed in Paris in 1800), has

> How did this depopulation occur? From the extermination of the natives by wars, from the kidnapping of the adult males to work on Peruvian plantations, from the abuse of strong liquors, and—why not admit it?—from all the evils that conquest brought to these islands when the conquerors belonged to the so-called civilized races.
>
> ***Propeller Island***



GEORGES ROUX

RAMPANT VIOLENCE disrupts the peace on a tropical island in the 1895 novel *Propeller Island*, one of many cautionary tales written after the death of Verne's longtime publisher, Pierre-Jules Hetzel.



LÉON BENETT

GIANT WEAPON built by the German protagonist, Herr Schultze, in Verne's 1879 novel *The Begum's Fortune* presages the militant fanaticism that beset Europe in the next century.

made it one of the most read and admired of all Verne's stories.

> "[Its shells] will be filled with liquefied carbonic acid.... When exploded, they will release a cloud of carbonic gas at a temperature of less than 100 degrees below zero, and everything living within 30 meters of the point of impact will be simultaneously asphyxiated and frozen solid!... And because the gas is heavier than air, the area will remain contaminated.... And with this particular system, there are no wounded, only the dead!" Herr Schultze was obviously feeling quite pleased as he enumerated the merits of his invention.
>
> ***The Begum's Fortune***

Interestingly, the genesis of this novel was quite turbulent. Verne and Hetzel strongly disagreed over the characterization of the commander of the *Nautilus,* Captain Nemo. Hetzel thought Nemo should be portrayed as a sworn enemy of the slave trade, thereby providing a clear ideological justification for his merciless attacks on certain seagoing vessels. Verne, however, wanted Nemo to be a Pole and his implacable hatred to be directed against the Russian czar (a reference to the bloody Russian suppression of the Polish insurrection five years earlier). But Hetzel was deeply concerned with possible diplomatic ramifications and the likelihood that the book would be banned in Russia—a lucrative market for Verne's books.

Author and publisher eventually compromised. They decided that Nemo's exact motives would remain intriguingly obscure. Nemo would simply be a vaguely defined champion of liberty and avenger of the oppressed. In an attempt to be more specific, the creators of the 1954 film of *Twenty Thousand Leagues under the Sea* showed the manufacturers of munitions as the primary target of Nemo's wrath.

Another famous film resulted from Verne's *Around the World in 80 Days,* his most financially successful novel. Unlike some of his other fictional journeys, which required fabulous inventions to transport his characters to faraway places, this tale, written in 1872, kept to existing conveyances. Verne drew ideas for the novel from many sources, including a travel article that had appeared in France after the opening of the Suez Canal a few years earlier, a promotional leaflet from Thomas Cook's travel agency and a short story by Poe called "Three Sundays in a Week" (which points out that a person traveling around the world to the east will gain a day by crossing the international date line).

In *Around the World in 80 Days,* Verne describes how an imperturbable Englishman and his resourceful servant hurriedly circle the globe, experiencing along the way a spate of adventures. The novel was initially published in serial form in a Parisian newspaper—a strategy that nearly tripled circulation while Verne's suspense-filled chapters were running. Published as a book a few weeks later, the novel quickly set new records both in France and abroad. Verne's fame further soared when celebrities, such as Nellie Bly, Jean Cocteau and S. J. Perelman, sought, with great fanfare, to circumnavigate the world in fewer than Verne's magical 80 days.

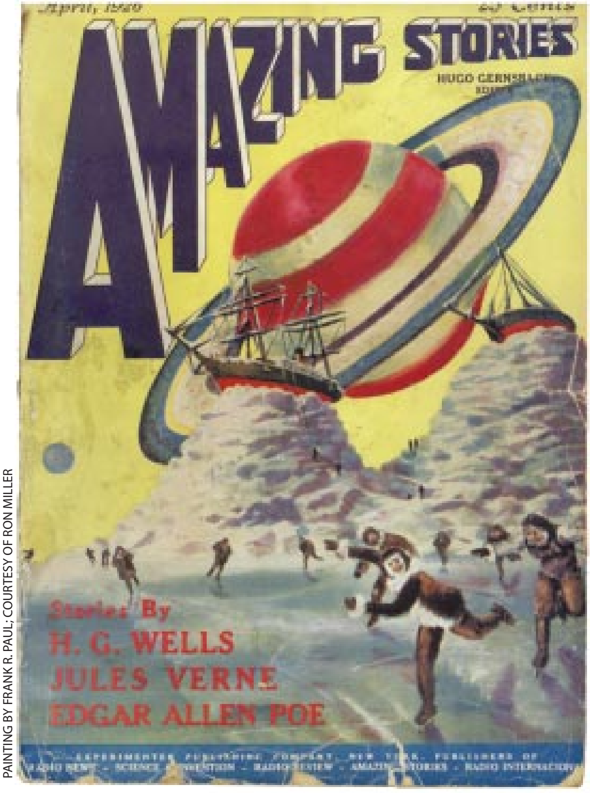
Although his next eight works all followed in the same vein as this great success, in 1879 Verne published a curious novel, *The Begum's Fortune.* This book recalls Verne's earliest writings and foreshadows the more overtly negative views of science and technology that he would adopt after Hetzel's death in the following decade. This novel tells the story of two highly symbolic characters—Dr. Sarrasin of France and Herr Schultze of Germany—who each receive a huge inheritance with which to build an ideal city in the wilds of the American Northwest. Sarrasin constructs a peaceful utopian village, whereas Schultze erects a fortresslike factory for the production of cannons and high-tech armaments. Reflecting French attitudes toward Germany after the Franco-Prussian War, Herr Schultze becomes Verne's first example of a truly evil scientist.

Prefiguring Germany's dictator of the next century, Schultze propounds fanatically Nietzschean evolutionary beliefs as he devotes himself to the extermination of the weaker elements of the human race and the glorious rise of a new ruling class of technological "Ubermensch." The dark portrait of Schultze in *The Begum's Fortune* marks an important shift in emphasis from Verne's previous novels. In this work, Verne points out for the first time that the power of technology can breed corruption and that scientific knowledge in the hands of evil people becomes evil.

The reaction to this novel by the French public proved uncharacteristically cool. Whereas most of Verne's works immediately sold between 35,000 and 50,000 hardbound copies in his native country (*Around the World in 80 Days* totaled 108,000), *The Begum's Fortune* sold less than half the usual number. Scientific pessimism, it appears, did not sit well with Verne's traditional readers.

Despite the clear commercial risk, Verne's later writings frequently reflected this same shift in attitude from his earlier novels. Themes of human morality and social responsibility grew more prevalent, and Verne often invented heroes who lacked any scientific orientation. What few scientists did remain were increasingly portrayed as crazed megalomaniacs.

Verne also tried to publicize some contemporary environmental and social abuses. For example, in *Propeller Island,* Verne described the plagues of politicians and missionaries who destroyed the native cultures of various Polynesian islands. In *The Ice Sphinx,* he pointed out the imminent extinction of whales. Verne also revealed to his readers the pollution caused by the oil industry in *The Will of an Eccentric,* and he exposed the slaughter of elephants for their ivory in his 1901 novel *The Village in the Treetops.*



PAINTING BY FRANK R. PAUL; COURTESY OF RON MILLER

KEY SCENE from Verne's *Off on a Comet* adorns the premier issue of the science-fiction magazine *Amazing Stories,* which was first published in New York City in April of 1926.

Perhaps the most striking examples of Verne's literary transformation are seen in sequels to works published much earlier. For instance, in *The Purchase of the North Pole,* the finale to a trilogy that began with *From the Earth to the Moon,* Verne's characters are not satisfied with shooting manned capsules into space. Instead they seek to alter the angle of the earth's axis with a blast from a gigantic cannon. Wholly indifferent to the catastrophic environmental and human damage that would result from such a project, their scheme is to melt the polar ice cap and uncover vast mineral wealth. The protagonists in this novel become caricatures of their former selves as Verne exposes their irresponsibility and hubris.

From Man to Myth

Despite occasional family bickering, increasingly poor health and the death of his beloved brother, Verne continued diligently to the end of his life to compose two or three novels each year. But his later works fared poorly. *Propeller Island* and *The Ice Sphinx,* for example, each sold fewer than 10,000 copies. Some of his final novels, such as *The Superb Orinoco, The Kip Brothers, Traveling Scholarships* and *The Invasion of the Sea,* did not even sell out their first printing of 4,000 to 5,000 apiece. In sad fact, these four works remain unavailable in English even today.

With an entire drawerful of nearly completed manuscripts in his desk, Verne fell seriously ill a few weeks after his 78th birthday. Lucid until the end, he told his wife, Honorine, to gather the family around him, and he died quietly on March 24, 1905. He was buried near his home in Amiens, and two years later a memorial sculpture was placed over his grave. It depicts Verne rising from his tomb, one arm reaching toward the stars.

Some two decades later an American periodical called *Amazing Stories*—the first magazine exclusively to feature tales of science and adventure—used a representation of Verne's tomb as a logo. To describe these narratives, the publisher, Hugo Gernsback, coined the term "scientifiction," which was later changed to science fiction. And, not long after, Jules Verne's overly simplistic reputation as a visionary champion of scientific progress became firmly rooted in American cultural folklore. SA

The Authors

ARTHUR B. EVANS and RON MILLER share a long-held admiration for Jules Verne's novels. Evans, who chairs the department of romance languages at DePauw University, is co-editor and publisher of the journal *Science-Fiction Studies.* He has written extensively about Verne in books and scholarly articles. Miller, a professional illustrator specializing in scientific subjects, has authored or co-authored nearly two dozen books, including a modern translation of Verne's *Twenty Thousand Leagues under the Sea.* His paintings enliven an array of magazines, books and films as well as U.S. Postal Service stamps that depict space exploration.

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by Shawn Carlson

The Joys of Armchair Ornithology

Fourteen was a rough age for me. Each member of my family dealt differently with my parents' bitter divorce. I withdrew into myself and my anger. In just a few weeks I became disconnected from everything that had mattered to me. I even stopped attending the monthly Boy Scout camping trips, which had, until then, been my only escape.

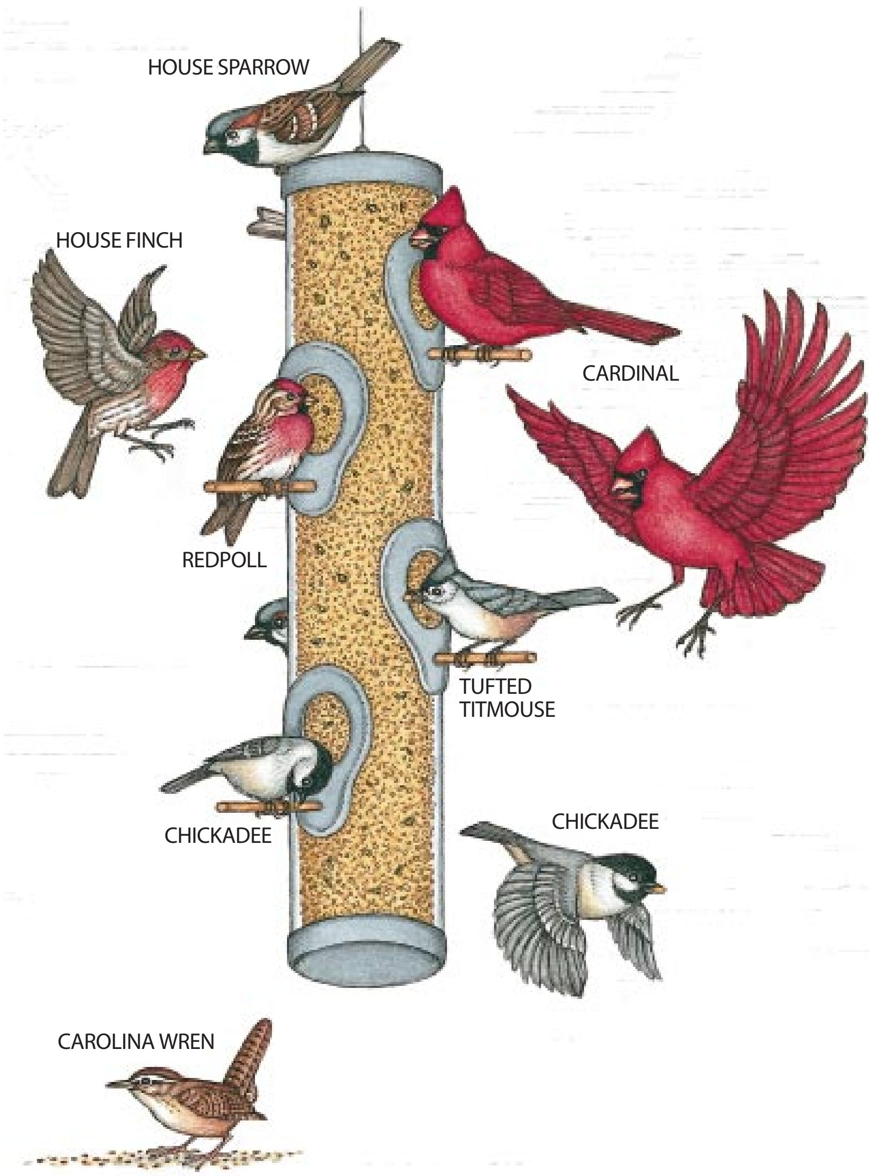
Fortunately for me, Troop 581 was led by a remarkable man. Joseph Kessler was a surrogate father to many of us scouts, and he reached out to me in a most extraordinary way. This longtime member of the National Audubon Society phoned me up one day and sternly insisted that I accompany him on the society's annual Christmas bird count. Of course, the fact that I knew absolutely nothing about birds didn't matter. That afternoon I learned to tell a Wandering Tattler from a Ruddy Turnstone and discovered a new sense of fellowship. Bird-watching has been a source of emotional renewal for me ever since.

I suspect that the rejuvenating power of birding may explain why there are so many amateur ornithologists out there. Their unwavering dedication has made the Christmas bird count one of the greatest amateur-based research programs ever. The first count began on Christmas Day in 1900 as a protest against what was then a tradition of holiday slaughter in which teams of hunters competed to shoot the most birds in one day. What started with just 25 groups of birders in the Northeast now involves more than 45,000 people in 1,600 teams across North America and parts of the Caribbean and Pacific. From mid-December to early January, this army of observers records an estimated 74 million birds of at least 1,200 species. The results appear every winter in a special issue of the National Audubon Society's magazine *Field Notes*.

The Christmas bird count database is unparalleled; it provides a yearly snapshot of bird distributions stretching back nearly 100 years. But that record is still only a snapshot. Birds are fantastically complex creatures, and the Christmas bird count does not provide enough information even to begin to explore the dynamics of their activities. For example, when environmental pressures, such as those caused by a severe winter, become too intense, entire populations may suddenly leave (ornithologists say "irrupt from") their normal range and invade another. Those species already in that area may feel the pressure of this competition and either irrupt into new areas or begin to die off. This muscling for resources takes place in addition to normal migration.

To study such phenomena requires a more comprehensive database. The ultimate record would require tens of thousands of dedicated observers spread all over the continent counting birds continuously throughout the year, but there aren't nearly enough professional biologists to do this job. Fortunately, there's another vital resource for quality observations—amateur scientists.

In 1987 ornithologists at the Cornell



PATRICIA J. WYNNE

BIRD FEEDER is a perfect site for gathering basic data on domestic bird populations.

WANDERING TATTLER

Lab of Ornithology (CLO) and Long Point Bird Observatory created a research program that couples the enthusiasm of amateur scientists with the expertise of professionals to create the most extraordinary research partnership I know. Project FeederWatch is revolutionizing our understanding of avian ecology and bringing the delight of hands-on science into homes all over North America. If you've got a bird feeder, some seeds and a comfy chair, your whole family can join.

Research has never been easier. Participants check their feeders for two consecutive days every two weeks and record the largest number of species they see at a feeder at any one time. FeederWatchers record their observations on computer-readable forms and send them to the CLO at the end of the season. That's all there is to it. *Birdscope,* the CLO's quarterly newsletter, reports the project's latest findings and other bird-related news. The autumn issue will discuss results from the 1996 season.

Last year amateur ornithologists sent in nearly 70,000 forms—far more data than are gathered for the Audubon Society's Christmas bird count. The FeederWatch database integrates half a million observations, making it by far the most extensive resource of its kind. The data have been a boon for science. Ornithologists can now look at subtle variations within a single species of feeder-visiting birds over both space and time.

For example, when its food supplies fail in winter, the small and extremely beautiful Common Redpoll undergoes a massive irruption. Millions of the birds head south in search of calories. Cornell ornithologists were able to track the movement of these birds week by week as they invaded more hospitable habitats to escape the winter of 1993–94. This was an ornithological first, one of many for FeederWatch.

These data are also revealing such subtleties as the effects of a single severe storm on bird population. FeederWatch observations showed that the numbers of Carolina Wrens on the fringe of their range in the northeast dropped rapidly immediately after a severe snowstorm in January 1994. Yet the wrens had seemed unaffected by a similar storm that occurred two months earlier. Apparently the wrens live on the edge of disaster. Evolution has barely equipped them to survive winter, and if the weather is too bad for too long, the Carolina Wren gets clobbered.

FeederWatchers are also helping chart the invasion of nonnative species. For instance, data show that the House Finch, accidentally introduced on Long Island in 1940, is still expanding in all directions. And when the House Finch is matched against the House Sparrow (introduced to the area in the mid-19th century) in head-to-head competition for resources, the House Sparrow loses badly, and its numbers plummet.

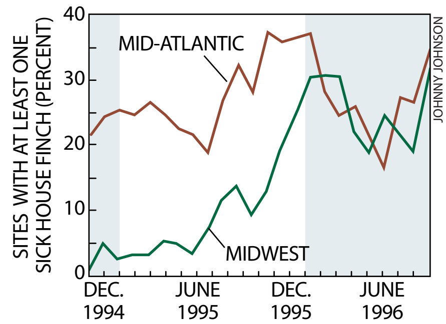
All is not rosy for the House Finch, however. A nasty bacterium called *Mycoplasma gallisepticum,* once a blight only on poultry, recently mutated and began infecting House Finches and a few related species that occasionally forage in chicken coops. This contagious bacterium infects the eyes and can eventually kill the unlucky host. FeederWatch scientists have developed a special questionnaire to help observers identify afflicted finches. After 24 months of data collection and 22,000 data forms, the researchers can now document the spread of the disease in impressive detail [*see illustration above, right*].

Project FeederWatch is the perfect research project for any budding naturalist, young or old. It costs next to nothing to get involved and requires only a little observation time. You will, of course, have to learn your local birds. I suggest you contact the CLO today and sign up your entire family. Then join your local Audubon Society. Invest in a good field guide and start networking with birders in your area.

Budgetary restrictions limit the data-collecting phase of the CLO's project to six months out of the year, so you have plenty of time to ease into what may well become a rewarding passion for the rest of your life. The next data cycle starts on November 8.

RUDDY TURNSTONE

By the way, Mr. Kessler's intervention did more than give me a love of birding. I eventually became an Eagle Scout. Kessler is still active in scouting and still takes part in the Christmas bird count, as he has for the past 25 years.



***FEEDER OBSERVATIONS** track the spread of eye disease among House Finches.*

To join Project FeederWatch, send $15 to the Cornell Lab of Ornithology, Project FeederWatch SA, P.O. Box 11, Ithaca, NY 14851-0011, or send e-mail to birdeducation@cornell. edu or call (607) 254-2440 or (800) 843-BIRD (2473). Or you can check out their World Wide Web site at http://www. ornith.cornell.edu In Canada, send C$20 to Bird Studies Canada/PFW/SA, P.O. Box 160, Port Rowan, Ontario N0E 1M0 (e-mail: pfw@nornet.on.ca). Educators should ask about Classroom FeederWatch. For more about other amateur scientist projects, call the Society for Amateur Scientists at (800) 873-8767 or (619) 239-8807 or visit their Web site at http://www.thesphere.com/SAS/

I gratefully acknowledge informative conversations with Andre Dhondt, Margaret Barker, Richard Bonney, Jr., and Sheila Buff.

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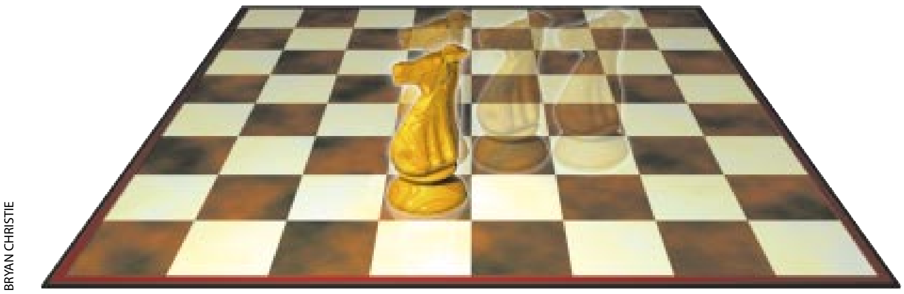
by Ian Stewart

Knight's Tours



IN A KNIGHT'S TOUR, the knight must move around the board in such a way that it visits every square only once.

Among the old favorites of recreational mathematics are "knight's tours," in which a chess knight is required to move across boards of various shapes and sizes in such a way that it visits every square only once. The knight, you may recall, moves two squares parallel to a side of the board, followed by one square at right angles. If it can return in the last move (which is not counted) to its starting square, the tour is said to be closed.

The problem seems to have originated around 1700 with the English mathematician Brook Taylor, who asked what knight's tours might exist on an ordinary 8 × 8 chessboard. The first solutions were given soon after by Pierre de Montmort and Abraham de Moivre. The question has since been extended to boards of other shapes, to three-dimensional "boards" and even to infinite boards. But in 1991 Allen J. Schwenk of West Michigan University in Kalamazoo observed that the available literature seemed to neglect an entirely natural question: Which rectangular boards support a closed knight's tour?

The literature on knight's tours is extensive but scattered. It includes such classics as *Amusements in Mathematics,* by H. E. Dudeney (Dover, 1958), *Mathematical Recreations and Essays,* by W. W. Rouse Ball and H.S.M. Coxeter (University of Toronto Press, 1974), and *Mathematical Recreations,* by M. Kraitchik (Dover, 1953). Schwenk's question is believed to have been answered by Leonhard Euler or Alexandre-Theophile Vandermonde, but there is no record of the actual result or its proof.

Of the sources listed, Kraitchik comes closest to providing an answer, but he assumes that one side of the rectangle has seven squares or less. Ball deals only with the 8 × 8 case. Dudeney gives several puzzles that reduce to the 8 × 8 case, together with a tour over the surface of an 8 × 8 × 8 cube.

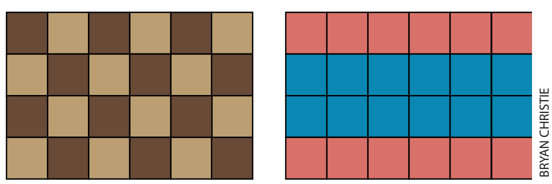
Schwenk himself developed a solution that illuminates a number of issues in discrete mathematics. Here I shall summarize his elegant analysis; for full details, see his article "Which Rectangular Chessboards Have a Knight's Tour?" (*Mathematics Magazine,* Vol. 64, No. 5, pages 325–332; December 1991).

Mathematically, the knight's tour quandary reduces to finding a "Hamiltonian cycle" in a graph. A graph is a collection of dots, called nodes, joined by lines, called edges. A Hamiltonian cycle is a closed path that visits each node exactly once. The graph of a given chessboard is obtained by placing a node at the center of each square and then drawing edges between nodes that are separated by one knight's move [*see illustration on opposite page*]. It helps to color the nodes dark and light, corresponding to the usual pattern on a chessboard. Notice that when the knight moves, it hops from a node of one color to one of the opposite color, so the nodes must be alternately dark and light around any Hamiltonian cycle. This pattern implies that the total number of nodes must be even.

The 3 × 5 board has 15 nodes, an odd number, so we have proved—without even trying—that no closed knight's tour is possible on the 3 × 5 board. The same goes for any rectangular board of size $m \times n$ where m and n are both odd.

This kind of argument is known as a parity proof. A more subtle parity proof, invented by Louis Pósa, demonstrates that there is no closed knight's tour on any 4 × n board. His idea is to introduce a second coloring in which the top and bottom rows of the board are red and the two middle ones are blue [*see illustration below*]. Blue nodes may be joined to either blue or red nodes, but every red node is joined only to blue nodes. Thus, any presumptive Hamiltonian cycle consists of single red nodes separated by one or more blue nodes.

But there are the same number of red and blue nodes, so in fact red and blue nodes must alternate around the cycle. The same is true, however, of dark and light nodes, using the more traditional coloring. So by starting at the top left-hand corner, we conclude that all red nodes are dark and all blue nodes are light. Because the two coloring schemes are obviously different, this conclusion is absurd; consequently, the presumed cycle cannot exist.



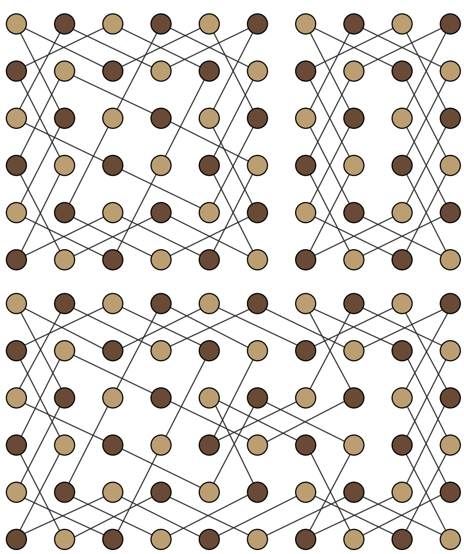
COLORING TRICK helps to solve the knight's tour problem for a 4 × 6 chessboard.

Schwenk provided a beautiful characterization of those rectangular boards that support knight's tours. He found that an $m \times n$ chessboard (here we make m less than or equal to n to avoid duplications) supports a knight's tour unless:

m and n are both odd
m = 1, 2 or 4
m = 3 and n = 4, 6 or 8

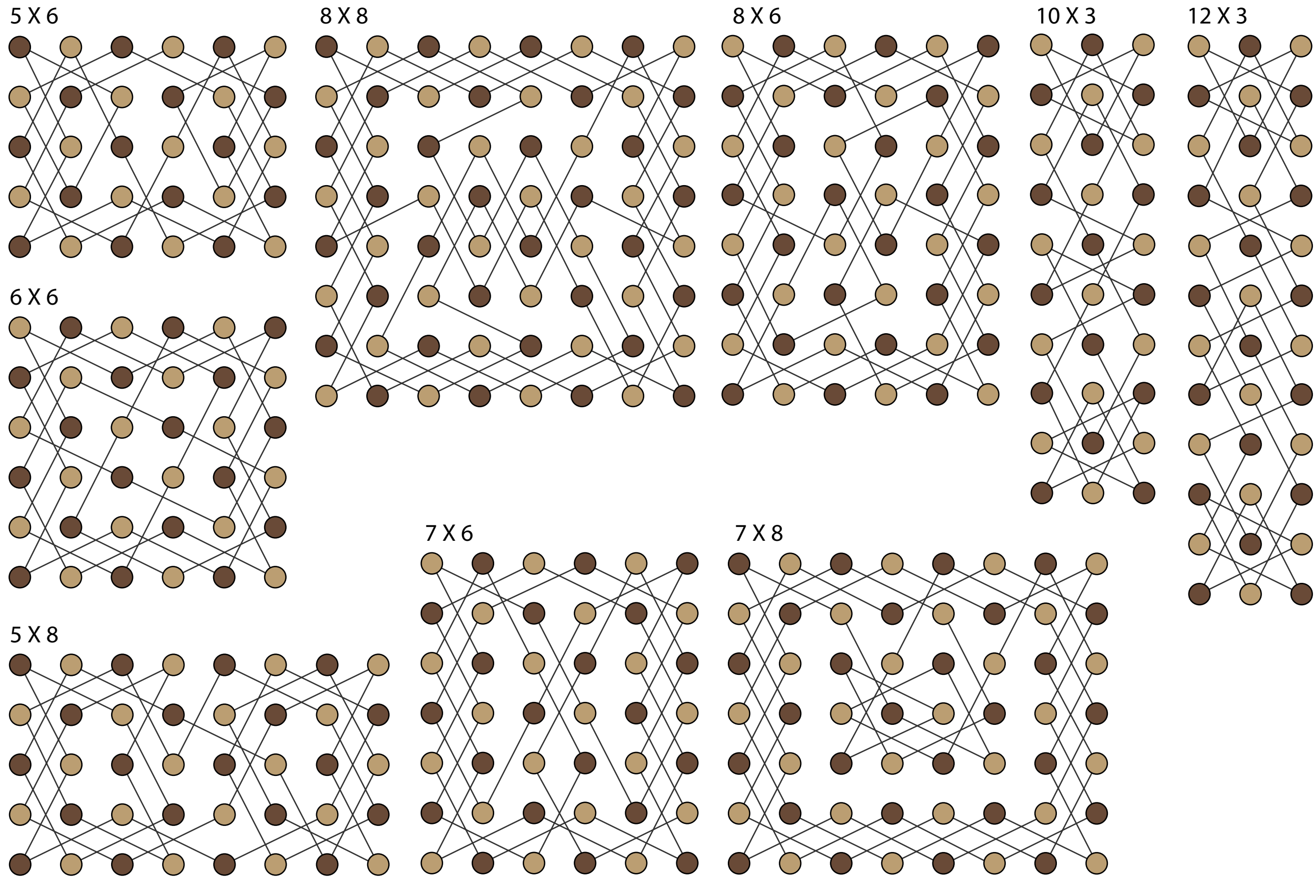
Let me sketch the proof. We have already disposed of the cases in which m and n are both odd, or $m = 4$. When $m = 1$ or 2, there just isn't room for the knight to get around the board. In fact, the top left-hand node has only one edge connected to it, so no closed cycle can pass through it. The 3×4 case is taken care of by Pósa's argument. For the 3×6 case, observe that removing two nodes at the top and bottom of column three divides the graph into three disconnected pieces. If there were a Hamiltonian cycle, which visits every node once, it should also be broken into three parts. Removing two nodes from a Hamiltonian cycle, however, always produces two disconnected pieces. The 3×8 case is more complicated; I suggest that you try it for yourself or consult Schwenk's article.

That completes the proof of impossibility in the designated cases. But it remains to be proved that tours exist on all other board sizes. The key idea is that a tour on an $m \times n$ rectangle can always be extended to one on an $m \times (n + 4)$ rectangle, provided that certain technical conditions about the existence of specific edges are satisfied [*see illustration below*]. Moreover, those conditions remain valid for the tour on the larger



BRYAN CHRISTIE

KNIGHT'S MOVES on a chessboard can be displayed in a graph: a dot represents each square; those dots between which a knight can jump are connected by lines. Extension of a knight's tour from a 6 × 6 chessboard (top left) *to a 6 × 10 one* (bottom) *is achieved by adding on a tour for a 6 × 4 board* (top right).



BRYAN CHRISTIE

***NINE GRAPHS** supply the templates from which, by extension, all other knight's tours can be constructed.*

rectangle, and accordingly the extension can be repeated indefinitely. By symmetry, a tour on an $m \times n$ rectangle can always be extended to one on an $(m + 4) \times n$ rectangle.

So, for example, if we start with a tour on a 5×6 rectangle, we know we can also find tours on rectangles of sizes 5×10, 5×14, 9×6, 9×10, 9×14, 13×6, 13×10, 13×14 and so on. Each "initial size" generates an entire family of sizes for which the existence of a knight's tour is guaranteed.

The final step is to find enough different initial sizes to generate all the required sizes. It turns out that nine are enough: the boards of sizes 5×6, 5×8, 6×6, 7×6, 7×8, 8×6, 8×8, 10×3 and 12×3 [*see illustration above*]. Starting from these and the corresponding diagrams rotated through a right angle, and adding multiples of four to each side, we can generate tours of all the possible sizes. The proof is complete. SA

FEEDBACK

"Monopoly Revisited" [October 1996] produced a big mailbag, full of new theoretical results. Mark Guttag of Alexandria, Va., was one of several eagle-eyed readers who spotted an error in the bar chart on page 118, where the label "Illinois Avenue" should be "Atlantic Avenue." (On the board that I am used to, they are Trafalgar Square and Leicester Square—a feeble excuse but better than none.) Jeffrey S. Lehman of the University of Michigan Law School told me about his book *1,000 Ways to Win Monopoly Games* (Dell, 1975), written with Jay Walker. They also used Markov chain analysis to work out Monopoly probabilities.

Isaac Lin informed me of a book that is "a must-read for die-hard fans of Monopoly," namely, *The Monopoly Book,* by Maxine Brady (D. McKay Company, 1974). It refers to a computer analysis run by Irvin R. Hentzel. David R. Miller of Arlington, Mass., was kind enough to send the reference to Hentzel's original article: it is "How to Win at Monopoly" (*Saturday Review of the Sciences,* Vol. 1, pages 44–48; April 1973). Hentzel's simulation included the effect of COMMUNITY CHEST and CHANCE cards and of the Jail rules; moreover, he worked out the average dollar income per turn of various properties and monopolies.

Eugene McManus of Okinawa, Japan, informed me that he used Monopoly as a vehicle for teaching management techniques to undergraduates. He and his students calculated return on investment (ROI) functions for each property, finding that there are some properties on which it is best not to build hotels—the maximum return comes from four, or sometimes only three, houses. He also commented on the symmetry of the game: "There are four 'neighborhoods.' There are four railroads, one in each neighborhood. Each railroad divides a neighborhood into two parts: a 'good side of the tracks' and a 'bad side of the tracks.' Property on the good side of the tracks has high rental ROI; property on the bad side of the tracks has far lower rental ROI."

—I. S.


RICHARD QUICK

ARTIFICIAL LIGHTNING ***streams from the terminal of a high-frequency Tesla coil. The eccentric inventor conceived the device as part of a system that might broadcast power through the earth's atmosphere.***

RECONSTRUCTING TESLA

Review by Ronald Kline

Wizard: The Life and Times of Nikola Tesla, Biography of a Genius
BY MARC J. SEIFER
Birch Lane Press, Carol Publishing Group, 1996 ($32)

The author begins this biography by recalling an incident in 1976 when he "stumbled upon a strange text entitled *Return of the Dove,* which claimed that there was a man not born of this planet who landed as a baby in the mountains of Croatia in 1856. Raised by 'earth parents,' an avatar had arrived for the sole purpose of inaugurating the New Age. By providing humans with a veritable cornucopia of inventions, he had created, in essence, the technological backbone of the modern era." The figure in question is none other than Nikola Tesla, the controversial and often mythologized electrical inventor. We do subsequently learn that he was actually born on the earth, not descended from the sky like Superman. But Marc J. Seifer—a graphologist, past editor of *MetaScience: A New Age Journal on Consciousness* and a teacher of psychology—often presents Tesla as larger than life, a born genius who used his tremendous eidetic capabilities to invent the electrical and electronic "backbone" of the 20th century.

Yet underneath the layers of hero worship, uncritical acceptance of Tesla's pronouncements and some dubious technical claims, the core of Seifer's book is a serious piece of scholarship. Perhaps we should not expect anything less paradoxical about a supposedly forgotten figure who has at least three organizations devoted to promoting his memory (the Tesla Memorial Society in Lackawanna, N.Y.; the International Tesla Society in Colorado Springs, Colo.; and the Tesla Museum in Belgrade, Yugoslavia). Tesla has been the subject of three previous full-length biographies, juvenile biographies, plays (including one by Seifer) and a novel. The U.S. Postal Service has honored Tesla with a stamp, and an international electrical unit is named after him.

The story of one of the most prolific, independent and iconoclastic inventors of this century is a fascinating one. Born to a leading Serbian family in a small village and trained at an Austrian polytechnic school, Tesla worked on a lighting installation in Strasbourg, where he secretly tested his idea for an alternating-current (induction) motor. In 1884 he emigrated to the U.S., where he worked on the installation of Thomas Edison's direct-current, incandescent-lighting central station in New York City. Unable to sell Edison on his AC plans, Tesla quit, found financial backing and applied for what turned out to be the controlling patents on the induction motor and the polyphase system of AC power transmission, the system in universal use today. Tesla's company sold the patent rights to Westinghouse Company in 1888; he probably received about $100,000 for them over a decade but failed to develop a commercial induction motor while working for Westinghouse in Pittsburgh.

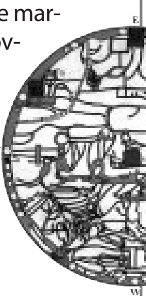
Tesla then turned his attention to high-frequency research and astounded the engineering and scientific communities with dramatic displays of high-voltage effects—often taken through his body—and of vacuum-tube lighting created with what was soon called the Tesla coil. Flush with financial, professional and social success (he hobnobbed with the likes of Mark Twain and lived in the posh Waldorf-Astoria), Tesla conceived the idea of transmitting messages and significant amounts of electrical power without wires, by using the earth or the upper atmosphere as a conductor. He raised money from John Jacob Astor and, in 1899, built a gigantic Tesla coil connected to a tall antenna in a laboratory in Colorado Springs.

Although forced to abandon his overambitious plan of using helium-filled balloons to conduct electricity through the upper atmosphere, Tesla claimed to have succeeded in transmitting a small amount of wireless power by setting up electrical waves with high-voltage discharges from the Tesla coil. He also as-

BRIEFLY NOTED

WATER: A NATURAL HISTORY, *by Alice Outwater. BasicBooks, 1996 ($23).*
American industry has largely cleaned up its act, as far as discharging toxic pollutants into waterways goes. Yet much of the nation's water is still dirty. Alice Outwater, a sludge management consultant, blames the land management activities that have short-circuited the cleansing paths water used to follow before swamps were drained and flood-prone riverbanks were lined with concrete. Her tale is persuasive and well crafted.

PHANTOM ISLANDS OF THE ATLANTIC, *by Donald S. Johnson. Walker and Company, 1996 ($21).*
Atlantis vanished long ago from maps of the world, but Frisland, Buss Island, Antillia and the isles of Saint Brendan first appeared during the age of exploration. Then they disappeared again. Faulty reckoning and a strong will to believe combined to make mariners think they had discovered lands of legend. As navigational skills improved, cartographers displaced the mysterious landmasses into ever less accessible seas, until there was no place left unexplored.

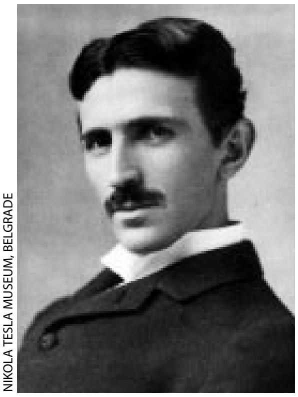


COURTESY OF THE NEWBERRY LIBRARY

A HISTORY OF CHEMISTRY, *by Bernadette Bensaude-Vincent and Isabelle Stengers. Translated by Deborah van Dam. Harvard University Press, 1997 ($35).*
How did chemistry get from the atoms of Democritus to the atoms of Pauling? Two historians of science trace the tensions between the empirical recipes that have long made chemistry useful—techniques for smelting, refining or compounding—and the philosophical hypotheses that explained what was "really" taking place in the retort or crucible. The authors make clear that theories of chemical structure were necessarily inextricable from experimental methods for assaying composition. Indeed, the notorious phlogiston hypothesis, a wrong turn on the way toward understanding oxidation, was well grounded in experiment; it stands as a scientific milestone because the existence of phlogiston could in fact be tested.

Continued on page 112

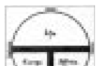
serted that he received signals from the planet Mars during the Colorado experiments; Seifer speculates that, ironically, Tesla had picked up signals sent across the English Channel by his rival, Guglielmo Marconi.



NIKOLA TESLA MUSEUM, BELGRADE

NIKOLA TESLA at 38, at the peak of his fame.

Sensational newspaper stories about the "sorcerer" inventor, along with Tesla's own audacious writings, caused scientists and engineers to distance themselves from him. Yet after his AC patents were upheld in 1900, Tesla raised $150,000 from J. P. Morgan to build a large transmission facility at Wardenclyffe (now Shoreham), Long Island. Stung by the success of Marconi's transatlantic wireless transmission in late 1901, Tesla ratcheted up his designs for a World Telegraphy Center, but after several years of work and a lack of support from Morgan, his "magnifying transmitter" was left unfinished. Tesla fell on hard times and lost the site because of outstanding hotel bills.



Around 1910 Tesla shifted his efforts to bladeless turbines, speedometers and vertical-lift airplanes, traveling to the Midwest as a consulting engineer on some projects. The media rediscovered him in his old age (he could often be found feeding pigeons in New York City's Bryant Park). He made the cover of *Time* magazine on his 75th birthday in 1931, and news stories at the time reported Tesla's claims to have invented a death ray. When he died early in 1943, the Federal Bureau of Investigation and the U.S. War Department examined his effects for evidence of the weapon, but electrical engineering professor John O. Trump found nothing of military value. Later that year, the Supreme Court overturned one of Marconi's basic radio patents on the grounds that it had been anticipated by Tesla.

Most of the story is familiar, but the author presents much new material on Tesla's youth, negotiations with backers, consulting work and relationships with close friends. Seifer admits that his hero was wrong about the safety of x-rays, made bad business decisions and had character faults such as "paranoid tendencies" and "greed, vanity and megalomania." Seifer bases his book on a large number of archival and primary sources and seems to be on solid ground when he discusses these aspects of Tesla's life. He should have consulted more secondary sources on Tesla's contemporaries, however, as he gets many details wrong. Charles Steinmetz's influential book on AC circuits, for example, was based on much more than Tesla's writings; similarly, Sebastian Ferranti's single-phase, high-voltage AC system was not indebted to Tesla's work. And Edwin H. Armstrong was the inventor of FM radio, not both AM and FM.

Most technically knowledgeable readers will also doubt Seifer's statements that "most likely, Tesla displayed actual laser beams" in 1892, that he and a colleague were "bouncing laserlike pulses off the moon" in 1918 and that he had designed a workable, particle-beam Strategic Defense Initiative–like weapon in the early 1940s (described in the last part of the book, where conspiracy theories abound). Seifer also makes up several conversations between protagonists, although he acknowledges in his endnotes that he has taken "literary license" in these cases.

Also problematic is the author's overall view of technology. Seifer promotes an interpretation, still fostered by the U.S. patent system and the popular media, that technological change largely results from solitary, heroic acts of invention. This perspective leads to many controversial claims sprinkled throughout the book. Seifer identifies the principles of such devices as sonar, television, fax machines, garage-door openers, digital recording and cable television scramblers as originating in Tesla's work, giving the implication that other people simply worked out Tesla's ideas.

For the past 40 years, historians and sociologists of technology have refuted the romantic model of innovation by publishing numerous case studies detailing the simultaneity of invention, the teamwork often associated with "lone" inventors, and the lengthy and complex process of technological development. To Seifer, gaining a court decision on a controlling patent counts far more than these supposedly mundane activities. Thus, he discounts the work of several European and U.S. engineers who transformed Tesla's prototype induction motor into a commercial product, and he characterizes the work of Marconi and his competitors as simply pirating Tesla's ideas.

Seifer does include a useful appendix that contrasts the opinions of scholars skeptical of Tesla's plan for the worldwide wireless transmission of industrial power with his own views and those of others who thought that the scheme was practical. Many people will also be interested in reading how Tesla repeatedly defied mainstream science—one reason for the continuing interest in this "forgotten genius."

RONALD KLINE is a historian of technology at Cornell University.

BRIGHT HISTORY OF A DARK SCIENCE

Review by Glenn Zorpette

The Codebreakers: The Comprehensive History of Secret Communication from Ancient Times to the Internet
BY DAVID KAHN
Scribner, 1996 ($65)

Originally published in 1967, *The Codebreakers* was a monumental achievement. It illuminated for the first time the shadowy world of cryptology with a mix of sharp tutorial and gossipy portraiture. The book's author, a 37-year-old newspaperman named David Kahn, was perhaps uniquely capable of pulling off such a feat; in addition to his doctorate in history, Kahn had a skilled reporter's ability to ferret out and enliven arcane facts, as well as a trove of practical knowledge he had gained as an amateur cryptologist. This revised version of his opus appears at a time when secret writing has become a focus of public debate, as spymasters and "cypherpunks" fight for control over the dissemination of new, essentially unbreakable codes.

Poised at the intersection of espionage, diplomacy, warfare and mathematics, the field of cryptology has been endowed with an abundance of psychedelically colorful characters. Take Edward Hebern. A shy, bookish demeanor notwithstanding, he stole a horse and served time for the transgression in San Quentin—where, around 1908, he appears to have conceived one of the most important inventions in 20th-century cryptography: the rotor-based enciphering machine. Then there's Herbert O. Yardley. In 1929 he was left jobless when the U.S. government summarily dissolved his code-breaking agency (known as the Black Chamber). After he ran out of money, the irreverent, womanizing raconteur and gambler wrote a tell-all book that captivated the nation but infuriated his former colleagues. Later, Yardley sold his cryptanalytic services to the Chinese and authored another book about his experiences as a poker player.

But personal details are just the icing on the cake of Kahn's thorough analysis of the origins of modern cryptography. This analysis becomes particularly absorbing when it describes Renaissance Italy, where a small group of dilettantes pioneered the kind of cipher that is now called polyalphabetic substitution. Cryptology was a booming business there, a consequence of the sharp competition and vendettas among the many city-states and various powers of the Roman Catholic Church.

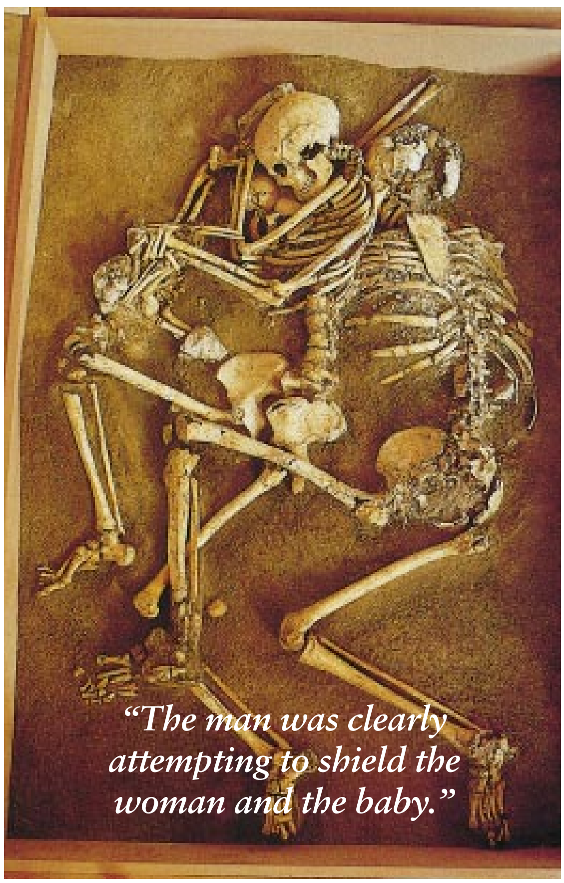
Kahn's narrative is also very strong on World War II and especially on U.S. penetrations of Japanese communications just before the "date which will live in infamy." He describes many tricks of the cryptanalytic trade and notes that at the height of tensions immediately before the Pearl Harbor bombing, an American janitor in Washington, D.C.,

THE ILLUSTRATED PAGE

Eyewitness to Discovery
EDITED BY
BRIAN M. FAGAN
Oxford University Press, 1997
($55)

The words of those who helped to make history have an immediacy that outweighs any probable lack of polish. And so it is with archaeology: from Champollion, the decipherer of the Rosetta Stone, to Konrad Spindler, who examined Otzi (the Neolithic corpse found in a glacier in 1991), 50-odd discoverers tell of their finds. Their stories are by turns chilling or prosaic: David Soren and Jamie James describe an ancient Roman couple and a baby (*right*), crushed by debris during an earthquake; Stuart Streuver notes that paleo-Indians along the Illinois River had a marked fondness for black walnuts.

This volume will awaken interest in rediscovery of the past or feed the curiosity of those already hooked. —*Paul Wallich*



"The man was clearly attempting to shield the woman and the baby."

MARTHA COOPER *Peter Arnold, Inc.*

BRIEFLY NOTED

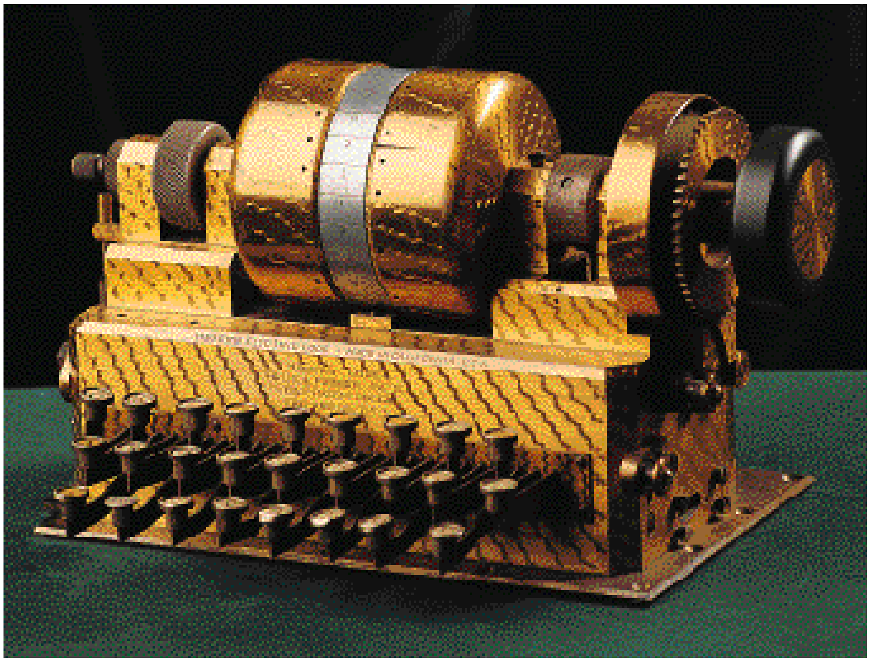
Continued from page 110

MASTERS OF BEDLAM, *by Andrew Scull, Charlotte MacKenzie and Nicholas Hervey. Princeton University Press, 1996 ($35).*
At the opening of the 19th century, care of the mad in England (as elsewhere) still took the form of barbaric incarceration. As straitjackets replaced iron fetters and "moral treatment" supplanted cupping and leeching, asylums both public and private became almost respectable. "Mad doctors"—who also became more respectable—even cured some of their patients. This scholarly narrative traces the lives of the half dozen or so physicians who played leading roles in the transformation of the concept and treatment of lunacy.

FANTASIA MATHEMATICA. *Edited by Clifton Fadiman. Copernicus, 1997 reissue ($19).*
Some of the plots may be dated (the original appeared in 1958), but this anthology of mathematically oriented short stories and poems should delight a new generation of readers. Although it is still impossible to arrange a map that requires just five colors or to paint only one side of a Möbius strip, the progress of mathematics has rendered at least one tale untenable: if you are making a sucker bet with the devil, don't demand a proof of Fermat's Last Theorem.

COMET OF THE CENTURY: FROM HALLEY TO HALE-BOPP, *by Fred Schaaf. Copernicus, 1997 ($29).*
Although neither as prominent nor as feared as they once were, comets still exert a magical draw even in today's light-polluted skies. The current apparition of Comet Hale-Bopp offers a chance to experience firsthand what is so compelling about these unpredictable, ghostly visitors. Two chapters here are devoted to Hale-Bopp, including an observer's guide (useful now but soon to be obsolete). The rest of the book offers a more durable introduction to the history, science and lore of comets, all related in an agreeably chatty style.

PAUL OSTWALD



STEVE GOTTLIEB

SEMINAL ENCIPHERING MACHINE was built around 1920 by Edward Hugh Hebern. It used a single rotor (top, center) *to complicate the enciphering pattern. Such machines were used until the 1960s.*

regularly dusted the Japanese embassy's ultrasecret "Purple" cipher machines—the objects of the most massive U.S. cryptanalytic effort of the war. It is hard to say which is more incredible: that the Japanese allowed the man into their code room or that U.S. intelligence failed to capitalize on that happenstance.

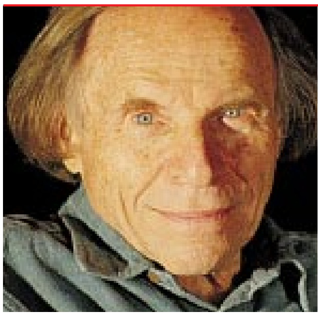
My only disappointment with this new version of the book stems from the fact that its "revised and updated" status is justified by a single, 15-page chapter that serves almost as an addendum to the original text. This final chapter breezily summarizes a few important revelations and developments that have occurred in the three decades since the original release. Kahn describes Ultra, the stunning British effort, based on earlier Polish and French work, that cracked Germany's wartime Enigma ciphers. He also writes about the Data Encryption Standard, a commercial encryption scheme promulgated in the U.S. in 1977, and about public-key cryptography, a method that uses different keys for encryption and decryption.

Missing or barely mentioned in *The Codebreakers* are a few issues that begged for Kahn's insights. Foremost among these are the revelations concerning the British invention of the Colossus proto-computers during World War II to solve German ciphers known as Tunny (tuna) and Sturgeon; the John Walker spy case, the trial of which dredged up tantalizing details regarding cryptology late in the cold war era; and cryptology during the Persian Gulf War. (Indeed, hardly anything at all about the modern encipherment of Arabic language exists in the open, English-language press.)

Kahn could have profitably compressed or excised some of the more obscure topics from the lengthy text and woven information about the new disclosures into the narrative where they more properly belonged. And although his work is a history, it would have benefited from longer discussions not only of public-key cryptography but also of the current controversy in the U.S. over what kinds of enciphering systems people are allowed to use or sell overseas.

Those who are not already familiar with cryptology—the bulk of the book's probable audience—are not likely to be bothered by these omissions. Anyone interested in mathematics, history, international affairs or espionage is in for a massively entertaining and illuminating experience.

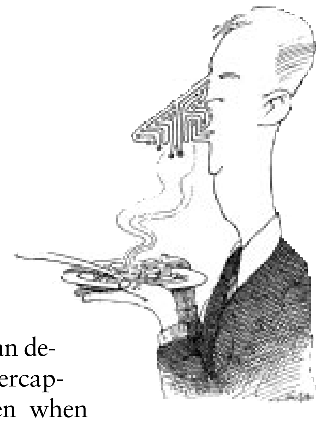
GLENN ZORPETTE is a staff writer for Scientific American.



WONDERS

by Philip Morrison

The Silicon Gourmet



DUSAN PETRICIC

Strange but enlightening news is at hand to help explain our human sense of smell. Worldwide, the industry of flavors and fragrances is beginning to employ workable, if still naive, PC-based simulators capable of the subtle discriminations made by the human nose. There are many sensor types that show reproducible electrical responses to small amounts of odorant vapors. (One early instance uses semiconductors that run quite hot. They vary in resistance when sample molecules oxidize on the conducting surface.) Yet these are still no match for the discerning power of the host of olfactory cells hidden in the nose.

The aggregate reports from a small collection of such assorted sensors, each with its own response to a great many odors, can be extracted by a number of mathematical weighting procedures, made verifiable mainly by their agreement. The most general means is through "neural network" computation. This wide class of unusual computer programs has a long history, dating back 30 years to a kind of computer called the perceptron. Such programs march to no firm clockbeat, carry out no precise logical chains, tolerate substantial error and indecision, and learn best from patterns shown to them as examples. (To be sure, they are usually realized on a PC program, designed to simulate the intertwined multiple feedback loops of the neural-network process.)

Simpler, analytical methods, such as the most sensitive versions of gas chromatography, can and do compete usefully, once a question can be chemically defined—say, determining the presence or absence of a few significant picograms of TNT. That is why specific chemical sensors have proved useful for security and in industry. But untiring, automated new electronic noses take a minute or two to judge complexity and can work on-line at quality control 24 hours a day.

Neural nets perform best when the task is to assess complex odors that defy description. A few examples: the artificial noses have routinely classified cheeses as acceptable Tilsit, Gruyère or Cheddar, distinguished the freshness of fish filets by estimating the number of days since the catch and identified varieties of chocolate in the vapor of melted candies. Each such program must be "trained" for its judgments by seeking to match decisions made by a jury of human experts. For the practical cases above, using a dozen or two varied sensors each, some 30 training inputs have been enough to ensure that the next try of the silicon gourmet will agree nine times out of 10 with the judgment of the carbonaceous gourmets on the panel. That is no less consistent than decisions by different expert juries. Will such systems one day steadily monitor the complex changing pollutants of urban air? Can a really savvy network compare vintages and sunny slopes?

The total population of a sniff is a billion trillion molecules.

Now for a closer examination of your own sense of smell. Take a good whiff. Your nose samples a small teacup volume of air, along with any odorous contaminants. One faint but familiar example of odor is the telltale of a slight gas leak. The major constituent of natural gas, however, is quite odorless methane. What betrays "gas" is a deliberately added unpleasant odorant, chosen for its effectiveness in trace amounts. (Usually it is the smallish molecule ethyl mercaptan, which differs from ethyl alcohol only in that a single sulfur atom has replaced the alcohol's single oxygen.) Humans can detect mercaptan even when its molecules are outnumbered a billionfold by plain air.

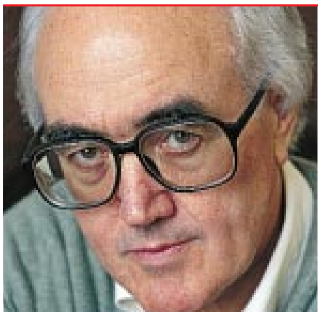
But in each breath we take, molecules pass in daunting multitudes. The total population of a sniff is a billion trillion molecules, nearly all of them normally in the mix we call air. The mercaptan in one sampling of a minimal gas leak counts up not to just a few odorant molecules but to a trillion of them!

Dogs are proverbially and in fact much better at odor detection than humans are. (Training makes a real difference in both species.) The K-9 Corps sniffers can detect many substances reliably at molecular counts thousands of times smaller than our best, a billion molecules or so.

Yet the wonderfully brushy antennae of certain large moths are chemical sensors more sensitive by far. The specialized moth antenna fibers respond to an airstream marked by only a few hundred scent molecules. Such virtuosity must be highly prepared at both the transmitter and at the receiver. The signal molecule of the sphinx moth, for instance, is a specific chain of 16 carbon atoms, generated in a female moth gland. The tale that a single molecule of the right kind can be sensed by an eager male moth seems exaggerated, for the signal must be suitably intermittent. This is chemical narrowcasting.

We humans almost surely have our own pheromones as well. A special auxiliary olfactory system, present in the nose mainly in utero and infancy, may play such a role. But a lifelong sense of smell is and must instead be built of a "wideband" set of detectors versatile enough to characterize an organism's varied chemical environment in life.

Continued on page 115



CONNECTIONS

by James Burke

Feathered Friends

DUSAN PETRICIC

I was reading John Keats's "Ode to a Nightingale" the other evening (well, why not?), and I was reminded of how nobody ever told us when I was at school that the English didn't invent Romanticism. That it all started in late 18th-century Germany with a group of scientist-scribblers in Weimar, most of whom had "domestic problems." People like Goethe (didn't), Friedrich W. J. Schelling (did) and the brothers August and Friedrich von Schlegel (both did).

It was August (whose wife was fancied by August's brother, till she ran away with Schelling) who formalized the rules of Romanticism for everybody hopping on the bandwagon, including Keats. Anyway, in 1804 August had the misfortune to fall for the queen of the chattering classes, Madame Germaine de Staël, famous for low-cut necklines, opinionated views on everything, and being on the run from the French police.

Poor old Schlegel was to spend the rest of his life chasing around Europe being Madame's lapdog and wishing she didn't have all those lovers. In between whom she managed to write a major work on German culture and a novel of "experience" and make an enemy of Napoléon with some caustic comments about emperors. Which was why she was on the run from his national security services. It's ironic he should have taken quite so much against her, given that it had been largely because of the inability of her father, Jacques Necker, to manage the French budget when he was finance minister that the events that brought Napoléon to power happened at all.

In 1778, before the French went revolutionary, Necker got a request from a Swiss inventor named François Argand, who had a new process for distilling brandy and wanted a monopoly in southern France in return for making the technique available. Necker agreed, and by 1782 Argand had three distilleries up and running. And problems with night shifts. So, being an inventor, he invented a light (on which I offered illumination in an earlier column). Given the fact that contemporary industrial revolution England was where it was all happening, technology- and marketwise, by 1784 Argand was having his lamps made there by a guy called Matthew Boulton. This canny type ran a factory in Birmingham, now turning out everything from Argand lamps to shoe buckles to medallions to steam pumps (Boulton's partner was James Watt).

Watt's steam pumps were so successful because they worked so well, thanks to the help he got, when he was Glasgow University repairman, from a chemistry professor called Joseph Black. Who'd done some whisky-making experiments and discovered latent heat, which inspired Watt's idea of the separate condenser that made his steam pump the best. Another of Black's protégés was James Graham, a medical student who went on to fame and fortune with quack electrical cures at his Temple of Health in London, where he employed a young ex-hooker, Amy Lyon.

One of the greater examples of history's connections comes home to roost.

After passing through the clutches of various aristocratic rakes, Amy eventually ended up as Emma and mistress, then wife of Sir William Hamilton, British minister to the Court of Naples. In Italy Sir William started "collecting" antique vases and stuff found in the newly excavated ruins of nearby Pompeii and Herculaneum. From time to time he would amass enough bootleg Roman crockery and broken Greek heads to put together a catalogue for discerning and well-heeled buyers in London. One of these books of Classical bric-a-brac inspired the English potter Josiah Wedgwood to design his famous Neoclassical dinner sets used by queens and for good publicity reasons named "Queen's ware."

On bright, moonlit nights Wedgwood joined a crowd of liberal thinkers, Freemasons, Quakers and the like, who would travel hill and dale to sit around in somebody's house and discuss everything from science to the latest doings of the rebels in America. A colleague of Wedgwood at these "Lunatic Society" meetings (they met at full moon), a Joseph Priestley, was, in time, to suffer for his support of the Americans by having his lab burned down by a mob.

In 1798 Priestley found himself across the Atlantic, among the Yanks he so admired. As one of the very few eminent European scientists to have done such an emigratory thing, he was wined and dined on all sides. On one such occasion at Yale, he bumped into and impressed the pants off a nervous young chemistry professor named Benjamin Silliman. Being a bit of a hypochondriac, Silliman was into "curative medicaments," so Priestley (inventor of soda water) was an instant role model. The fact that soda water was supposed to remedy all known disorders encouraged Silliman into a disastrous soda-fountain venture in New York. Luckily for him, it was his mother's money.

The Silliman family made up for this pseudoscientific blooper when, in 1855, Benjamin Silliman II analyzed some sludge oozing from a creek in Pennsylvania and pronounced it to be "rock oil," later known as petroleum. There was only one problem with this amazing new energy source. What was the source? And how could you find more? Fortunately for would-be oil barons, the answer was at hand thanks to the work of somebody whose stultifying single-mindedness had already burst on an astonished world back in 1826.

Alcide D'Orbigny had spent the previous seven years preparing a large work on a small subject: the thousands of different species of the fossil marine microorganism foraminifera. These jobbies range from the supermicroscopic (0.01 millimeter) to the gigantic (100 millimeters). And the profitable thing about foraminifera is that where two or three dead ones are gathered together, so to speak, there's likely to be oil close by. That's partly why much oil exploration consists of people getting eyestrain.

D'Orbigny grew up in the small Loire village of Couëron. A boyhood pal of his was a chap who shared Alcide's passion for natural history, and the two of them spent happy days on the banks of the Loire hunting for birds' eggs. Because the other guy also had a talent for drawing and was as crazy about live birds as D'Orbigny was about dead bugs, he started to sketch (and then to paint watercolors of) almost anything with plumage. After he moved to the U.S., this childhood hobby would end up making him world famous among 19th-century naturalists. And equally well known today to anybody who's gotten up on a raw winter's morning to count migrants on the wing.

The fact that our painter was no good at figures may account for why, early in his career, he was such a disaster with investments. At one point, in 1812 or so, before he hit the jackpot with his pictures, James J. Audubon was living in Louisiana and got involved with a venture to run steamboats on the Mississippi. The whole speculative schemozzle ran aground and took with it the life savings of a couple of young English immigrants named George and Georgiana who had come to America shortly after their wedding. I don't know what happened to the newlywed newly bankrupts, but the husband's famous brother wrote to them from England saying, in effect: "Audubon had better hope we don't ever meet on a dark night."

Guess who the brother was (and this is one of the greater examples of history's connections coming home to roost)? John Keats. Well, gotta fly. SA

Wonders, continued from page 113

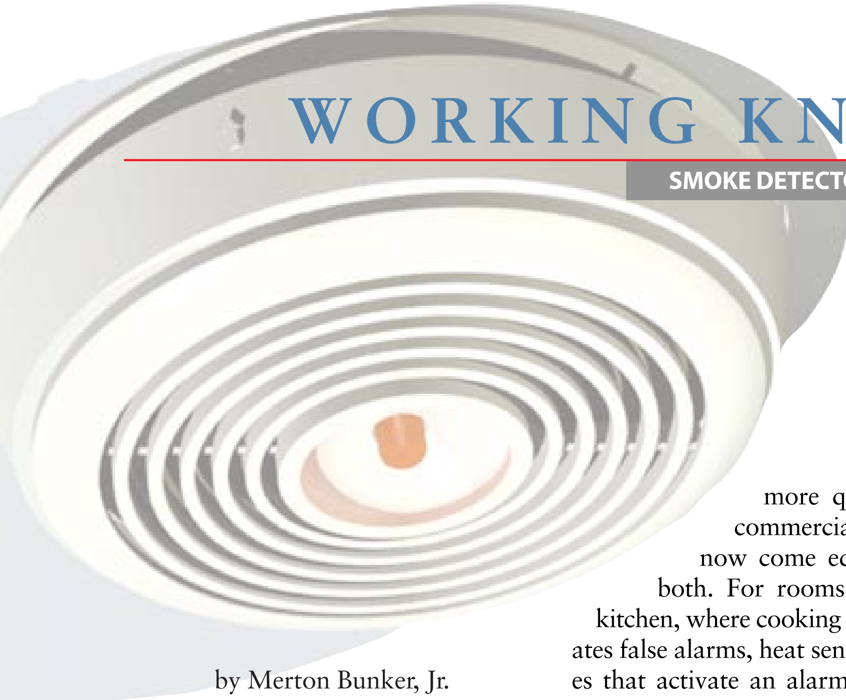
Open either eyelid, and the eye lens projects an optical image on the active photosensory screen we call a retina. Analogously, with every intake of our breath, air flows up to the arched top of each nasal passage, where we have a pair of mucus-covered olfactory patches, each the size of a thumbnail. In mature life, each of your two patches is occupied by some three million receptor cells buried only skin deep. Each receptor sends a tiny dendrite to feather out into a few dozen tendrils on the wetted surface. Together these tendrils cover the olfactory patches, set to sample intimately whatever molecules may diffuse into the special watery mucus. Every receptor cell also sends one nerve fiber upward an inch or two. These fibers, bundled into scores of fine cables, carry their electrochemical pulses through small holes in a thin bone plate to join one of the left-right pair of olfactory bulbs at the very front of the brain.

The ways we process visual images and olfactory impressions are quite different. Smell has no simple counterpart to the three basic color sensors of the retina. The optic nerve that carries the retinal output to the brain is a thick cable with a million signal paths. Each retinal receptor remains traceable as its signal traverses that living cable. Even within the brain itself, the output of a small retinal patch can be traced as it is relayed again and again, until finally layers with more complex signal processing are reached.

The space of odors is home to no such simple mapping. Even a natural dimensionality seems absent; long efforts to choose a limited number of basic odor dimensions have led nowhere. The best recent work suggests there are 1,000 or more distinct odor receptor types in the nose; many neurons each respond to many odors. Diversity counts more than any defining set of basic stimuli. And the neural pathways found in the olfactory bulb are visibly tangled and loopy.

Details are not plain as yet, but we can already scent best-bet associations made by a complex neural network. This most ancient sense seems to be processed at once by such a network, one not encountered in the hardwired visual system until much higher, more intricate levels of the brain are reached. SA

SMOKE DETECTORS



by Merton Bunker, Jr.

In the late 1930s the Swiss physicist Walter Jaeger tried to invent a sensor for poison gas. He expected that gas entering the sensor would bind to ionized air molecules and thereby alter an electric current in a circuit in the instrument. His device failed: small concentrations of gas had no effect on the sensor's conductivity. Frustrated, Jaeger lit a cigarette—and was soon surprised to notice that a meter on the instrument had registered a drop in current. Smoke particles had apparently done what poison gas could not.

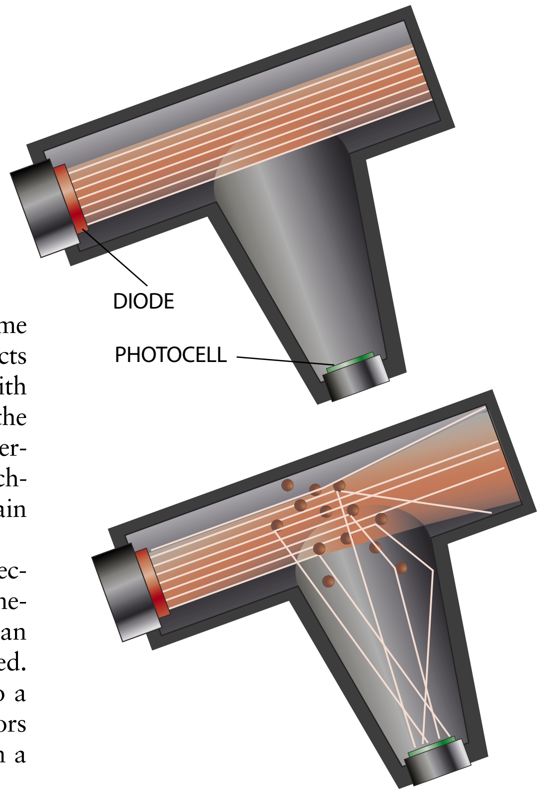
Jaeger's experiment was one of the advances that paved the way for the modern smoke detector. It was 30 years, however, before progress in nuclear chemistry and solid-state electronics made a cheap sensor possible. The first commercial smoke detectors came to market in 1969. Today they are installed in 93 percent of U.S. homes.

Smoke detectors fall into two major classes. Ionization detectors, the most common units, trigger an alarm after smoke particles attach themselves to ionized air molecules. In contrast, a photoelectric unit can detect light that is scattered by smoke particles onto a photocell, thereby initiating an alarm. In another type of photoelectric device, smoke can block a light beam. In this case, the reduction in light reaching a photocell sets off the alarm.

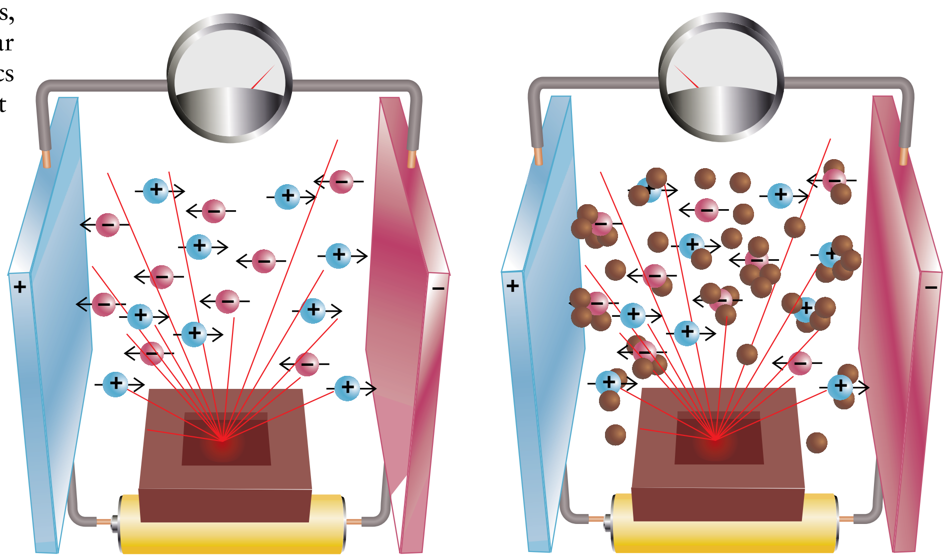
Ionization detectors respond faster to flaming fires than do photoelectric detectors, which sense smoldering fires more quickly. Some commercial products now come equipped with both. For rooms such as the kitchen, where cooking smoke generates false alarms, heat sensors—switches that activate an alarm at a certain temperature—are most appropriate.

The simple technology of fire detection has continued to undergo refinement. Alarms with strobe lights can even awaken the hearing impaired. These measures have contributed to a heartening statistic: smoke detectors have reduced the chance of dying in a fire at home by roughly half.

MERTON BUNKER, JR., is the senior electrical engineer for signaling systems at the National Fire Protection Association. The association produces the National Fire Codes, which includes a standard for fire alarms.



PHOTOELECTRIC DETECTOR functions by employing a light-emitting diode that sends a beam of light unimpeded across a chamber (*top*). When smoke enters, light scatters in all directions. A photocell at an angle to the diode senses the light and sets off an alarm (*bottom*).



ILLUSTRATIONS BY MICHAEL GOODMAN

IONIZATION DETECTOR operates by ionizing air molecules (*pink and blue spheres*) with alpha particles from a radioactive material, americium 241 (*red lines*). The ions then carry a small current between two electrodes (*left*). Smoke particles (*brown spheres*) attach to the ions (*right*), thus reducing current flow and initiating an alarm.

