SIGN LANGUAGE AND THE BRAIN ▪ HOW DO FLIES FLY? (SEE P. 48)

# SCIENTIFIC AMERICAN

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## The Paradox of the Sun's Hot CORONA

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A Low-Pollution Engine

North to Mars!

Controlling Hair Growth

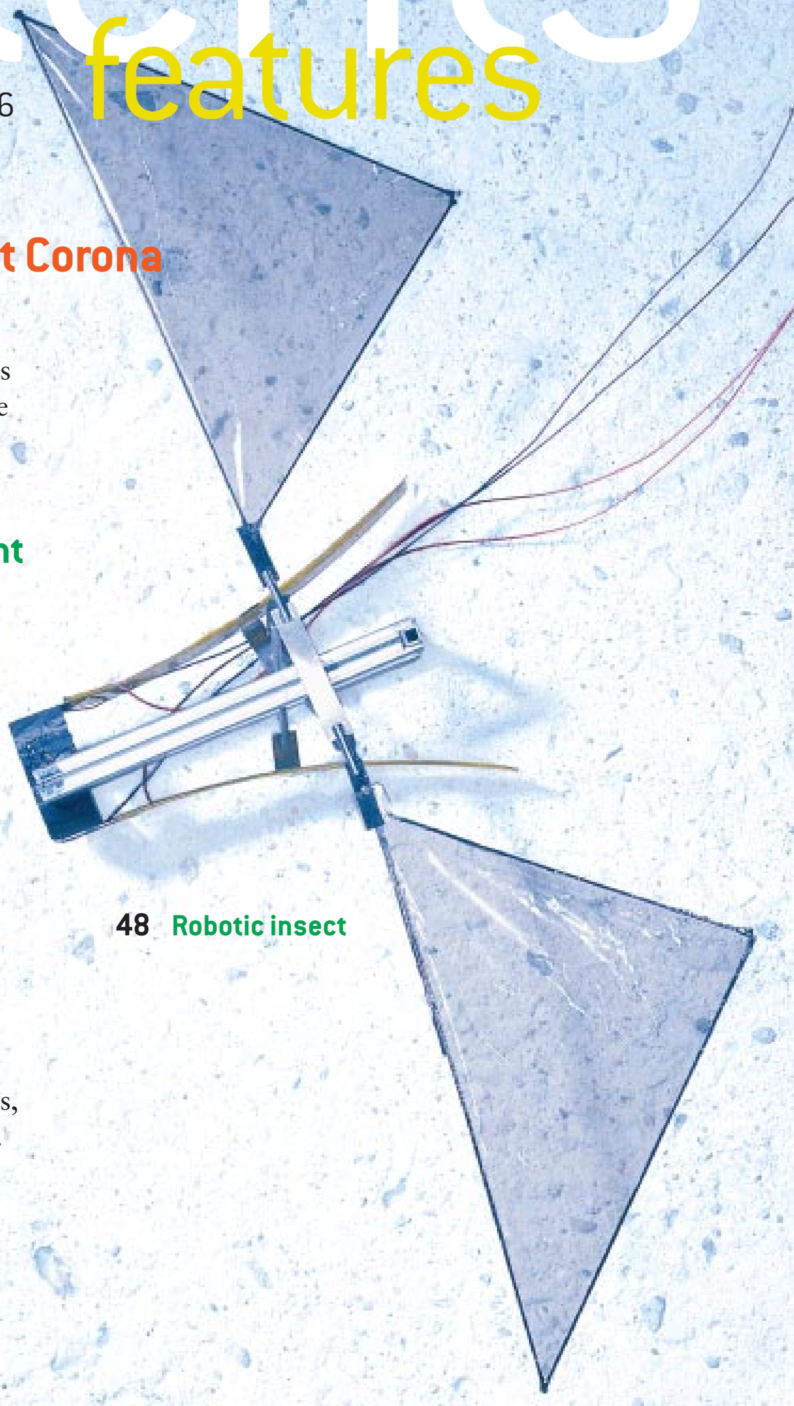
june 2001

# contents

## features

SCIENTIFIC AMERICAN Volume 284 Number 6





48 Robotic insect

Volume 284 Number 6

# departments



24

24D

38 Marcia K. McNutt, head of MBARI



# columns



**Cover ultraviolet image by NASA Goddard Space Flight Center, showing ionized helium at 60,000 kelvins, taken by SOHO on September 14, 1997; preceding page: Timothy Archibald; this page (*clockwise from top left*): The Boeing Company; Mark A. Garlick; Edward Caldwell**

# SA Perspectives

## Faith-Based Reasoning

**Scientists are often lampooned** as living in an ivory tower, but lately it seems that it is the scientists who are grounded in reality and the U.S. political establishment that is floating among the clouds. In March the Bush administration gave up a campaign promise to control emissions of carbon dioxide and withdrew U.S. support for the Kyoto Protocol. “We must be very careful not to take actions that could harm consumers,” President George W. Bush wrote in a letter to four Republican senators. “This is especially true given the incomplete state of scientific knowledge of the causes of, and solutions to, global climate change.”

PEACEKEEPER ICBM test

ROGER RESSMEYER *Corbis*

Yet incomplete knowledge doesn’t seem to be a concern when it comes to strategic missile defense. After another failed test last summer, candidate Bush issued a statement: “While last night’s test is a disappointment, I remain confident that, given the right leadership, America can develop an effective missile defense system.... The United States must press forward to develop and deploy a missile defense system.” And press forward he has. The U.S. is reportedly on the verge of withdrawing unilaterally from the 1972 Anti-Ballistic Missile Treaty.

In one case, the president invokes uncertainty; in the other, he ignores it. In both, he has come down against the scientific consensus.

Presidents, needless to say, must protect the country’s economic interests and shield the nation from nuclear death. That is precisely why the administration’s inconsistency is so worrisome. Ample research indicates that human activity is the main cause of global warming. Estimates of the economic damage by midcentury range in the hundreds of billions of dollars per year—uncertain, to be sure, but if you’ve been smoking in bed, it makes sense to take out some fire insurance. Kyoto is far from perfect; its emissions targets represent a diplomatic agreement rather than any careful weighing of cost and benefit. But it is a start.

Regarding strategic missile defense, researchers’ best guess is that a reliable system is infeasible. The burden of proof is now on the proponents of missile defense. Until they can provide solid evidence that a system would work against plausible countermeasures, any discussion of committing to building one—let alone meeting a detailed timeline—is premature. It is one thing for a software company to hype a product and then fail to deliver; it is another when the failure concerns nuclear weapons, for which “vaporware” takes on a whole new, literal meaning.

Perhaps the most exasperating thing about missile defense is how the Bush administration has so quickly changed the terms of the debate. Journalists and world leaders hardly ever comment anymore on the fundamental unworkability of the system or the many ways it would fail to enhance security. Now the talk is of sharing the technology so that other countries, too, could “protect” themselves.

It would be nice not to have to shell out money for emissions controls. It would be nice to have a magic shield against all nuclear threats. It would be nice to be perfectly sure about everything, to get 365 vacation days a year and to spend some of that time on Mars. But we can’t confuse wants with facts. As Richard Feynman said, “Science is a way of trying not to fool yourself.” The dangers of ignoring its messages are greater than merely making politicians look foolish.

**THE EDITORS** editors@sciam.com

# Letters

EDITORS@SCIAM.COM

**"I HAVE X ENVY after reading 'Why the Y Is So Weird' [by Karin Jegalian and Bruce T. Lahn]," protests Lane Yoder of Kaneohe, Hawaii. "I learned that the human Y 'fell into such disrepair' that it is now in a 'severely shrunken state,' a 'shadow of its original self.' The X maintained its 'integrity' by recombining with other Xs. A scientist across the Freudian divide might describe the findings differently: Abstaining from the entanglements of DNA swapping, the human male chromosome brought forth a few highly evolved genes. The estranged X's indiscriminate coupling with other Xs condemned it to the primitive, bloated state of its reptilian ancestors. We can't expect complete objectivity. Still, it's quite a stretch to say that nature consistently selected a 'failure' that spread to thousands of new species over hundreds of millions of years and now exists in its most extreme form in the most dominant species."**

**Abstaining from this particular entanglement ourselves, we invite you to check out others, in letters about the February issue.**


## (WHAT YOU DIDN'T THINK YOU WANTED TO KNOW ABOUT) RECYCLED WASTEWATER

**The use of effluent** recycled as drinking water is hardly unique to such water-short areas as Namibia ["How We Can Do It: Waste Not, Want Not," by Diane Martindale]. Every major river in the world carries someone's treated effluent downstream to another community's source of drinking water. In California several indirect potable-water-recycling projects—those that would put recycled water into underground aquifers or surface water reservoirs—have been derailed because of local politics and the "yuck" factor when a project is labeled as "Toilet to Tap."

This public concern persists despite the fact that two of the state's major sources of drinking water now contain recycled wastewater: the Colorado River receives the treated effluent from Las Vegas, and the Sacramento/San Joaquin Delta is downstream of the discharge of dozens of Central Valley communities. Several Southern California projects recycle more than 170,000 acre-feet of highly treated effluent every year into underground water supplies used by three million to four million people. Some of these projects have operated safely and reliably for nearly 40 years.

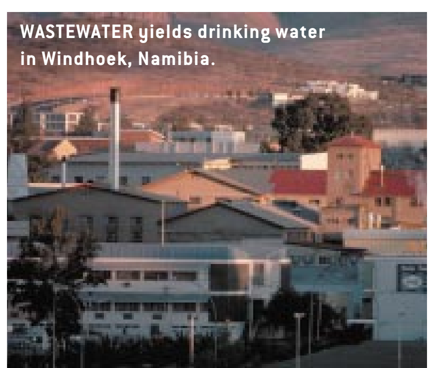
ROBIN G. SAUNDERS
Vice President, Northern California Chapter
WateReuse Association
Santa Clara, Calif.

## UNPERSUADED

**Is Robert B. Cialdini** ["The Science of Persuasion"] really trying to tell us that 17 percent of our population is willing to chaperone juvenile delinquents on a day trip to the zoo? Where I live the schools have a hard time getting chaperones to take a group of first-graders to the museum. If your numbers are correct, then there would be no need for social programs to help the needy, bring meals to the terminally ill or read to the aged in nursing homes. All we'd have to do is put a few people on the street asking passersby if they would be willing to spend a few nights alone in a cell with an inmate on death row. Once they rejected that, then we'd have 50 percent of the population volunteering for whatever we could dream up for social reform.

JOHN LOMAX
Novato, Calif.

*CIALDINI REPLIES: We solicited volunteers with an in-person, one-on-one request: "We're recruiting volunteers to chaperone a group of kids from the County Juvenile Detention Center on a*


WASTEWATER yields drinking water in Windhoek, Namibia.

PETER JOHNSON Corbis

*trip to the zoo. It would be voluntary, unpaid and would require about two hours of one afternoon or evening. Would you be interested in being considered for one of these positions?"*

*Increasingly, charity and community-based requests occur in an impersonal fashion. There is clear evidence that face-to-face, one-on-one requests are most successful; second best are phone requests, and third best are written requests. Why have requesters chosen the less effective media? It is simply easier to use impersonal routes; moreover, it is possible to reach many, many more people that way. Therefore, even though the* percentage *of compliers drops significantly, the overall* number *of compliers can actually be higher. The combination of ease of implementation and reach has triumphed over impact of contact.*

## PYTHAGORAS, PLATO AND EVERYTHING

**If a "theory of everything"** ["100 Years of Quantum Mysteries," by Max Tegmark and John Archibald Wheeler] were to be totally mathematical, with "no concepts at all," perhaps the best interpretation of this would be Pythagorean. That is, to date we have assumed that the mathematics describes some reality that is going on; this has led to all sorts of mental gymnastics about what electrons and the like are "really" doing between observations—gymnastics that have gotten us into all kinds of trouble, not to mention many-worlds, consistent histories, "rampant linguistic confusion" and even Zen.

All this results from assigning a descriptive role to mathematics. Perhaps, following Pythagoras, we should assign a *prescriptive* role to the math: assume the equations are real and that matter is formless and comports itself in accordance with them. That is, the equations do not describe what matter does; rather, they tell it what to do.

ALBERT S. KIRSCH
Brookline, Mass.

***TEGMARK REPLIES:*** *With such a viewpoint, which might also be termed Platonic, the mathematical structure encapsulated by the equations wouldn't merely describe the physical world. Instead this mathematical structure would be one and the same thing as the physical world, and the challenge of physics would be to predict how this structure is perceived by self-aware substructures such as ourselves.*

## IN FORESTS, THE OLDER THE BETTER

**Several points made** in "Debit or Credit?" by Sarah Simpson [News and Analysis] lose sight of the fact that forests can contribute legitimately to lasting reductions in atmospheric carbon dioxide. We can continue to manage forests in the usual fashion globally (where deforestation is the second-largest source of $CO_2$) and nationally (where the forest sink has been declining for the past decade), or we can take the positive steps envisioned in the Kyoto Protocol, which calls for the maintenance and enhancement of existing forests. Significant and long-lasting gains can be made by reducing carbon emissions from deforestation and by enhancing carbon stocks through maintaining older forests. In the next 50 years these gains will be far larger than those from newly planted forests.

SANDRA BROWN
Winrock International
Corvallis, Ore.

LAURIE A. WAYBURN
President, Pacific Forest Trust
Santa Rosa, Calif.

**ERRATUM** Re "How We Can Do It: Leaking Away," by Diane Martindale]: Volt VIEWtech ended its involvement with New York City's Residential Water Survey Program in 1995. The program is currently overseen by Honeywell DMC Services.

# 50, 100 & 150 Years Ago

## Hormones ▪ Howitzers ▪ Horsepower

### JUNE 1951

THE IDIOT BOX—"A survey of the programs on TV was recently carried out in preparation for public hearings to be held before the Federal Communications Commission. Science and informational programs amounted to about three percent of one week's broadcasts. But most of the entertainment programs did not rise above the rut of two-dimensional formula productions. A depressingly large proportion of the 'entertainment' offered on TV was uninspiring, monotonous and ultimately derogatory of human dignity."

NOTEWORTHY CHEMISTRY—"The Harvard University chemist Robert B. Woodward last month announced an achievement that was at once recognized as a milestone in the history of chemistry—the total synthesis of a steroid. Woodward's steroid is strictly a synthetic product, not identical with any natural substance. But because one steroid has been converted into another in a number of cases, the achievement opens the way to the complete synthesis of natural steroids such as cortisone, testosterone and progesterone. From the synthetic steroid it may be possible to produce cortisone in a few simple chemical steps. Cortisone is now made in 37 steps from a component of bile that is so scarce that it takes 40 cattle to supply one day's cortisone for an arthritic patient."

### JUNE 1901

KRUPP ARMAMENTS—"The Krupp metallurgic establishments, in the Ruhr River basin, now form the greatest works in the world. On the first of April, 1900, the number of men employed by Friedrich Krupp was 46,679. At the end of 1899 the steel works of Essen had manufactured and sold 38,478 guns. The Krupp works do not limit their activity to the manufacture of guns, ammunition and accessories, but produce also what a pamphlet, published at Essen, calls 'peace material'—that is to say, car wheels, rails, steel castings for steamships, etc."

YELLOW FEVER—"The Surgeon-General of the United States Army has approved the report of a special medical board, which has reached the conclusion that the mosquito is responsible for the transmission of yellow fever. The medical department is moving energetically to put into practical operation the methods of treatment for prevention of yellow fever. The liberal use of coal oil to prevent the hatching of mosquito eggs is recommended." [*Editors' note: The report was submitted by U.S. Army bacteriologist Walter Reed.*]

A ONE-HORSEPOWER "IT"?—"Our illustration shows a most curious invention by Mitchell R. Heatherly of Mundell, Kansas: a single-wheel vehicle. The contrivance consists of a curved tongue pivoted to the harness, bearing a single wheel. Above the axle of the wheel are stirrups for the rider or driver."


BEFORE SCOOTERS: A single-wheel idea, 1901

FROM SCIENTIFIC AMERICAN

### JUNE 1851

IRON AGE OF SHIPS—"For Lord Jocelyn's steam navigation committee in England, Captain Claxton gave evidence in favor of iron steamers and of the screw, which, he avers, must ere many years elapse be applied universally as the motive power of sea-going vessels. The advantages which he ascribes iron-built vessels being durability, inexpensiveness in repairs, greater capacity in proportion to tonnage than wooden vessels, healthiness, and swift sailing. As for durability, he described the state of the *Great Britain*, lying for many months exposed to a series of heavy gales in Dundrum Bay, Ireland."

TOPICAL ANESTHETIC—"The difficulty in the use of chloroform thus far has been the danger of suffocation, or of otherwise injuring the body by a total stoppage of some of its function. A new application claims the merit of escaping the danger, according to the scientific critics in Berlin. The fluid (some 10 to 20 drops) is dropped on the part affected or on a lint bandage, and then bound up in oil silk. After from two to ten minutes the part becomes insensible, and the pain is no longer felt, whether it be from rheumatic, nervous, or other disorders."

FALSE LIGHTS—"Three years ago there was nothing heard of in England but 'Staite's Electric Light.' It was patented, published, and puffed from one end of the world to the other. It was to send all the gas companies into Egyptian darkness in short order, and so potent was the sympathetic influence of the excitement (for the shrewdest and wisest are subject to such influences) that the stocks of gas companies were at a very low discount. Well, a few weeks ago this Electric Light became insolvent, and it was executed by a number of indignant creditors."

PUBLIC HEALTH

# A Touch of Poison

THE EPA MAY WEAKEN A REGULATION LIMITING ARSENIC IN WATER **BY MARK ALPERT**

**Arsenic has long been used** as a poison, most famously by the pair of elderly aunts in the play *Arsenic and Old Lace*. The murderous spinsters added a teaspoonful to a gallon of wine, but it takes a lot less than that to prove fatal. Scientists have discovered that arsenic may be hazardous even in the minute quantities found in many wells and municipal water systems in the U.S. In January, just before President George W. Bush took office, the Environmental Protection Agency finalized a long-awaited regulation reducing the amount of arsenic allowed in drinking water from 50 micrograms per liter—the U.S. standard since 1942—to 10 micrograms per liter, which is the standard used by the European Union and the World Health Organization. But in March the EPA—under the new leadership of Bush's appointee, Christie Whitman—withdrew the pending rule. And in April the agency asked the National Academy of Sciences (NAS) to reassess the research on arsenic, delaying a final decision until February 2002.

The scientists who have studied arsenic's health effects immediately assailed Whitman's decision. A growing number of epidemiological studies indicate that drinking arsenic-tainted water can cause skin, lung, liver and bladder cancers. A 1999 report by the NAS estimated that daily ingestion of water containing 50 micrograms of arsenic per liter would add about 1 percent to a person's lifetime risk of dying from cancer. That's about the same as the additional risk faced by a person who's living with a cigarette smoker. "The evidence against arsenic is very strong," says epidemiologist Allan H. Smith of the University of California at Berkeley. "But the EPA has created a false appearance of uncertainty."

Perhaps the best evidence comes from a long-term study of 40,000 villagers in southwestern Taiwan whose wells had high arsenic levels. (Because arsenic seeps into aquifers through the weathering of rocks and soils, it's

ARSENIC-TAINTED water can cause various cancers.

KEVIN HORAN *Stone*

## THE MYSTERIOUS CARCINOGEN

**Arsenic is in food as well as water, but researchers say a typical daily diet contains only 10 to 15 micrograms of inorganic arsenic—the compounds that are hazardous (food contains much more organic arsenic, but that form passes harmlessly through the body). Although toxicologists aren't sure how arsenic attacks the body's cells, a new study by scientists at Dartmouth Medical School indicates that the substance disrupts the activity of hormones called glucocorticoids, which help to regulate blood sugar and suppress tumors. Arsenic interferes with these processes by binding to the glucocorticoid receptors in cells and changing their structure. The study suggests that arsenic, instead of causing cancer by itself, promotes the growth of tumors triggered by other carcinogens. Arsenic-induced effects appeared at concentrations as low as two micrograms per liter.**

generally more concentrated in groundwater than in lakes or streams.) In villages with the most severely contaminated wells, the death rates from bladder cancer were dozens of times above normal. Similar studies in Argentina and Chile later corroborated those findings. In a region of northern Chile, for example, researchers determined that 7 percent of *all* deaths among people over the age of 30 could be attributed to arsenic.

In the Taiwan study, the lowest median level of arsenic was 170 micrograms per liter. To determine the risk at the 50- and 10-microgram levels, epidemiologists extrapolated the health effects in a linear way (that is, half the exposure leads to half the cancer risk). Some toxicologists have criticized this approach, saying that arsenic concentrations may have to exceed a threshold level to cause cancer. But new research suggests that if this threshold exists, it is most likely well below 10 micrograms per liter.

In the U.S., most public water systems with high arsenic concentrations are in the western states [*see table at right*]. The EPA originally proposed lowering the arsenic standard to five micrograms per liter, but the agency doubled the allowable level after representatives of the water systems complained about the expense of removing the carcinogen. In the regulation issued in January, the agency estimated that 4,100 systems serving some 13 million people would have to pay a total of $180 million annually to implement the 10-microgram standard. The EPA claimed that the rule would prevent 21 to 30 deaths from lung and bladder cancer each year, but

ABANDONED MINE in Butte, Mont., is laced with arsenic.

WALTER HINICK *Montana Standard/AP Photo*

some epidemiologists say the standard could save 10 times as many lives.

So what prompted the EPA to suddenly call for a reassessment of the standard? Some environmentalists speculate that industry groups such as the National Mining Association, which filed a court petition in March to overturn the arsenic rule, put pressure on the Bush administration. The tailings from mines are often laced with arsenic. Because the EPA's cleanup regulations are based on drinking-water standards, tightening the restrictions on arsenic could vastly increase the cost of decontaminating abandoned mines, many of which are Superfund sites.

Whitman has asked the NAS to review the EPA's risk analysis of arsenic. Many researchers fear that she will use the new report to justify a limit of 20 micrograms per liter, a standard that would cost about $110 million less than the stricter regulation but save only half as many lives. "The weaker standard would not be sufficient to protect public health," says Chuck Fox, who headed the EPA's Office of Water until the change of administrations. "The standard for arsenic should be as close to zero as feasible."



NEED TO KNOW:
## DANGER ZONES

**Large municipal water systems with average arsenic levels above the proposed 10-microgram standard:**

| CITY | ARSENIC LEVEL (micrograms per liter) |
|---|---|
| Norman, Okla. | 36.3 |
| Chino Hills, Calif. | 30.2 |
| Lakewood, Calif. | 15.1 |
| Lancaster, Calif. | 14.5 |
| Albuquerque, N.M. | 14.2 |
| Moore, Okla. | 12.6 |
| Rio Rancho, N.M. | 12.4 |
| Victoria, Tex. | 11.6 |
| Midland, Tex. | 11.1 |
| Scottsdale, Ariz. | 11.1 |

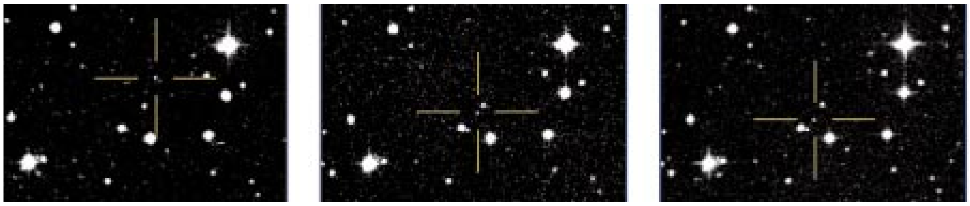
*SOURCE: Natural Resources Defense Council*

ASTRONOMY

# Galactic Archaeology

DIGGING INTO THE MILKY WAY'S PAST EXPOSES ITS LIFE AS A CANNIBAL BY GEORGE MUSSER

**For years, archaeologists** have been speaking the language of astronomers. Remote-sensing techniques have found lost cities; celestial alignments have shed light on temples and pyramids. But lately the flow of ideas has reversed. Astronomers have realized that our galaxy is an intricately layered place—a *Tel Galaxia* that encodes a rich history like buried strata of an ancient city. Celestial excavations are starting to provide a much needed reality check on theories not just of the galaxy but also of the broader cosmos. "It's not all that easy to find experimental verification of these theories," says Heather L. Morrison of Case Western Reserve University. "Studies of the Milky Way



WHITE DWARF, seen drifting across the sky over a period of 43 years, may represent a hitherto unrecognized population of stars.

NIGEL C. HAMBLY *University of Edinburgh*; SIMON T. HODGKIN *University of Cambridge*

can give us some pretty solid constraints."

She and other galactic archaeologists tell layers apart by playing a game of which-stars-are-not-like-the-others. The sun and most other stars swirl around the galactic center within a thin circular disk. Nearly a century ago, however, astronomers noticed that some stars orbit not within a disk but within a sphere—a "halo" that envelops the disk. Halo stars are older than disk stars, and their irregular orbits suggest they formed before material orbiting every which way had a chance to lose energy, flatten out and fall into lockstep.

The disk, the halo—astronomers thought that was all. Over the years, though, and especially in the past decade, they have found strange patterns in the halo: anomalously young stars, stars separated by vast distances yet flying in formation, even entire galaxies embedded within. As for the disk, astronomers have given up talking about "the" disk. There is a thin disk, at least one thick disk and maybe a so-called protodisk—stacked like layers of an Oreo cookie. This mess of a galaxy must have taken shape over time rather than in one fell swoop, as once thought.

This past January one of the ongoing digs, the 2dF Old Stellar Populations Survey, delved into the origins of the thick disk. Rosemary F. G. Wyse of Johns Hopkins University and her colleagues mapped 1,500 sunlike stars located outside the thin disk. Two thirds looked like the usual halo or thick-disk stars. The rest, however, had half the expected amount of orbital angular momentum—in fact, a value characteristic of the Milky Way's small satellite galaxies.

The results argue for an 1980s-era theory that the thick disk arose when the Milky Way devoured one of its satellites. In the process, whatever stars were around at the time got stirred up, puffing the thin disk into the thick disk. Interstellar gas presumably got stirred up, too, but gas (unlike stars) can easily dissipate energy and settle back into a thin disk. Subsequent generations of stars, forged from this gas, constitute the thin disk we see today. A corollary is that no sizable mergers have occurred since the thick disk took shape an estimated 12 billion years ago, although more modest mergers continue to the present day.

Other surveys have focused on the solar neighborhood. Halo and thick-disk stars occasionally pass through, moving at conspicuously high velocities relative to the sun. A whole new breed of interloper has recently emerged: very cool, very dim, very old white dwarf stars. In March, Ben R. Oppenheimer of the University of California at Berkeley and his colleagues reported 38 white dwarfs within 480 light-years of the sun. "This population may trace the oldest building blocks of the galaxy," says Rodrigo A. Ibata of Strasbourg Observatory, who has conducted similar surveys.

Unfortunately, astroarchaeology has a tragic flaw: it does not pin down the full three-dimensional distribution of objects. An intense debate has erupted over whether the skulking dwarfs are part of the halo, thin disk, thick disk or putative protodisk. Similarly, astronomers dispute whether shards from galactic mergers account for the whole halo or just a small part of it. Depending on how these issues shake out, the newly discovered populations could explain the results of dark-matter surveys over the past decade—which hinted at undetected bodies but could not identify them—and thereby complete the inventory of ordinary matter in the galaxy.

That still leaves the extraordinary matter, the cold dark matter, which seems to make up its own, far vaster halo. Galaxies ruled by it should grow the same way that planets do: from the agglomeration of smaller units. The layering of the Milky Way bears that out. On the other hand, cold-dark-matter theories have trouble explaining the inferred number of satellite mergers, the shape of stellar streams and the rate of disk formation. Whatever the fate of this or that theory, astronomers' perspective on our home galaxy has fundamentally changed. They have come to see it not as a thing, sculpted long ago and left for us to admire, so much as a place, an arena where empires of stars rise and fall over the course of cosmic time.

## PREY OF THE MILKY WAY

**Cosmological models suggest the Milky Way originally had dozens of small satellite galaxies. Now there are 11. The closest is the Sagittarius dwarf galaxy, discovered seven years ago on the opposite side of the Milky Way from the sun. Despite its distance from us, it spans a quarter or more of the sky—a sure sign of its being stretched, shredded and assimilated by our galaxy. The unexpected extent of the Sagittarius dwarf galaxy emerged recently from several surveys: the "Spaghetti" Survey (so named because the stellar streams pulled off incoming galaxies look like spaghetti), the APM carbon star survey and the Sloan Digital Sky Survey. Such studies have unearthed shards of at least five hapless galaxies.**

PHYSICS

# New Trick from Old Dog

A MAGNESIUM COMPOUND IS A STARTLING SUPERCONDUCTOR BY GRAHAM P. COLLINS

**You can buy magnesium boride** ready-made from chemical suppliers as a black powder. The compound has been known since the 1950s and has typically been used as a reagent in chemical reactions. But until this year no one knew that at 39 degrees above absolute zero it conducts electric current perfectly—it is a superconductor. Although its superconducting temperature is far below that of the copper oxide high-temperature superconductors, the compound has set off a flurry of excited activity among researchers. Magnesium boride overturned theorists' expectations and promises technological applications.

Jun Akimitsu of Aoyama-Gakuin University in Tokyo announced the surprising discovery at a conference in Japan on January 10, after he and his co-workers stumbled on magnesium boride's properties while trying to make more complicated materials involving magnesium and boron. Word of the discovery sped around the world by e-mail, and in three weeks the first research papers by other groups were posted on the Internet. In early March a special session on magnesium boride was hastily put together in Seattle at the American Physical Society's largest annual conference: from 8 P.M. until long after midnight, nearly 80 researchers presented ultrabrief summaries of their results.

MAGNETIC FLUX at low levels, seen here penetrating a film of magnesium boride, destroys the material's superconductivity.

Until January standard wisdom ruled out the possibility of a conventional superconductor operating above about 30 kelvins. Conventional superconductors are understood by the so-called BCS theory, formulated in 1957. The magnesium boride result seemed to imply that either a new superconducting mechanism had been discovered or that the BCS theory needed to be revised.

Almost all the experimental evidence so far supports the idea that magnesium boride is a standard BCS superconductor, unlike the copper oxides. For example, when researchers use the isotope boron 10 in place of boron 11, the material's critical temperature rises slightly, as expected, because the lighter isotope alters vibrations of the material's lattice of atoms, a key component of BCS theory. How, then, has the magic 30 kelvins been exceeded? "Those predictions were premature," says Robert Cava of Princeton University, with 20/20 hindsight. Magnesium boride has a combination of low-mass atoms and favorable electron states that was overlooked as a possibility.

Physicists are trying to push the BCS limit even further to produce higher critical temperatures by doping the material with carefully selected impurities. Groups have added aluminum or carbon (neighbors of boron in the periodic table), but these both decrease the critical temperature. Calcium is expected to work better, but no one has succeeded in producing calcium-doped magnesium boride. "It's like Murphy's Law," Cava gripes.

Even undoped, magnesium boride has several attractive features for applications. First, the higher operating temperature would allow cooling of the superconductor by refrigeration instead of by expensive liquid helium, as is needed for the most widely used superconductors. The high-temperature copper oxide superconductors beat magnesium boride hands-down on that count, but they have proved difficult to manufacture into convenient wires. Also, the supercurrent does not flow well across the boundaries of microscopic grains in copper oxides.

Magnesium boride, in contrast, has already been fashioned into wires using simple techniques, and the supercurrent flows effortlessly between grains. One drawback, however, is that magnesium boride loses its superconductivity in relatively weak magnetic fields, fields that are inescapable in applications. But with the progress seen already in a scant few months, and with many tricks still up their sleeves, researchers are confident they can overcome such problems.

T. H. JOHANSEN ET AL. *University of Oslo*

## NEED TO KNOW: GETTING HIGH

The high-temperature superconductor mercury-barium-calcium copper oxide superconducts below 164 kelvins—but only when it is subjected to tremendous pressure, greater than 10,000 atmospheres. At ordinary atmospheric pressure the record temperature is held by the same substance, but at 138 kelvins. Hints of room-temperature superconductivity have often emerged over the years, but none of the claimed results has ever been successfully reproduced. Recently some press reports have hyped such claims by a group at the University of Zagreb in Croatia, but superconductivity experts have concluded that those results have no merit. Among researchers, such sightings of irreproducible, anomalously high superconducting temperatures are known as USOs, for unidentified superconducting objects.

WEAPONS TECH

# Robotic Bombers

UNMANNED STRIKE AIRCRAFT BEGIN TO TAKE OFF BY STEVEN ASHLEY

**Later this summer,** or perhaps in early autumn, a small pilotless plane will rise into the clear air over southern California's desert salt flats on its maiden flight. From all appearances, the new aircraft will look similar to the many other unmanned vehicles that have soared into the sky on solo spy missions and scientific surveys in recent years. This robotic airplane, however, will differ significantly from its predecessors. Rather than toting surveillance cameras and radars, it will carry "smart" bombs and missiles, should the system eventually be deployed in the field. Moreover, this new unmanned combat air vehicle (UCAV) is designed to fly for the most part autonomously, in squadrons that will sweep over heavily defended battle zones in waves making coordinated ground strikes.

The first of a new generation of pilotless attack aircraft, the X-45A is one of a pair built by Boeing Phantom Works in St. Louis as part of a $131-million program sponsored by the U.S. Air Force and the Defense Advanced Research Projects Agency (DARPA). Though strictly a technology demonstrator, the Boeing aircraft is designed to meet real requirements for hazardous combat missions in which airplanes fly directly into the teeth of surface-to-air missile batteries. If the concept proves itself in flight tests planned for the next two years, production UCAVs could be in the air by around 2010.

With a shovel-shaped nose, boomerang-like swept wings, a fuselage resembling a manta ray and no tail, the stealthy prototype can haul up to a ton and a half of weapons to points as far as 1,000 miles away. Video cameras, a Global Positioning System (GPS) and radar carry out precision-targeting tasks.

The X-45A is one of several UCAVs being developed. The U.S. Navy and DARPA are designing an unmanned bomber that will operate from naval vessels. The Pentagon is reportedly developing another, still classified UCAV design. Meanwhile Sweden's Saab Aerospace and France's Dassault have introduced their own robotic combat aircraft.

Although keeping pilots out of harm's way is one benefit, it's not the main purpose of unmanned aircraft. First, UCAVs should have greater chances of survival than their manned counterparts, explains Rich Alldredge, Boeing's UCAV Advanced Technology Demonstration (ATD) program manager. Being smaller, they would be harder to detect by radar. In addition, the lack of a cockpit means that the engine air intake can be buried in the upper fuselage, which is the most favorable position for maintaining low observability. Second, "the pilot in the cockpit doesn't always have the best idea of what's happening out on the battlefield," Alldredge continues. "With UCAVs, we can put the operator in the combat air operations center, right where all the intelligence is collected."

Cockpit-less UCAVs should also be cheaper to build and operate than conventional strike aircraft, says Col. Michael Leahy, DARPA UCAV ATD program manager. "Pilots need hundreds of hours each year in the air to maintain combat readiness," he notes. "UCAV operators can train in simulators." The team believes that the UCAV can be deployed for a third the acquisition price of the new Joint Strike Fighter. Operational and support costs are expected to total three quarters of that needed for a manned tactical squadron.

A UCAV is more than just an unmanned aerial vehicle with weapons. The aircraft will be able to execute predetermined "scripts" at certain points in its mission. All decisions regarding lethal force will be left in the hands of the operator, however. "You always have to have a person confirm a target and then, at the last possible moment, make the decision to deploy the weapons or not," Leahy says.


NO PILOT: Unmanned combat air vehicles (UCAVs) will keep humans in control but out of danger.

THE BOEING COMPANY

## BETTER THAN TODAY'S MISSILES?

**Why UCAVs may be more suitable than missiles:**

"Every time you fire a cruise missile you lose all your high-cost targeting sensors. With UCAVs you keep the sensors on the vehicle and release the cheapest ordnance you can. Also, cruise missiles are fine if you know exactly where the target is, but they can't hunt down mobile, relocatable targets."
—Col. Michael Leahy, DARPA UCAV ATD program manager

**Why they may not be:**

Precision standoff missiles, which are launched from afar by manned aircraft, could accomplish many of the same tasks as UCAVs. In fact, some Pentagon planners are unconvinced that UCAVs are worth developing.

COMETS or asteroids could rescue Earth.

NEED TO KNOW:
DRAWBACKS

Sending a giant rock toward Earth every 6,000 years has its dangers:

- **Collision** The asteroid could hit Earth, rather than flying by it.
- **Orbital destabilization** The change in Earth's orbit could disturb the motions of the other planets.
- **Loss of the moon** Most likely, the moon would be stripped away from Earth unless some additional energy-expensive shepherding were arranged. The moon helps to stabilize Earth's axial tilt, and its absence could radically upset our planet's climate.

ASTRO-ENGINEERING

# Save the Earth

DELAYING OUR PLANET'S ULTIMATE DEMISE—BY SHIFTING ITS ORBIT BY MARK A. GARLICK

**One billion years**—that's about all the time we have until the increasing luminosity of the aging sun cooks our planet to near death. But it does not have to be this way. Researchers argue that gradually moving Earth farther from the sun is possible.

Since the sun formed 4.6 billion years ago, it has steadily grown and gotten brighter. Already it shines about 30 to 40 percent brighter than it did when it first entered the main sequence, its current long-lived period of stability. In about one billion years the sun will be 10 percent more luminous than it is now—more than adequate to make land-based life difficult or even impossible.

A team led by Donald G. Korycansky of the University of California at Santa Cruz has developed an ambitious yet feasible plan that could add another six billion years to our planet's sell-by date. The process is an unusual application of the well-known gravitational slingshot. As a spacecraft closes in on a planet, gravity accelerates the probe, and it shoots away with added energy. That extra energy does not come free, though: the planet suffers equal and opposite changes in energy and momentum.

In the same way, the team's paper, published in the March *Astrophysics and Space Science,* shows how Earth's orbit can be increased very slightly if a suitable asteroid (or any object about 100 kilometers across and weighing about $10^{16}$ metric tons) can be made to fly in front of Earth as it moves in its orbit. In doing so, the asteroid imparts some of its orbital energy to Earth, shifting it to a slightly larger orbit. The orbit of the asteroid is engineered such that, after its flyby of Earth, it heads toward Jupiter or Saturn, where in the reverse process it picks up the orbital energy it lost to Earth. Then, when the asteroid reaches its farthest distance from the sun, a slight course correction is applied—by, say, firing engines on the asteroid using fuel manufactured from materials mined there—sending it once more toward Earth.

Korycansky and his collaborators calculate that for Earth to enjoy the same intensity of sunlight it does now, our planet would have to be nudged outward about once every 6,000 years, on the average, for the entire remaining main-sequence lifetime of the sun. In 6.2 billion years Earth would be just beyond the current orbit of Mars. The scenario sounds like science fiction, but it actually uses technology that is mere decades away from being reality.

Ambitious though the scheme is, it is no solution when the sun encounters its fate—as a cool, dim white dwarf. At the very end, escaping to another star system is ultimately the only option.

*Mark A. Garlick, a former astronomer, is a writer and artist based in Brighton, England.*

MARK A. GARLICK

CONSERVATION

# Unfair Game

THE BUSHMEAT TRADE IS WIPING OUT LARGE AFRICAN MAMMALS BY JOSEPHINE HEARN

**BIOKO ISLAND, EQUATORIAL GUINEA—** "How would you like it if I cooked porcupine tonight?" our cook asks hopefully. After four weeks in Central Africa, I had become accustomed to eyebrow-raising questions. "How about fish?" I suggest. Fish is readily available on Bioko, an island 32 kilometers off the coast of Cameroon that forms part of the tiny African nation of Equatorial Guinea. On the mainland, however, seafood isn't always an option. Across tropical Africa, where timeless village ways are meeting the cash economy, the bushmeat trade—hunting wildlife for food—is fast becoming big business. In a surprise even to battle-worn conservationists, the trade is eradicating mammals from the rain forests with remarkable ferocity. According to the Convention on International Trade in Endangered Species (CITES), the practice affects 30 endangered species—among them gorillas, chimpanzees, elephants, duikers (forest antelopes) and monkeys. At stake is not only biodiversity but also vital information about the origins of viruses such as Ebola and HIV, which have been linked to the eating and handling of bushmeat.

For decades, conservationists worried most about habitat destruction, but these days "bushmeat is recognized as the most significant threat to wildlife populations," says Heather Eves, director of the Bushmeat Crisis Task Force based at the American Zoo and Aquarium Association in Silver Spring, Md. Many forests in West and Central Africa have been hunted so heavily that no species larger than a squirrel survives. David Wilkie, a biologist at Boston College and with the Wildlife Conservation Society, estimates that in the Congo Basin alone, bushmeat consumption measures one million metric tons annually, equivalent to seven million head of cattle. But that figure, he notes, is far below the actual volume of meat taken from the forest. Many animals rot in wire snares before hunters collect them. "In some places, that wastage rate is up to 80 percent," Wilkie says.

Many conservationists have been working to unravel the myriad factors that influence bushmeat hunting and consumption. Humans have been stalking prey in tropical forests for thousands of years, but only recently has the bushmeat crisis become apparent. Perhaps the single biggest factor is logging. In Cameroon, Gabon and the Republic of Congo, multinational loggers have dominion over more than 60 percent of the land. Although their techniques tend to be ecologically friendly—felling only a few select trees per hectare—the roads they construct through once impenetrable forests offer hunters easy access. Sometimes the logging camps themselves have hundreds, or even thousands, of hungry workers, creating instant demand. One logging camp in Congo harvested 8,251 animals in a single year.

Logging, as well as farming and ranching, has fragmented many forests. According to John Oates, a primatologist at Hunter College of the City University of New York, "because the areas are getting small, [hunters can] have a devastating impact on what little wildlife is left." Last fall Oates reported the probable extinction of Miss Waldron's red colobus (*Procolobus badius waldroni*), a monkey that had survived only in isolated chunks of forest in Ghana and the Ivory Coast. Miss Waldron's—named after the traveling companion of the collector who discovered the species in 1933—is the first primate lost in centuries.

PAUL T. TELFER

WORTH MORE DEAD than alive, monkeys such as this mandrill are prime hunting targets throughout Africa.

To stem the bushmeat trade, conservationists are taking several approaches. They are developing partnerships with loggers to limit hunting on logging concessions and to offer alternative sources of protein to workers. And they are encouraging loggers to adopt codes of good conduct set by the Forest Stewardship Council and other groups. On Bioko Island, the Bioko Biodiversity Protection Program works with the local university to inform people about the educational and scientific value of wildlife. The program also employs villagers to guard one of the island's protected areas. Similar strategies have succeeded in a handful of parks across Africa. "No single answer is going to solve the bushmeat problem," Eves remarks. "It's a mosaic of solutions."

Deep within Bioko's southern protected area, one solution may be falling in place. After a morning hike through a section abundant in wildlife, Claudio Posa Bohome leans over to me and says conspiratorially, "You know, I used to be a hunter." Bohome, now an agronomist at the National University of Equatorial Guinea, explains how he pursued game not far from here. "But now," he states, motioning to the tape that marks the conservation trails, "I think this is the right thing to do."

*Josephine Hearn lives in Washington, D.C.*

## WHEN BUSHMEAT IS A DELICACY

**Social forces play a significant role in the bushmeat business. On Bioko, logging and habitat fragmentation are not threats; still, the island is not the wildlife paradise one might expect. Its seven species of monkeys—five of them endangered throughout their ranges—are heavily hunted for bushmeat and then marketed at prices only the upper classes can afford. Four subspecies are found nowhere else in the world. As the big city on the island grows and becomes affluent, more people demand the foods and smells of their ancestral villages. In a 39-month study, more than 26,000 animals passed through the main bushmeat market, far above sustainable levels.**

BY THE NUMBERS

# The American Terrorist

A PINCH OF POLITICS, A POUND OF HATE BY RODGER DOYLE

Say **"terrorism,"** and most people think Osama bin Laden and Timothy McVeigh, but they are just a small, if scary, part of a much larger American problem. The accumulation of solid data on U.S. terrorism is only now beginning, most notably with the FBI's tabulation of hate crimes starting in the early 1990s. These and other reports suggest that the number of terrorist acts against Americans worldwide over the past 20 years is 250,000 to 300,000. During this time, at least 1,500 Americans have died in terrorist incidents that, in their timing, were utterly unpredictable. Most died as a result of bombings.

Fewer than 3,000 of the terrorist acts were committed abroad, most prominently by Muslim groups, who have killed about 600 Americans since 1982 (the majority of them in the bombings of the U.S. Marine barracks in Lebanon in 1983 and Pan Am Flight 103 in 1988). The biggest domestic terrorist act in recent years was, of course, the 1995 bombing of the Federal Building in Oklahoma City.

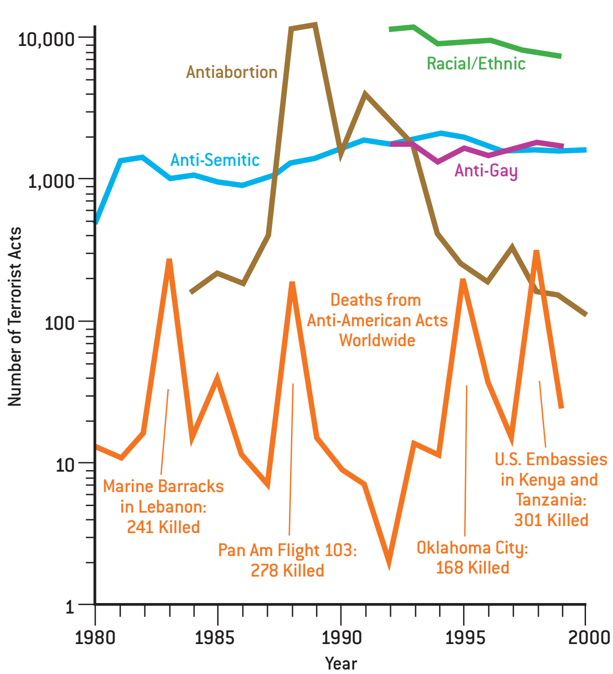
Political beliefs have little to do with domestic terrorism. The McVeigh group and other organized, overtly ideological extremists—whether right-wing, left-wing, anti-Muslim, pro-Muslim, anti-Castro, Puerto Rican nationalist, eco-terrorist, animal liberationist or cyber-terrorist—probably accounted for a small number of incidents since 1982, when the FBI began keeping systematic records. Rather the largest categories of terrorist offenses are racial/ethnic crimes (mostly against blacks), followed by religious (mostly anti-Semitic) and anti-gay crimes. The occurrence of racial/ethnic offenses declined during the 1990s, while religious and anti-gay offenses held steady. Many, perhaps most, of these incidents were spur-of-the-moment acts by individuals or ad hoc groups.

Another important category, one that is not adequately covered by official statistics, is attacks against and harassment of abortion-services providers. The National Abortion Federation, in its incomplete tabulation of violence and threats, estimates such incidents at 12,000 from 1984 to 2000, with a substantial decline since 1988–89, the peak years of clinic protests.

Unfortunately, there are no reliable statistics on other kinds of terrorism, such as student attacks on other students, exemplified by the infamous Columbine shootings in 1999, and police violence against civilians, as in the notorious Rodney King episode of 1992. It would be useful to include such acts, as well as anti-abortion terrorism, in the national reporting system. That way, Americans will have a comprehensive and reliable picture of all types of terrorist acts.

*Rodger Doyle's e-mail is rdoyle2@aol.com*

**TERRORISM AT HOME AND ABROAD**




SOURCES: FBI; U.S. Department of State; Anti-Defamation League; National Abortion Federation

RODGER DOYLE

## DEFINING TERRORISM

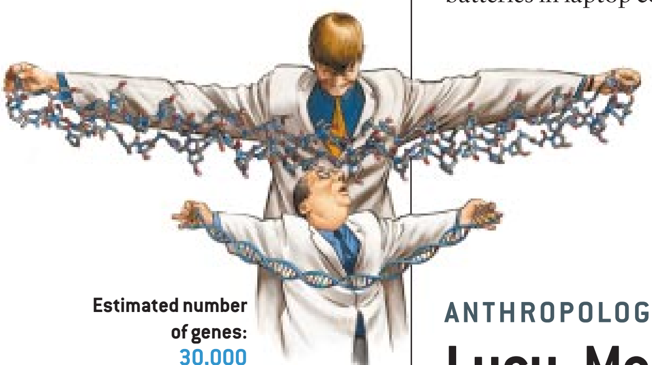
**There is no agreement on what constitutes terrorism. The U.S. State Department says it is "premeditated, politically motivated violence by subnational groups or clandestine agents, usually intended to influence an audience." The FBI says it is "the unlawful use, or threatened use, of force or violence against persons or property in furtherance of political or social objectives." In this article "terrorism" is defined as the use or threat of violence to make a statement about ideological or cultural beliefs. The conscious aim may or may not be to coerce a government or a group of people into granting the terrorists' demands.**

## DATA POINTS: GET YOUR PROTEINS

As a sequel to the Human Genome Project, scientists in early April discussed plans for an analogous search for proteins, called the human proteome project. Meanwhile a joint venture of Myriad Genetics, Hitachi and Oracle called Myriad Proteomics promises to identify all human proteins for $500 million.

Number of human chromosomes: 46

Length of unraveled DNA: 0.7 to 3.3 inches



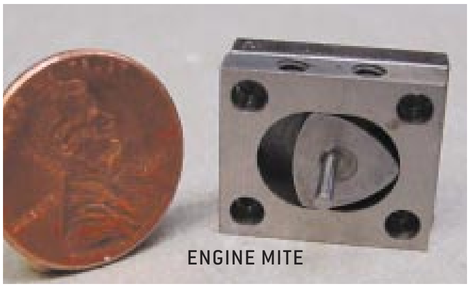
Estimated number of genes: 30,000

Estimated number of proteins: 300,000 to a few million

Time that the Human Genome Project took to finish first draft: 10 years

Time that Myriad Proteomics says it will finish its project: 3 years

*SOURCES: Celera Genomics; Human Genome Project; Myriad Proteomics*



ENGINE MITE

ENGINEERING

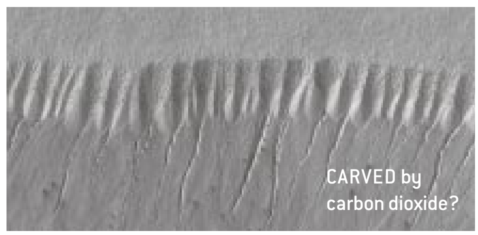
# The Little Engine That Might

**Carlos Fernandez-Pello** and his colleagues at the University of California at Berkeley have been boosting the output of their penny-size rotary internal-combustion engine—the smallest engine ever to deliver continuous power. This mini engine, which runs on a high-energy liquid hydrocarbon such as butane or propane, produced four watts of electricity as of April, up from 0.7 watt in February. A refined, more powerful version might replace batteries in laptop computers and other portable devices. Furthermore, a version fashioned out of silicon could someday shrink the engine down to the size of a pinhead. *—Alison McCook*

ASTRONOMY

# Not So Watery

**In the April 1** *Geophysical Research Letters,* researchers propose that the gullies seen on Mars last year may have been carved by carbon dioxide rather than by water. They theorize that the arrival of spring warms liquid $CO_2$ trapped in the pores of the rocky surface; after expanding and bursting through the surface, the liquid quickly vaporizes, and some of it condenses into $CO_2$ snow. Along with rocky debris, the snow becomes suspended in the remaining $CO_2$ gas; this suspension, the researchers say, flowed and carved the gullies. The model would explain why the gullies are located where the planet is coldest and where underground liquid $CO_2$ is most likely to be stable. Another strike against Martian water appears in the April 5 *Nature*. Ridge features on the planet's northern hemisphere were thought to be remnants of an ancient shoreline. New data gathered by the Mars Global Surveyor, however, suggest that tectonic stress created the ridges. *—Philip Yam*

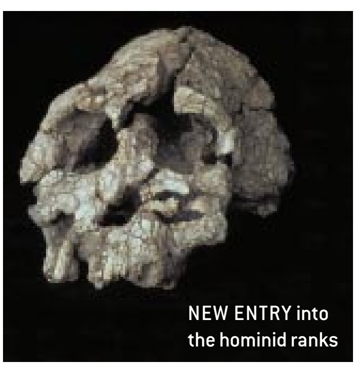


CARVED by carbon dioxide?

ANTHROPOLOGY

# Lucy, Meet *Ken*

**When the American Association** of Physical Anthropologists gathered in Kansas City, Mo., in March, *Kenyanthropus platyops* stole the show. Meave Leakey of the National Museums of Kenya talked about the 3.2-million to 3.5-million-year-old fossil remains from northern Kenya's Turkana Basin. Previously, the only hominid thought to have existed during that time was *Australopithecus afarensis,* the species to which the famed Lucy fossil belongs and from which all later hominids—including ourselves—appeared to be descended. But the new fossil leaves Lucy's ancestral status uncertain. This early hominid diversity, Leakey says, may have resulted from adaptations to new ecological niches opened up by the spread of so-called C4 plants, which created bushy grasslands and grassy woodlands—a shift that has been used to explain diversification among other mammals from that period. Not everyone agrees that the new fossil warrants a new genus, however. "Time will tell whether we were right or wrong," Leakey remarked. "At least this makes people ask more questions." *—Kate Wong*



NEW ENTRY into the hominid ranks

UNIVERSITY OF CALIFORNIA, BERKELEY, MICRO-ROTARY COMBUSTION LAB (*top*); MATT COLLINS (*middle left*); NASA/JPL/MALIN SPACE SCIENCE SYSTEMS (*middle right*); FRED SPOOR, © NATIONAL MUSEUMS OF KENYA (*bottom*) news SCAN

AIDS

## Locating the Latent Enemy

HIV virus via computer modeling

MICHAEL FREEMAN *Corbis*

**Frustrating treatment** for HIV-positive patients is the virus's ability to hide in T cells. These immune system cells must be turned on by a foreign particle (antigen) but can later turn off and hibernate in the blood for many years. Scientists have found hidden copies of the virus in retired T cells and, more recently, in newborn T cells, which have yet to be activated. In the April *Nature Medicine,* researchers suggest that some of these HIV-infected "naive" T cells originate from an HIV-infected thymus, the organ that makes T cells and releases them into the blood. To test this theory, they added substances that mimicked the action of a T cell antigen to a culture of HIV-infected thymus tissue that was extracted from a mouse. Within 24 hours the amount of viral genes in the culture jumped 30-fold. These results may explain why most patients experience a resurgence in viral levels years after becoming infected and may help in developing new therapies against latent HIV. —*Alison McCook*

BIOLOGY

## Boning Up

**A purring cat** is not necessarily a happy one; many species—including cheetahs and some lions—also purr when wounded or anxious. Some researchers speculate that this lovely rumble may serve a function: to heal fractures and strengthen bones. In an as yet unpublished study from the Fauna Communications Research Institute in Hillsborough, N.C., investigators determined that the frequency at which many cats purr, between 27 and 44 hertz for house cats, matches the frequency that seems to help human bones strengthen and grow. If correct, the theory may explain why cats heal so quickly after injury. —*Alison McCook*

PURRING as bone builder

SOCIOLOGY

## Aborted Crime Wave, Part 2

**Two years ago** Steven D. Levitt of the University of Chicago and John J. Donohue III of Stanford University achieved notoriety by proposing that up to 50 percent of the drop in crime in the 1990s was attributable to the legalization of abortion: fewer unwanted children meant less crime. Now another economist has analyzed the same crime data, as well as other indicators, and has reached a different conclusion. "There is nothing to suggest anything related to legalized abortion," says Theodore J. Joyce of Baruch College. Based on his analysis, Joyce believes instead that the most plausible explanations are the waning of the crack epidemic and a combination of police action, incarceration and economic growth. Donohue and Levitt's report, now finally peer-reviewed, appears in the May *Quarterly Journal of Economics*. Joyce plans to submit his for publication in a few months. —*Marguerite Holloway*

COMPUTERS

## Copy Unprotected

**It's strike one** for proponents of hardware-embedded copyright protection. In April the committee that designates technology standards voted against a proposal to install a program called content protection for recordable media (CPRM) directly onto a computer's hard drive. Opponents have long feared that CPRM, which would block users from downloading copyright-protected material, could compromise open-source software and copying for personal use [see "To Protect and Self-Serve," Cyber View, by Wendy M. Grossman, March]. But because compliance with these technology standards is voluntary, the group that produced CPRM can still sell it. —*Alison McCook*

WWW.SCIAM.COM/NEWS
BRIEF BITS

- **Cognitive behavioral therapy seems to help insomniacs, offering an alternative to long-term drug use. /041101/2.html**
- **Scientists created a composite material that has a negative index of refraction. It may lead to unusual lenses and electromagnetic devices. /040901/3.html**
- **Researchers have discovered just how the mutant protein in Huntington's disease does its neuron-destroying job—and have reversed the impending cell death in the lab dish. /032301/4.html**
- **Insulin-like hormones dictate the aging process across several species—a possible explanation for why low-calorie diets, which reduce insulin levels, extend life. /040601/1.html**

# The Mice That Warred

**Natural selection picks the best antibodies to fight invading microbes—and it also determines who survives to sell these molecules as drugs** By GARY STIX

**Monoclonal antibodies** are biotechnology's biggest comeback story. Until the late 1990s, monoclonals, which had been dubbed magic bullets, appeared to be shot from a gun that couldn't shoot straight.

A monoclonal is an exact copy of a single antibody that binds to a specific antigen—a molecule on, say, a bacterium, virus or cancer cell. It then triggers a cascade of events in the immune system that destroys or neutralizes the interloper. Although they had the potential of being highly targeted drugs, monoclonals did not fulfill their promise. The antibodies, manufactured in mice, provoked an immune response in humans that made them unusable as pharmaceuticals.

NILS LONBERG developed mice that produce human antibodies.

OLIVIER LAUDE

The race to rectify this early defect generated ferocious competition among start-ups and provides a compelling example of how biotechnology companies weather the legal struggles that may prove more critical to survival than technical and scientific prowess. A number of researchers responded to the early debacles with mouse antibodies by creating transgenic mice that produce antibodies that are mostly human but still partly rodent. Ideally, a transgenic mouse bearing genes for an entire human antibody would produce a fully human monoclonal. The antibody-making cell could then be isolated to generate an unlimited supply of antibodies.

In 1989 Nils Lonberg, a postdoctoral student at Memorial Sloan-Kettering Cancer Center in New York City, was hired by GenPharm International, then located in South San Francisco, Calif., to create just such a mouse. During the early 1990s he and his group labored on several big technical challenges: they had to inactivate the key genes the mouse uses to produce its own antibodies and then insert human genes. They could only hope that the transplanted human antibody genes, which differ from those of the mouse, would succeed in initiating the maturation cycle that leads to antibodies able to bind tightly enough to antigens to prove effective.

Their plan worked remarkably well. "We were lucky we didn't encounter problems," Lonberg says. "There was no way to guarantee that the differences between mouse and human genes wouldn't have severe consequences. We just had to try it." A culmination came at an industry conference in late 1993, when Lonberg gave a presentation on a mouse that produced fully human antibodies with high affinities for a target, a feat that Cell Genesys in Foster City, Calif., GenPharm's chief rival, had yet to achieve.

For GenPharm, the announcement became a public declaration that the company had arrived—and it served as a claim of leadership in this race to produce a mouse capable of making human antibodies. Shortly thereafter, GenPharm planned its first public stock offering, which would give it the financial wherewithal to launch clinical trials of monoclonal antibody drugs and to set up the manufacturing facilities needed to supply antibodies to pharmaceutical company partners.

On February 1, 1994, a few days before GenPharm's filing for an IPO, Cell Genesys, which had already received a cash infusion by going public, sued the company, charging it with having stolen a trade secret for inactivating a mouse gene. "They were clearly behind in terms of technology but clearly ahead in terms of money," Lonberg says. "We were on our last legs in terms of money. We had 110 people and a significant burn rate. We couldn't figure out what we were being sued for. I didn't take it that seriously. The people on the ground at the technical level thought it was ridiculous. But it derailed our public offering. It was harder and harder to get money from venture capitalists."

The company fired everyone but a skeleton staff and began to try to find a buyer, but the lawsuit stood in the way. GenPharm, which at one point had a mere $15,000 in cash and owed large sums to lawyers and banks, had to survive on barter; it tended mouse cages for another biotechnology concern in exchange for a sliver of laboratory space. It held a fire sale to get rid of furniture, laboratory equipment and patents. A professor of developmental biology from Stanford University came down and inspected a surgical microscope as a possible toy for his kid.

GenPharm countered with an antitrust lawsuit and two patent suits against Cell Genesys. Two weeks before the trial in early 1997, Cell Genesys dropped its suit—purportedly because GenPharm had gained a patent that gave the company a superior intellectual-property position. Within months, the two companies hammered out a cross-licensing agreement that provided access to each other's technologies. Meanwhile GenPharm scrapped its remaining litigation. As part of the accord, Cell Genesys and a partner agreed to pay GenPharm nearly $40 million. The former legal foes were now poised to share a lock on this potential bonanza technology.

GenPharm's technology—if not the original company—survived to become a significant player in what has become perhaps the hottest area of biotechnology. After the debacle, the company needed cash fast to meet the obligations venture-capitalist firms had to their investors, so it began to seek a buyer. "We were on the road immediately shopping the company," Lonberg says.

In the fall of 1997 Medarex, an antibody company based in Annandale, N.J., bought GenPharm, a deal that provided manufacturing facilities and other resources it had been unable to acquire during the years of the lawsuit. Lonberg, who now holds the title of scientific director at Medarex, is the only remaining employee who has worked on the program since its inception. His bitterness remains. "The final story is not that we prevailed but that [Cell Genesys] actually succeeded in its strategy. It was able to use litigation to capture a technology."

Cell Genesys spun off its mouse technology into a separate company: Abgenix in Fremont, Calif. Abgenix disputes the contention that it used lawsuits to catch up, saying that scientific papers show that its mouse was definitively better than the Medarex rodent. It doesn't really matter anymore who is right. Things have been good for both Medarex and Abgenix, which have become the

**Lonberg's work on monoclonals has been revived from its near-death encounter.**

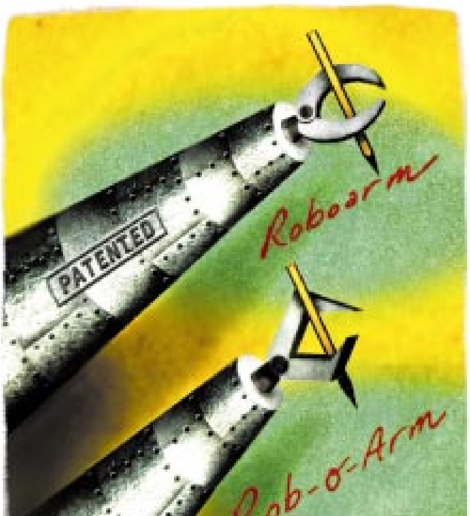
Coke and Pepsi of the antibody world. Monoclonals have boomed. More than 90 monoclonal antibodies are now in clinical trials, most using the older technologies that retain some of the properties of the mouse. About 10 have made it to market, including drugs for breast cancer and non-Hodgkin's lymphoma, and constitute an estimated $2.1 billion in revenue for 2001. The market may grow to more than $5 billion by 2004.

The advantages of all-human antibodies in immunogenicity and in speed and cost of development have revived Lonberg's work from its near-death encounter. Beginning in 1998, Medarex began to strike partnerships with large drug companies and biotech concerns to provide monoclonal-producing mice. By 2000 it was entering into an agreement with another company nearly every month—it now has 31 partnerships in addition to launching its own clinical trials of a few drugs. And last year the mouse technology propelled a $400-million Medarex stock offering. Human-antibody mice mark a step toward fulfilling the dream for these drugs. But Lonberg's experience also confirms the musings of immunologist and Nobel Prize winner Paul Ehrlich, who, around the start of the 20th century, conceived of the notion of a "magic bullet" against disease. He said, "Magic substances like the antibodies, which affect exclusively the harmful agent, will not be so easily found." That may be true, though perhaps not for the technical reasons Ehrlich contemplated. SA

# A License for Copycats?

**A court decision may clarify what is patentable while giving a free ride to knockoffs** By GARY STIX

**Should someone be able to patent** an invention that blatantly duplicates a previously patented creation except for some minor alterations—changing a rivet to a bolt, for instance? The Court of Appeals for the Federal Circuit, the judiciary that handles appeals in patent cases, has effectively said yes. Its recent ruling dramatically weakens a body of common law that lets patent holders expand coverage of their patents to fend off imitators. Whether it casts a chill on innovation or enlivens it still remains to be seen.




Some legal analysts have termed the November 29, 2000, decision—*Festo* v. *SMC*—a fatal strike against the so-called doctrine of equivalents, which protects an inventor against a copycat who creates a different but functionally equivalent product. To prevent abuse of that principle, a past restriction has prohibited patent applicants from narrowing a claim to persuade examiners that an invention is original and then, after the patent is issued, using the doctrine of equivalents to broaden the scope of the claims. Under *Festo,* the reach of this rule grows: virtually any narrowing of a claim, even one that clarifies the patent language, precludes later use of the equivalence argument.

If the ruling stands, the fallout may be huge. Applicants routinely make changes in filings in the back-and-forth negotiations with patent examiners. Many patents—some critics say virtually all—would be affected by the decision. A copycat can now examine which claim provisions in a patent have been amended and then design an invention with only minimal alterations to those components.

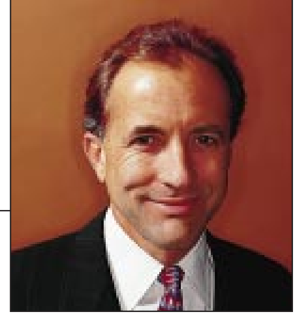
The case may not be closed, though. Festo, a manufacturer that brought an infringement suit against rival SMC over a part used in a robotic arm, wants to take the case to the Supreme Court. If the Supreme Court lets *Festo* stand, the effect of this case, which applies retroactively to patents issued as far back as the mid-1980s, could cheapen the value of existing patent portfolios. An exclusive license issued from a patent holder would be worth less if someone else could readily manufacture and market virtually the same technology without infringement. "It has the potential to dramatically decrease the value of patents and, as a result, dramatically decrease the incentives for innovation," says Jay Alexander of the law firm Kirkland and Ellis in Washington, D.C. The patent application process could become longer and more expensive as companies spend more time drafting claims that would not need amendment later, a burden in particular for small companies and individual inventors.

A number of large corporations, including IBM, Ford and Kodak, all of which filed friend-of-court briefs in the case, welcomed the *Festo* decision. Before *Festo,* they contend, it was impossible to tell if a new widget would infringe on a competitor's patent because the doctrine of equivalents might be invoked. Big companies worry about getting broadsided by a lawsuit from an individual or small company that is trying to rake a large firm. Arthur Neustadt, the attorney for SMC, argues that the decision will encourage more innovation because patent claims will be clearer.

Whether *Festo* introduces more certainty into patent law is still unknown. But both sides will continue to promote themselves as champions of innovation and technological advancement in their bids to gain the upper hand in this epic battle. SA

*Please let us know about interesting or unusual patents. Send suggestions to: patents@sciam.com*

BRIAN STAUFFER



# Fox's Flapdoodle

**Tabloid television offers a lesson in uncritical thinking** By MICHAEL SHERMER

**The price of liberty** is, in addition to eternal vigilance, eternal patience with the vacuous blather occasionally expressed from behind the shield of free speech. It is a cost worth bearing, but it does become exasperating, as when the Fox Broadcasting Company aired its highly advertised special "Conspiracy Theory: Did We Land on the Moon?" NASA, viewers were told, faked the Apollo missions on a movie set.

Such flummery should not warrant a response, but in a free society, skeptics are the watchdogs against irrationalism—the consumer advocates of ideas. Debunking is not simply the divestment of bunk; its utility is in offering a better alternative, along with a lesson on how thinking goes wrong. The Fox show is a case study, starting with its disclaimer: "The following program deals with a controversial subject. The theories expressed are not the only possible explanation. Viewers are invited to make a judgment based on all available information." That information, of course, was not provided, so let's refute Fox's argument point by point in case the statistic at the top of the show—that 20 percent of Americans believe we never went to the moon—is accurate.

*Claim:* Shadows in the photographs taken on the moon reveal two sources of light. Given that the sun is the only source of light in the sky, the extra "fill" light must come from studio spotlights. *Answer:* Setting aside the inane assumption that NASA and its co-conspirators were too incogitant to have thought of this, there are actually *three* sources of light: the sun, the earth (reflecting the sun) and the moon itself, which acts as a powerful reflector, particularly when you are standing on it.

*Claim:* The American flag was observed "waving" in the airless environment of the moon. *Answer:* The flag waved only while the astronaut fiddled with it.

*Claim:* No blast crater is evident underneath the Lunar Excursion Module (LEM). *Answer:* The moon is covered by only a couple of inches of dust, beneath which is a solid surface that would not be affected by the blast of the engine.

*Claim:* When the top half of the LEM took off from the moon, there was no visible rocket exhaust. The LEM instead leaped off its base as though yanked up by cables. *Answer:* First, the footage clearly shows that there was quite a blast, as dust and other particles go flying. Second, without an oxygen-rich atmosphere, there is no fuel to generate a rocket-nozzle flame tail.

*Claim:* The LEM simulator used by astronauts for practice was obviously unstable—Neil Armstrong barely escaped with his life when his simulator crashed. The real LEM was much larger and heavier and thus impossible to land. *Answer:* Practice makes perfect, and these guys practiced. A bicycle is inherently unstable, too, until you learn to ride it. Also, the moon's gravity is only one sixth that of the earth's, so the LEM's weight was less destabilizing.

**NASA, viewers were told, faked the Apollo missions on a movie set.**

*Claim:* No stars show in the sky in the photographs and films from the moon. *Answer:* Stars don't routinely appear in photography shot on the earth, either. They are simply too faint. To shoot stars in the night sky, even on the moon, you need to use long exposures.

The no-moonie mongers go on and on in this vein, weaving narratives that include the "murder" of astronauts and pilots in accidents, including Gus Grissom in the Apollo 1 fire before he was about to go public with the hoax. Like most people with conspiracy theories, the landing naysayers have no positive supporting evidence, only allegations of cover-ups. I once asked G. Gordon Liddy (who should know) about conspiracies. He quoted *Poor Richard's Almanack:* "Three people can keep a secret if two of them are dead." To think that thousands of NASA scientists would keep their mouths shut for years is risible rubbish. SA

*Michael Shermer is the founding publisher of* Skeptic *magazine (www.skeptic.com) and the author of* How We Believe *and* The Borderlands of Science.

BRAD HINES

# Piloting through Uncharted Seas

**The privately funded Monterey Bay Aquarium Research Institute enables scientists and engineers to engage in radical pursuits. As long as Marcia K. McNutt likes their ideas** BY JOHN ADAM

**MOSS LANDING, CALIF.**—"Come on, just be a little bit careful because the tide's low." We hop on board the day boat *Point Lobos,* and Marcia Kemper McNutt—a marvel of efficiency on land—noticeably relaxes. This old hulk is the size of a tugboat, converted from servicing offshore oil rigs to plying the canyons of Monterey Bay for science. "Hey, Knute, how was your day today?" she calls out to the pilot of a remotely operated vehicle. She seems to know not just the first name but the welfare of every one of the 200-some engineers, scientists and operations crews who work for her.

## MARCIA K. MCNUTT: GOING DEEP

- Husband, Ian Young; daughters Meredith and twins Ashley and Dana
- Best-known fact: president of 38,000-member American Geophysical Union
- Least-known fact: Navy SEAL-certified demolitions expert
- On research: "In principle, we still retain the concept of international waters. But the fact is that she who owns the technology owns the oceans."

McNutt raised more than a few eyebrows when she left an endowed chair at the Massachusetts Institute of Technology four years ago. Not only was she odds-on favorite to become department head in a year, but she also held a key post associated with the Woods Hole Oceanographic Institution, an estimable leviathan of ocean research. Instead she headed west to direct the Monterey Bay Aquarium Research Institute (MBARI, pronounced "em-BAHR-ee"), a relatively backwater institute substantially overshadowed by its namesake sister 20 miles south, the actual tourist-beloved aquarium.

By McNutt's logic, improving on the past department chair's job at M.I.T. would be impossible. MBARI seemed "poised to make a huge impact," she says. All it needed was some tweaking. Now, as president of MBARI, this 49-year-old Minneapolis native finds herself one of the world's most influential ocean scientists.

Offbeat choices are nothing new for McNutt. She chose Colorado College even though her perfect-800 SAT scores could have gained her entry nearly anywhere. Her adviser there discouraged her from taking physics, deeming it unsuitable for women. McNutt's response: to switch advisers. She graduated summa cum laude with a physics degree in three years.

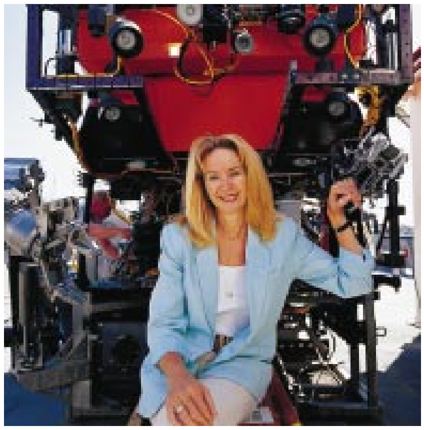
Then, in the early 1970s, she read John F. Dewey's article on plate tectonics in *Scientific American*. "This is so beautiful, so simple," she recalls thinking of the then relatively new theory. "It's got to be right." She went on to obtain a Ph.D. in earth sciences at the Scripps Institution of Oceanography in La Jolla, Calif. She began to travel to sea, sometimes to study the midocean ridge system, where plates meet and new oceanic crust forms.

Science ships are tight for space, so students needed a skill to justify their presence. "I went out to be the shooter," she remarks. A summer with the U.S. Navy SEALs taught McNutt how to handle explosives, wrap them in detonation cords and time the charges precisely

PHOTOGRAPHS BY EDWARD CALDWELL

so that a clean blast would acoustically map ocean geology. "I love going to sea," she says. "There's a camaraderie. Everyone is focused on the same mission." She eventually met her husband, a captain, when she was chief scientist at sea. McNutt manages to continue her geophysics research—in May she joined an institute research vessel off Hawaii to examine hot spots. But she spends most of her time keeping MBARI shipshape.

The institute is the brainchild of David Packard. The billionaire engineer and cofounder of Hewlett-Packard took a keen interest in oceans during the last years of his life, thanks in part to his daughters, who studied marine science. Packard founded MBARI in 1987 as a private-sector complement to government-dominated ocean research. Engineers working beside top scientists could, he believed, open up deep-ocean research.



PRIDE OF MBARI: McNutt with a submersible and on a data-gathering mooring (*opposite page*).

The David and Lucile Packard Foundation pours about $40 million a year into MBARI. Researchers there, unencumbered by teaching or the federal grant application process, can move nimbly, assuming McNutt likes their ideas. They can also carry out risky long-term technology-intensive projects that might otherwise be quashed under peer review. One example: 12 years of monitoring for global temperature change from Monterey Bay ultimately paid off, McNutt explains, when "we could see a trend in the data" showing that the bay's relatively small increase in temperature resulted in disproportionately large decreases in its algal biomass productivity.

Unlike other institutes, MBARI schedules its growing fleet of vessels on its own. (Other institutes, beholden to federal funds, cooperatively schedule their fleets for the nation's marine scientists.) Such autonomy endows McNutt's post with great influence. It is "much more powerful than a typical institution's director" position, says G. Ross Heath of the University of Washington, who was McNutt's predecessor at MBARI. Shortly after Packard died in 1996, McNutt became director. Although Packard is still revered at MBARI, his presence made it tough for others to move without fear of being second-guessed.

McNutt stepped in just as MBARI's new buildings, its two research ships, its two remotely operated vehicles (ROVs) and its systems for acquiring and cataloguing information were operational, or nearly so. "We underestimated the time it would take to build a new institute," confesses Julie Packard, who assumed the chair of MBARI's board from her father. Only now, she says, with all the equipment working well, are the scientific benefits being reaped, as shown by a rise in MBARI-affiliated authorship in prestigious journals.

Credit McNutt for smoothing relations and squeezing the most out of her diverse crew. One of her first actions was to shift some engineers into coveted ocean-view offices that had been an exclusive province of scientists. (Her own office is efficiently austere, with a view of the twin smokestacks across the harbor.) MBARI engineers bring scientists vicariously to ever greater depths. The institute's first ROV, modified from an oil-industry machine, dove to depths of nearly two kilometers; its second had more homemade innovations and reached four kilometers. McNutt proudly shows me MBARI's yellow autonomous underwater vehicle, still in the shop; the submersible will soon be swimming untethered as deep as 4.5 kilometers and will launch from MBARI's third research vessel, the *Zephyr*.

For the most part, the ocean's major events remain unobserved. "Plankton bloom. Volcanoes erupt. Plates slip in earthquakes. Fish spawn," McNutt says. "The chance of being in the right time and in the right place to catch such events in action is very small." Eventually schools of swimming robots could remedy that. In short, it's a race to see whether these tools can be made to address such pressing oceanic problems as global warming, energy production and sustainable fisheries.

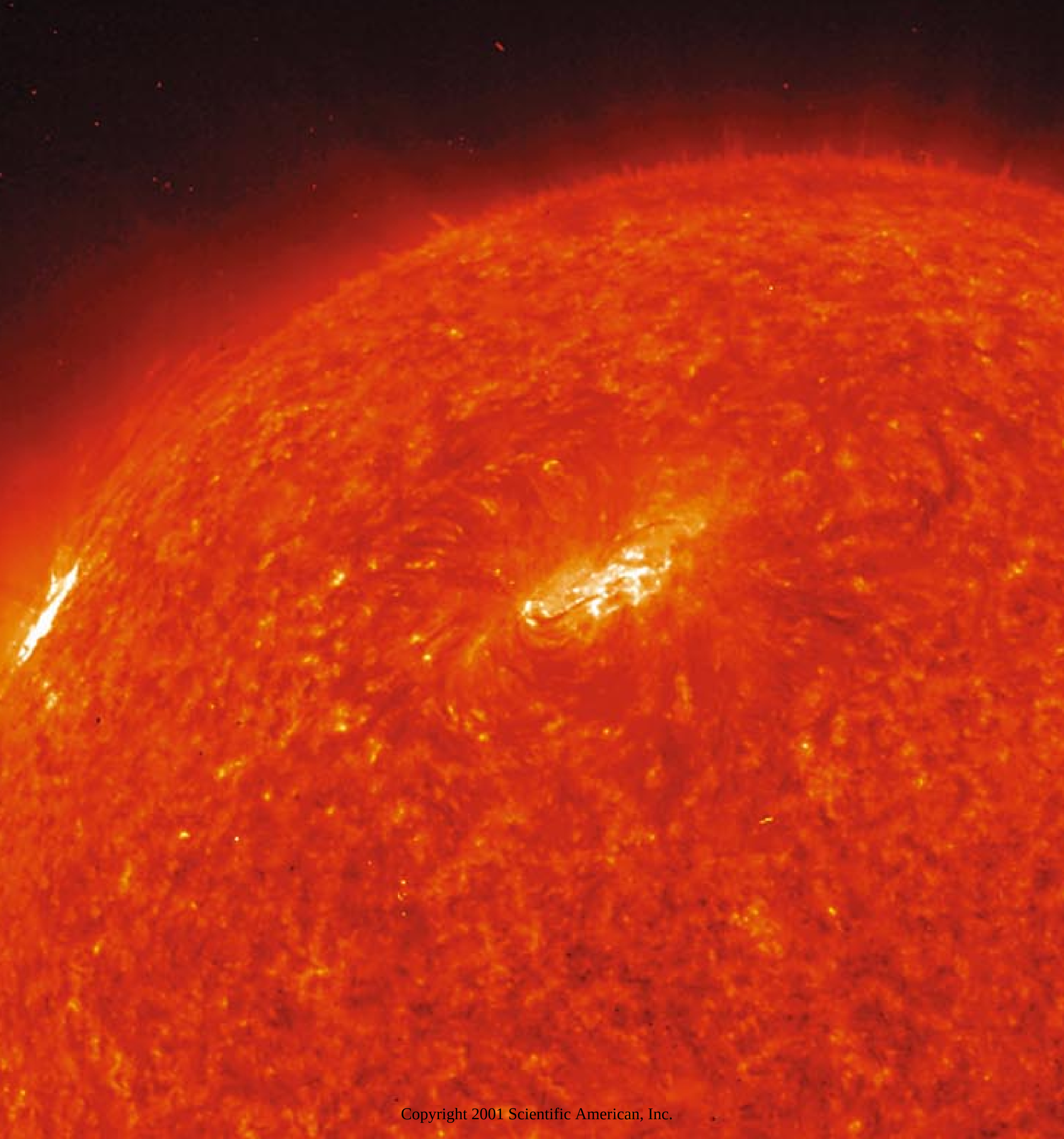
With all the various interests seeking to exploit or conserve the ocean, McNutt keeps an open mind and has learned to moderate controversy with lessons learned from home. "So many times my twins get into an argument. Both are absolutely firm in their convictions. And if you say to either one of them they're wrong, then they start tuning you out." So McNutt tries to make the 15-year-olds aware of the other's position and values.

That trick apparently worked when McNutt recently chaired the President's Panel on Ocean Exploration. First she made sure the committee had no deadweight. "We didn't want people sitting around the table, taking up space and wasting our time when they aren't in a position to give first-class science input," she recalls. The group of eminent scientists and educators reached a consensus calling for a 10-year, $750-million effort to inventory and explore the Exclusive Economic Zone (an area that extends 200 nautical miles from all U.S. coasts), continental margins, the Arctic and other regions.

With roughly 95 percent of the ocean unknown and unexplored, it would seem that McNutt has much work ahead. She intends to add another 60 permanent positions and bring in a wider assortment of visiting scientists and student interns to keep MBARI connected with the broader research community—and, she hopes, a step or two ahead. SA

*John Adam is a technology writer based in Washington, D.C.*

Like a boiling teakettle atop a **COLD** stove,
the sun's **HOT** outer layers sit on the relatively cool surface.
And now astronomers are **FIGURING OUT WHY**



# the paradox of the Sun's hot corona

by Bhola N. Dwivedi and Kenneth J. H. Phillips

SUSPENDED IN MIDAIR, a prominence (*wispy stream on right side*) has erupted off the sun's surface into its atmosphere—the corona. The coronal plasma is invisible in this image, which shows ultraviolet light from cooler gas in the prominence and underlying chromosphere. White areas are high density; red are low density.

**On August 11, 1999, tens of millions of people across** Europe and Asia were witness to one of the most beautiful spectacles in all of nature: a total eclipse of the sun. The two of us were among them. One of us (Phillips) watched from Bulgaria as the glaring disk of the sun was blotted out by the cool black moon, bringing forth the full glory of the gleaming corona. The other (Dwivedi) watched from India as the glaring disk of the sun was blotted out by a dull haze of clouds at just the wrong time. But all was not lost, for the spectacle in the heavens was replaced by one on the ground. Across the holy river Ganges, chants reverberated as vast crowds waded in and prayed for the sun god to reappear.

Millions more will have their view this month as the moon's shadow sweeps across southern Africa. Astronomers will get another of their rare opportunities to make detailed studies of the enigmatic corona from Earth's surface—another chance to make sense of one of the most enduring conundrums in astronomy.

The sun might look like a uniform ball of gas, the essence of simplicity. In actuality it has well-defined layers akin to a planet's solid part and atmosphere. Solar radiation, on which all life on Earth ultimately depends, derives from nuclear reactions deep in the core. The energy gradually leaks out until it reaches the visible surface, known as the photosphere, and escapes into space. Above that surface is a tenuous atmosphere. The lower part of the atmosphere, the chromosphere, is visible as a bright red crescent during total eclipses. Beyond it is the pearly white corona, extending out millions of kilometers. And from the corona's outer reaches emanates the solar wind, the stream of charged particles that blows through the solar system.

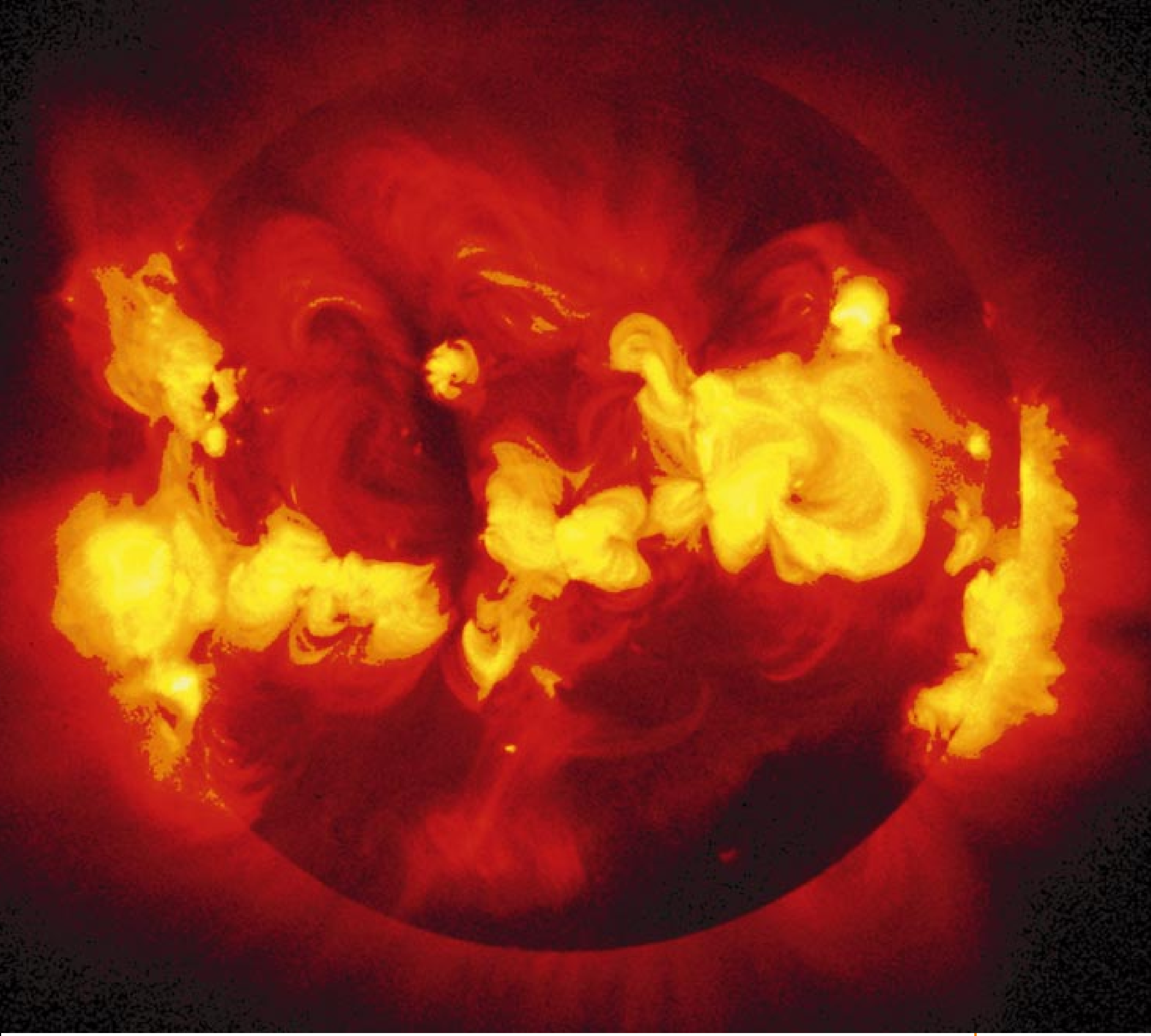
As you might expect, the sun's temperature drops steadily from its core, 15 million kelvins, to the photosphere, a mere 6,000 kelvins. But then an unexpected thing happens: the temperature gradient reverses. The chromosphere's temperature steadily rises to 10,000 kelvins, and going into the corona, the temperature jumps to one million kelvins. Parts of the corona associated with sunspots get even hotter. Considering that the energy must originate beneath the photosphere, how can this be? It is as though you got warmer the farther away you walked from a fireplace.

The first hints of this mystery emerged in the 19th century when eclipse observers detected spectral emission lines that no known element could account for. In the 1940s physicists associated two of these lines with iron atoms that had lost up to half their normal retinue of 26 electrons—a situation that requires extremely high

NASA GODDARD SPACE FLIGHT CENTER (*preceding page*); TRACE/NASA (*below*)

## The loops, ARCHES and holes appear to trace out the sun's MAGNETIC FIELDS.

CORONAL LOOP, seen in ultraviolet light by the TRACE spacecraft, extends 120,000 kilometers off the sun's surface.



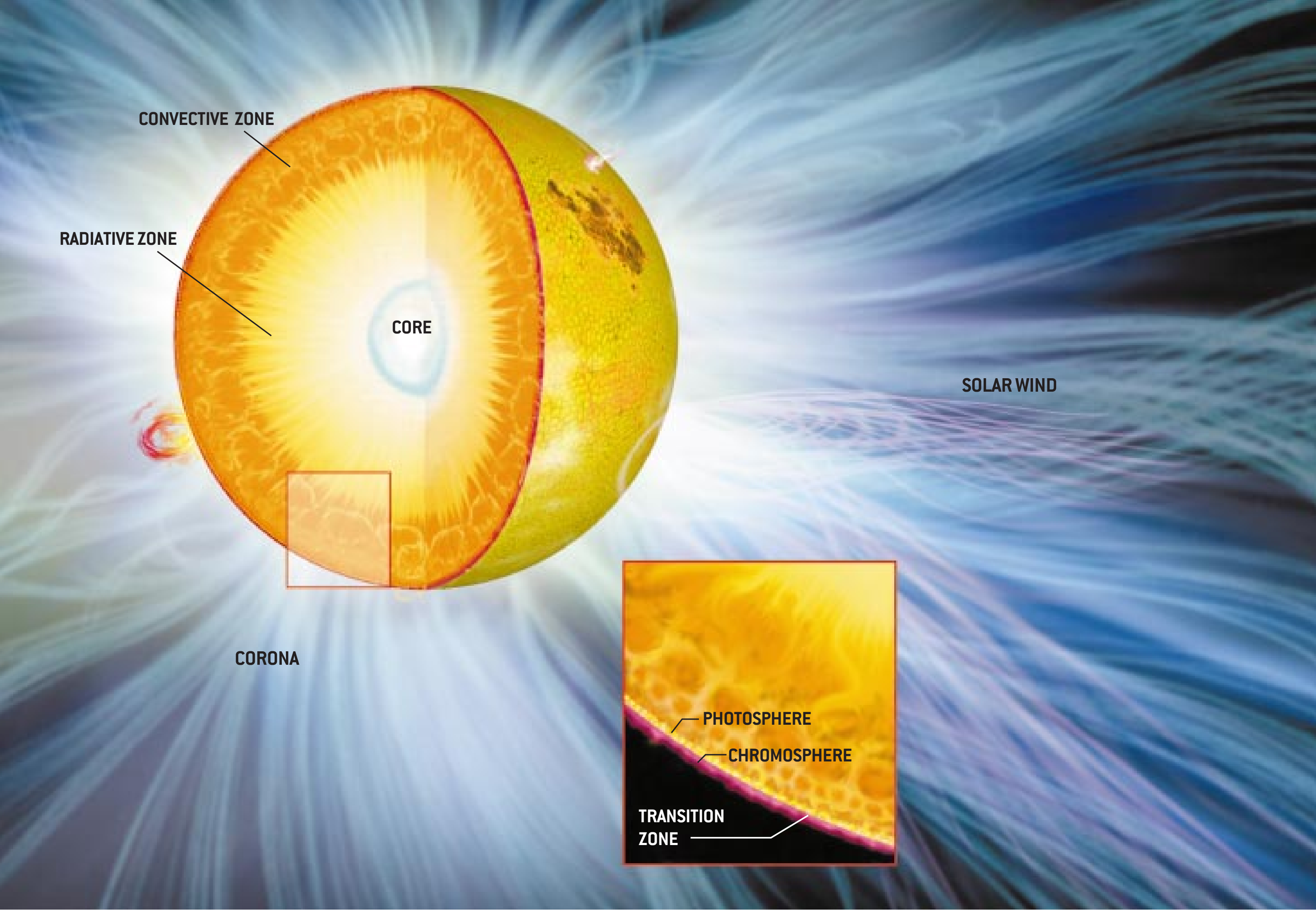
X-RAY IMAGE **from the Yohkoh spacecraft shows structures both bright (associated with sunspots) and dark (the polar coronal hole).**

INSTITUTE OF SPACE AND ASTRONAUTICAL SCIENCE, JAPAN; LOCKHEED-MARTIN SOLAR AND ASTROPHYSICS LABORATORY; NATIONAL ASTRONOMICAL OBSERVATORY OF JAPAN; UNIVERSITY OF TOKYO; NASA

temperatures. Later, instruments on rockets and satellites discovered that the sun emits copious x-rays and extreme ultraviolet radiation—as can be the case only if the coronal temperature is measured in megakelvins. Nor is this mystery confined to the sun: most sunlike stars appear to have x-ray-emitting atmospheres.

At long last, however, a solution seems to be within our grasp. Astronomers have implicated magnetic fields in the coronal heating; where those fields are strongest, the corona is hottest. Such fields can transport energy in a form other than heat, thereby sidestepping the usual thermodynamic restrictions. The energy must still be converted to heat, and researchers are testing two possible theories: small-scale magnetic field reconnections—the same process involved in solar flares—and magnetic waves. Important clues have come from complementary observations: spacecraft can observe at wavelengths inaccessible from the ground, while ground-based telescopes can gather reams of data unrestricted by the bandwidth of orbit-to-Earth radio links. The findings may be crucial to understanding how events on the sun affect the atmosphere of Earth [see "The Fury of Space Storms," by James L. Burch; Scientific American, April].

The first high-resolution images of the corona came from the ultraviolet and x-ray telescopes on board Skylab, the American space station inhabited in 1973 and 1974. Pictures of active regions of the corona, located




DON DIXON

above sunspot groups, revealed complexes of loops that came and went in a matter of days. Diffuse x-ray arches stretched over millions of kilometers. Away from active regions, in the "quiet" parts of the sun, ultraviolet emission had a honeycomb pattern related to the granulation of the photosphere. Near the solar poles were areas of low x-ray emission—the so-called coronal holes.

## Connection to the Starry Dynamo

EACH MAJOR SOLAR SPACECRAFT since Skylab has offered a distinct improvement in resolution. Since 1991 the x-ray telescope on the Japanese Yohkoh spacecraft has routinely imaged the sun's corona, tracking the evolution of loops and other features through one complete 11-year cycle of solar activity. The Solar and Heliospheric Observatory (SOHO), a joint European-American satellite launched in 1995, orbits a point 1.5 million kilometers from Earth on its sunward side, giving the spacecraft the advantage of an uninterrupted view of the sun [see "SOHO Reveals the Secrets of the Sun," by Kenneth R. Lang; Scientific American, March 1997]. One of its instruments, the Large Angle and Spectroscopic Coronagraph (LASCO), observes in visible light using an opaque disk to mask out the main part of the sun. It has tracked large-scale coronal structures as they rotate with the rest of the sun (a period of about 27 days as seen from Earth). The images show huge bubbles of plasma known as coronal mass ejections, which move at up to 2,000 kilometers per second, erupting from the corona and occasionally colliding with Earth and other planets. Other SOHO instruments, such as the Extreme Ultraviolet Imaging Telescope, have greatly improved on Skylab's pictures.

The Transition Region and Coronal Explorer (TRACE) satellite, operated by the Stanford-Lockheed Institute for Space Research, went into a polar orbit around Earth in 1998. With unprecedented resolution, its ultraviolet telescope has revealed a vast wealth of detail. The active-region loops are now known to be threadlike features no more than a few hundred kilometers wide. Their incessant flickering and jouncing hint at the origin of the corona's high temperature.

The loops, arches and coronal holes appear to trace out the sun's magnetic fields. The fields are thought to originate in the upper third of the solar interior, where energy is transported not by radiation but by convection. The circulation acts as a natural dynamo, converting about 0.01 percent of the outgoing radiation into magnetic energy. Differential rotation—whereby low latitudes rotate slightly faster than higher lati-

**The sun might look like a UNIFORM BALL, the essence of simplicity. In actuality, it has well-defined LAYERS.**

tudes—distorts the lines of magnetic force into characteristic patterns. At sites marked by sunspot groups, ropelike bundles of field lines pierce the photosphere and extend outward into the corona.

For a century, astronomers have measured the magnetism of the photosphere using magnetographs, which observe the Zeeman effect: in the presence of a magnetic field, a spectral line can split into two or more lines with slightly different wavelengths and polarizations. But Zeeman observations for the corona have yet to be done; for the spectral lines that the corona emits, the splitting is too small to be detected with present instruments. So astronomers have had to resort to mathematical extrapolations from the photospheric field. These extrapolations predict that the magnetic field of the corona generally has a strength of about 10 gauss, 20 times Earth's magnetic field strength at its poles. In active regions, the field may reach 100 gauss.

## Space Heaters

THESE FIELDS ARE WEAK compared with those that can be produced with laboratory magnets, but they have a decisive influence in the solar corona. This is because the corona's temperature is so high that it is almost fully ionized: it is a plasma, made up not of neutral atoms but of protons, electrons and atomic nuclei (mostly helium). Plasmas undergo a wide range of phenomena that neutral gases do not. The magnetic fields of the corona are strong enough to bind the charged particles to the field lines. Particles move in tight helical paths up and down these field lines like very small beads on very long strings. The limits on their motion explain the sharp boundaries of features such as coronal holes. Within the tenuous plasma, the magnetic pressure (proportional to the strength squared) exceeds the thermal pressure by a factor of at least 100.

One of the main reasons astronomers are confident that magnetic fields energize the corona is the clear relation between field strength and temperature. The bright loops of active regions have a temperature of about four million kelvins, whereas the giant arches of the general corona have a temperature of about one million kelvins.

Until recently, however, ascribing coronal heating to magnetic fields ran into a serious problem. To convert field energy to heat energy, the fields must be able to diffuse through the plasma, which requires that the corona have a certain amount of electrical resistivity—in other words, that it not be a perfect conductor. A perfect conductor cannot sustain an electric field, because charged particles instantaneously reposition themselves to neutralize it. And if a plasma cannot sustain an electric field, it cannot move relative to the magnetic field (or vice versa), because to do so would induce an electric field. This is why astronomers talk about magnetic fields being "frozen" into plasmas.

This principle can be quantified by considering the time it takes a magnetic field to diffuse a certain distance through a plasma. The diffusion rate is inversely proportional to resistivity. Classical plasma physics assumes that electrical resistance arises from so-called Coulomb collisions: electrostatic forces from charged particles deflect the flow of electrons. If so, it should take about 10 million years to traverse a distance of 10,000 kilometers, a typical length of active-region loops.

Events in the corona—for example, flares, which may last for only a few minutes—far outpace that rate. Either the resistivity is unusually high or the diffusion distance is extremely small, or both. A distance as short as a few meters could occur in certain structures, accompanied by a steep magnetic gradient. But researchers have come to realize that the resistivity could be higher than they traditionally thought. Over the past few years, physicists have observed instabilities in laboratory plasmas such as those in fusion devices. Those instabilities can stir up small-scale turbulence and fluctuations in the bulk electric charge, providing a source of resistance more potent than random particle encounters.

## Raising the Mercury

ASTRONOMERS HAVE TWO basic ideas for coronal heating. For years, they concentrated on heating by waves. Sound waves were a prime suspect, but in the late 1970s researchers established that sound waves emerging from the photosphere would dissipate in the chromosphere, leaving no energy for the corona itself. Sus-

THE AUTHORS

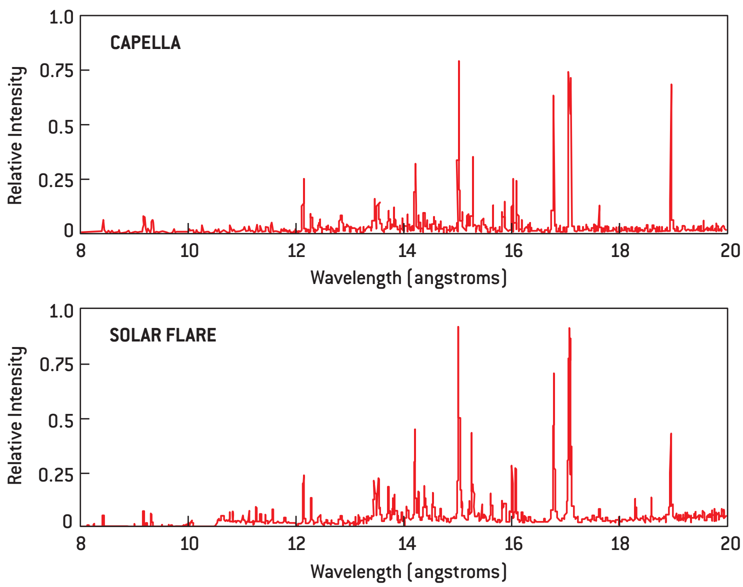
*BHOLA N. DWIVEDI* and *KENNETH J. H. PHILLIPS* began collaborating on solar physics a decade ago. Dwivedi teaches physics at Banaras Hindu University in Varanasi, India. He has been working with SUMER, an ultraviolet telescope on the SOHO spacecraft, for more than 10 years; the Max Planck Institute for Aeronomy near Hannover, Germany, recently awarded him one of its highest honors, the Gold Pin. As a boy, Dwivedi studied by the light of a homemade burner and became the first person in his village ever to attend college. Phillips is the leader of the solar research group at the Rutherford Appleton Laboratory in Didcot, England. He has worked with x-ray and ultraviolet instruments on numerous spacecraft—including OSO-4, SolarMax, IUE, Yohkoh and SOHO—and has observed solar eclipses using CCD cameras.

## Spacecraft imaging is TOO SLUGGISH to capture the periodic FLUCTUATIONS caused by magnetic waves.

picion turned to magnetic waves. Such waves might be purely magnetohydrodynamic (MHD)—so-called Alfvén waves—in which the field lines oscillate but the pressure does not. More likely, however, they share characteristics of both sound and Alfvén waves.

MHD theory combines two theories that are challenging in their own right—ordinary hydrodynamics and electromagnetism—although the broad outlines are clear. Plasma physicists recognize two kinds of MHD pressure waves, fast and slow mode, depending on the phase velocity relative to an Alfvén wave—around 2,000 kilometers per second in the corona. To traverse a typical active-region loop requires about five seconds for an Alfvén wave, less for a fast MHD wave, but at least half a minute for a slow wave. MHD waves are set into motion by convective perturbations in the photosphere and transported out into the corona via magnetic fields. They can then deposit their energy into the plasma if it has sufficient resistivity or viscosity.

A breakthrough occurred in 1998 when the TRACE spacecraft observed a powerful flare that triggered waves in nearby fine loops. The loops oscillated back and forth several times before settling down. The damping rate was millions of times faster than classical theory predicts. This landmark observation of "coronal seismology" by Valery M. Nakariakov, then at the University of St. Andrews in Scotland, and his colleagues has shown that MHD waves could indeed deposit their energy into the corona.




X-RAY SPECTRA of the twin stars Capella (between flares) and the sun (during a flare) both indicate a temperature of six million kelvins—typical for Capella but anomalously high for the sun.

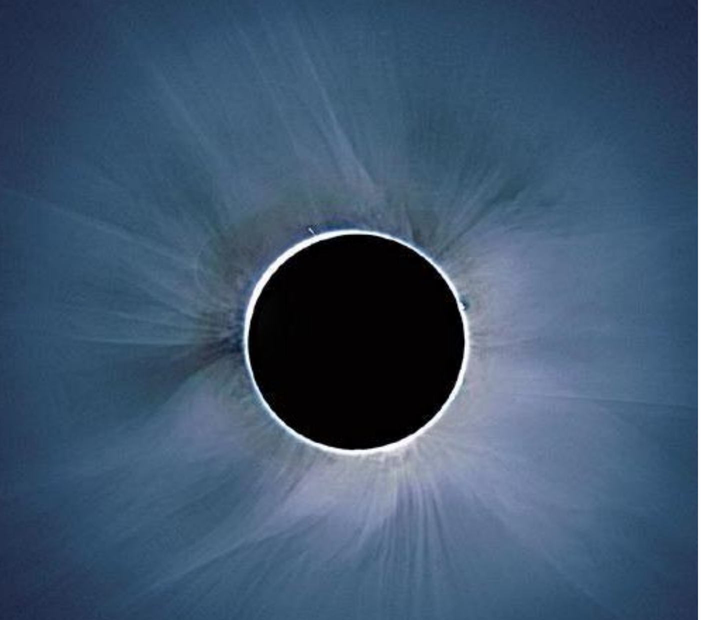
Despite the plausibility of energy transport by waves, a second idea has been ascendant: that coronal heating is caused by very small, flarelike events. A flare is a sudden release of up to $10^{25}$ joules of energy in an active region of the sun. It is thought to be caused by reconnection of magnetic field lines, whereby oppositely directed lines cancel each other out, converting magnetic energy into heat. The process requires that the field lines be able to diffuse through the plasma.

A flare sends out a blast of x-rays and ultraviolet radiation. At the peak of the solar cycle (now occurring), several flares per hour may burst out all over the sun. Spacecraft such as Yohkoh and SOHO have shown that much smaller but more frequent events take place not only in active regions but also in regions otherwise deemed quiet. These tiny events have about a millionth of the energy of a full-blown flare and so are called microflares. Hard x-ray emission from them was first detected in 1980 by Robert P. Lin of the University of California at Berkeley and his colleagues with a balloon-borne detector. During the solar minimum in 1996, Yohkoh also recognized events as small as $10^{17}$ joules.

Flares are not the only type of transient phenomena. X-ray and ultraviolet jets, representing columns of coronal material, are often seen spurting up from the lower corona at several hundred kilometers per second. But tiny x-ray flares are of special interest because they reach the megakelvin temperatures required to heat the corona. As we and Pawel T. Pres of Wroclow University in Poland have found, following up work by renowned solar physicist Eugene N. Parker of the University of Chicago, the observed flare rates can be extrapolated to even tinier events, or nanoflares. The total energy could then account for the radiative output of the corona, about $3 \times 10^{18}$ watts.

Which mechanism—waves or nanoflares—dominates? It depends on the photospheric motions that perturb the magnetic field. If these motions operate on timescales of half a minute or longer, they cannot trigger MHD waves. Instead they create narrow current sheets in which reconnections can occur. Very high resolution optical observations of bright filigree structures by the Swedish Vacuum Tower Telescope on La Palma

LAURIE GRACE



ORDINARY LIGHT, EXTRAORDINARY SIGHT: the corona photographed in visible light on August 11, 1999, from Chadegan in central Iran.

JEAN MOUETTE AND SERGE KOUTCHMY, © INSTITUT D'ASTROPHYSIQUE DE PARIS

in the Canary Islands—as well as SOHO and TRACE observations of a general, ever changing "magnetic carpet" on the surface of the sun—demonstrate that motions occur on a variety of timescales. Although the evidence now favors nanoflares for the bulk of coronal heating, waves may also play a role.

## Fieldwork

IT IS UNLIKELY, for example, that nanoflares have much effect in coronal holes. In these regions, the field lines open out into space rather than loop back to the sun, so a reconnection would accelerate plasma out into interplanetary space rather than heat it. Yet the corona in holes is still hot. Astronomers have scanned for signatures of wave motions, which may include periodic fluctuations in brightness or Doppler shift. The difficulty is that the MHD waves involved in heating probably have very short periods, perhaps just a few seconds. At present, spacecraft imaging is too sluggish to capture them.

For this reason, ground-based instruments remain important. A pioneer in this work has been Jay M. Pasachoff of Williams College. Since the 1980s he and his students have used high-speed detectors to look for modulations in the coronal light during eclipses. Analyses of his best results indicate oscillations with periods of one to two seconds. Serge Koutchmy of the Institute of Astrophysics in Paris, using a coronagraph, has found evidence of periods equal to 43, 80 and 300 seconds.

The search for those oscillations is what led Phillips and his team to Shabla, a small town on the Black Sea coast of Bulgaria, for the August 1999 eclipse. Our instrument consists of a pair of fast-frame CCD cameras that observe both white light and the green spectral line produced by highly ionized iron. A tracking mirror, or heliostat, directs sunlight into a horizontal beam that passes into the instrument. During the two minutes and 23 seconds of totality, the instrument took 44 images per second. Analyses by Pawel Rudawy of Wroclaw and David A. Williams of the Queen's University of Belfast have revealed localized oscillations, generally along loop structures. The periods are between two and 10 seconds. Elsewhere, however, our instrument detected no oscillations. Therefore, MHD waves are likely to be present but not pervasive or strong enough to dominate coronal heating. We will take our equipment to Zambia for the June 21 eclipse and later adapt it for a coronagraph. (Although the opaque disk inside a coronagraph allows year-round observing, it cannot mask out the sun as effectively as the moon during an eclipse.)

Insight into coronal heating has also come from observations of other stars. Current instruments cannot see surface features of these stars directly, but spectroscopy can deduce the presence of starspots, and ultraviolet and x-ray observations can reveal coronae and flares, which are often much more powerful than their solar counterparts. High-resolution spectra from the Extreme Ultraviolet Explorer and the latest x-ray satellites, Chandra and XMM-Newton, can probe temperature and density. For example, Capella—a stellar system consisting of two giant stars—has photospheric temperatures like the sun's but coronal temperatures that are six times higher. The intensities of individual spectral lines indicate a plasma density of about 100 times that of the solar corona. This high density implies that Capella's coronae are much smaller than the sun's, stretching out a tenth or less of a stellar diameter. Apparently, the distribution of the magnetic field differs from star to star. For some stars, tightly orbiting planets might even play a role.

The mystery of why the solar corona should be so hot has intrigued astronomers for more than half a century, but the reason is now within our grasp, given the latest findings from spacecraft and fast imaging of the corona during eclipses. But even as one mystery begins to yield to our concerted efforts, others appear. The sun and other stars, with their complex layering, magnetic fields and effervescent dynamism, still manage to defy our understanding. In an age of such exotica as black holes and dark matter, even something that seems mundane can retain its allure. SA

## MORE TO EXPLORE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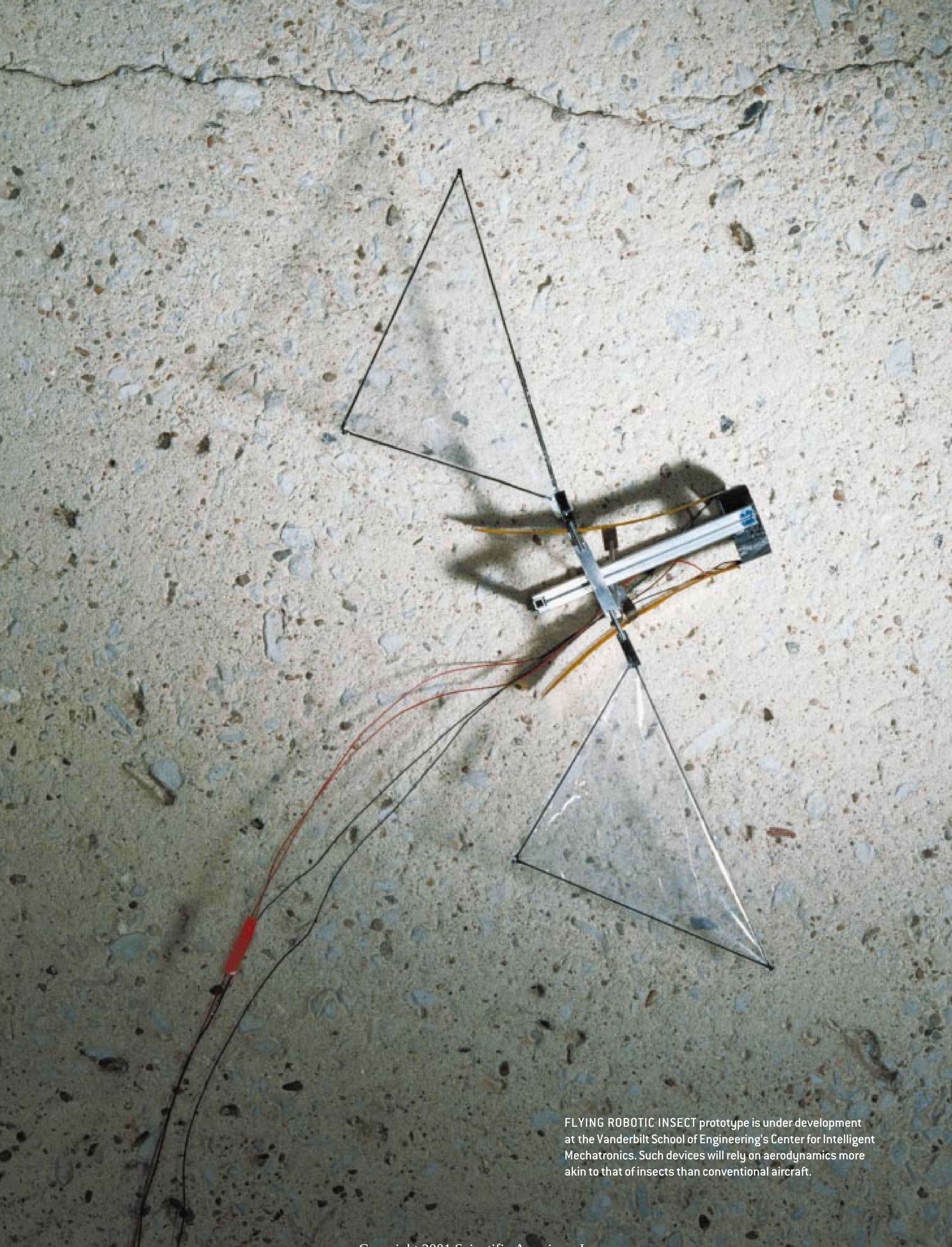


FLYING ROBOTIC INSECT prototype is under development at the Vanderbilt School of Engineering's Center for Intelligent Mechatronics. Such devices will rely on aerodynamics more akin to that of insects than conventional aircraft.

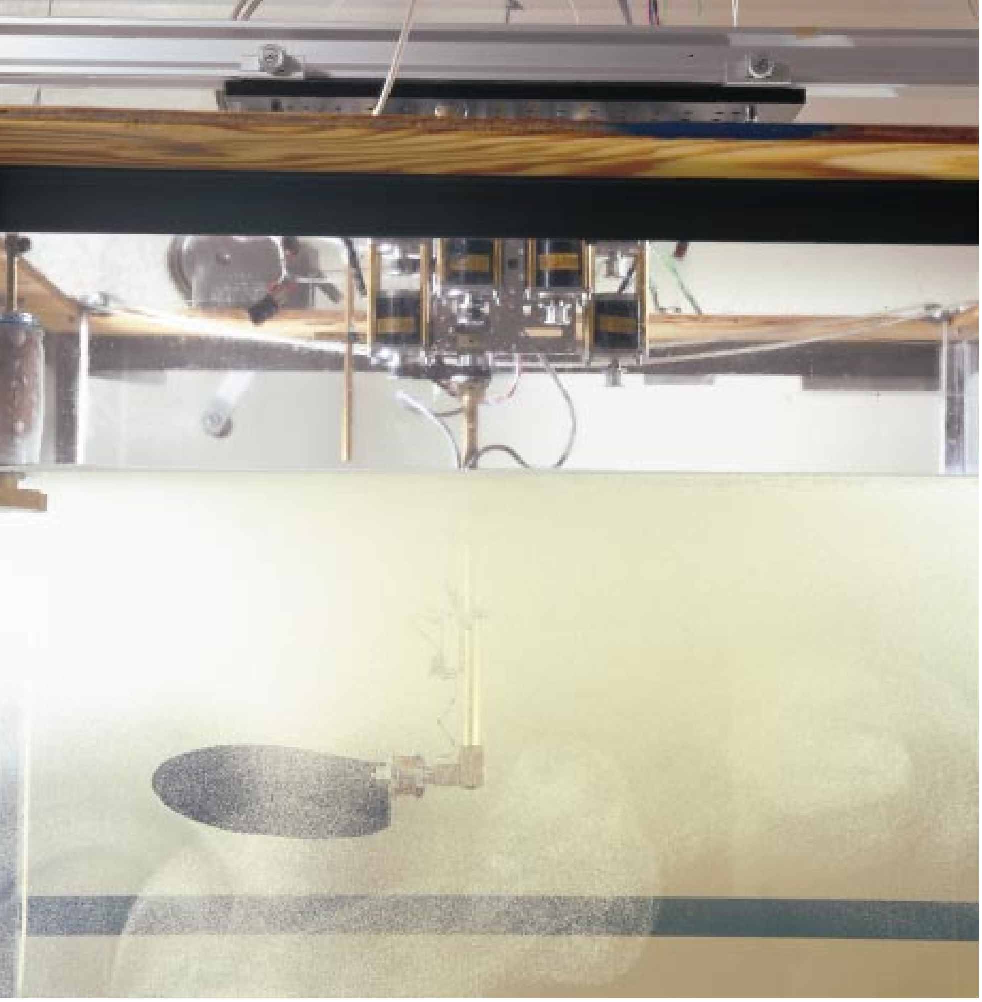
# Solving the Mystery of INSECT FLIGHT

## INSECTS USE A COMBINATION OF AERODYNAMIC EFFECTS TO REMAIN ALOFT

BY MICHAEL DICKINSON
Photographs by Timothy Archibald

In a two-ton tank of mineral oil, a pair of mechanical wings flap continuously back and forth, taking a leisurely five seconds to complete each cycle. Driven by six computer-controlled motors, they set the fluid swirling, a motion that is revealed by millions of air bubbles immersed in the liquid (the tank has a strong resemblance to a giant glass of beer, albeit one with a 60-centimeter-wingspan mechanical fly thrashing around in it). Flashing sheets of green laser light illuminate the scene, and specialized video cameras record the paths of the glistening, churning bubbles. Sensors in the wings record the forces of the fluid acting on them at each moment.

My research group constructed this odd assortment of specialized equipment to help explain the physics of one of the commonest of occurrences—the hovering of a tiny fruit fly. The fly knows nothing of the aerodynamics of vortex production, delayed stall, rotational circulation and wake capture; it merely employs their practical consequences 200 times each second as its wings flap back and forth. The fly's mechanical simulacra, dubbed Robofly, imitates the insect's flapping motion, but at a thousandth the speed and on a 100-fold larger scale. Awed by the rapidity and the small size of the real thing, my colleagues and I pin our hopes on Robofly for understanding the intricate aerodynamics that allows insects to do what they do so routinely—that is, how they are able to fly.



ROBOFLY FLAPPING SLOWLY in viscous mineral oil simulates the aerodynamics of fruit-fly wings flapping rapidly in air. Laser beams illuminate air bubbles in the oil to reveal the intricate flows produced, and sensors in the wings record the forces generated.

As measured by sheer number of species, ecological impact or total biomass, insects are the dominant animals on our planet. Although numerous factors contribute to their extraordinary success, the ability to fly ranks high on the list. Flight enables insects to disperse from their birthplace, search for food over large distances and migrate to warmer climes with the changing seasons. But flight is not simply a means of transport—many insects use aerial acrobatics to capture prey, defend territories or acquire mates. Selection for ever more elaborate and efficient flight behavior has pushed the design of these organisms to the limit. Within insects we find the most sensitive noses, the fastest visual systems and the most powerful muscles—all specializations that are linked one way or another to flight behavior. Until recently, however, an embarrassing gap has marred our understanding of insect flight: scientists have had a difficult time explaining the aerodynamics of how insects generate the forces needed to stay aloft.

That difficulty has even made its way into an urban legend of science, typically recounted as "a scientist 'proved' that a bumblebee can't fly" and often cited as an inspiring example for persevering in the face of overbearing dogma. The bumblebee story can be traced back to a 1934 book by entomologist Antoine Magnan, who refers to a calculation by his assistant André Sainte-Laguë, who was an engineer. The conclusion was presumably based on the fact that the maximum possible lift produced by aircraft wings as small as a bumblebee's wings and traveling as slowly as a bee in flight would be much less than the weight of a bee.

In the decades since 1934, engineers and mathematicians have amassed a body of aerodynamic theory sufficient to design Boeing 747s and stealth fighters. As sophisticated as these aircraft may be, their design and function are based on steady-state principles: the flow of air around the wings and the resulting forces generated by that flow are stable over time. The reason insects represent such a challenge is that they flap and rotate their wings from 20 to 600 times a second. The resulting pattern of airflow creates aerodynamic forces that change continually and confound both mathematical and experimental analyses.

In addition to resolving an old scientific puzzle, understanding how insects fly may have practical applications. Recently engineers have begun to explore the possibility of developing thumb-size flying robots for applications such as search and rescue, environmental monitoring, surveillance, mine detection and planetary exploration. Although humans have succeeded in constructing model aircraft as small as a bird, no one has built a fly-size airplane that can fly. The viscosity of air has greater importance at such tiny sizes, damping out the kind of airflows that keep larger aircraft aloft. Insects flap their wings not simply because animals have never evolved wheels, gears and turbines, but because their Lilliputian dimensions require the use of different aerodynamic mechanisms. Robotic insects of the future may owe their aerodynamic agility to their natural-world analogues.

## A BLUR OF WINGS

IT IS APPARENT to the casual observer that a hovering insect, its wings a blur, does not fly like an aircraft. Much less obvious is the complexity of the flapping motion. Insect wings do not merely oscillate up and down like paddles on simple hinges. Instead the tip of each wing traces a narrow oval tilted at a steep angle. In addition, the wings change orientation during each flap: the topside faces up during the downstroke, but then the wing rotates on its axis so that the underside faces up during the upstroke.

THE AUTHOR

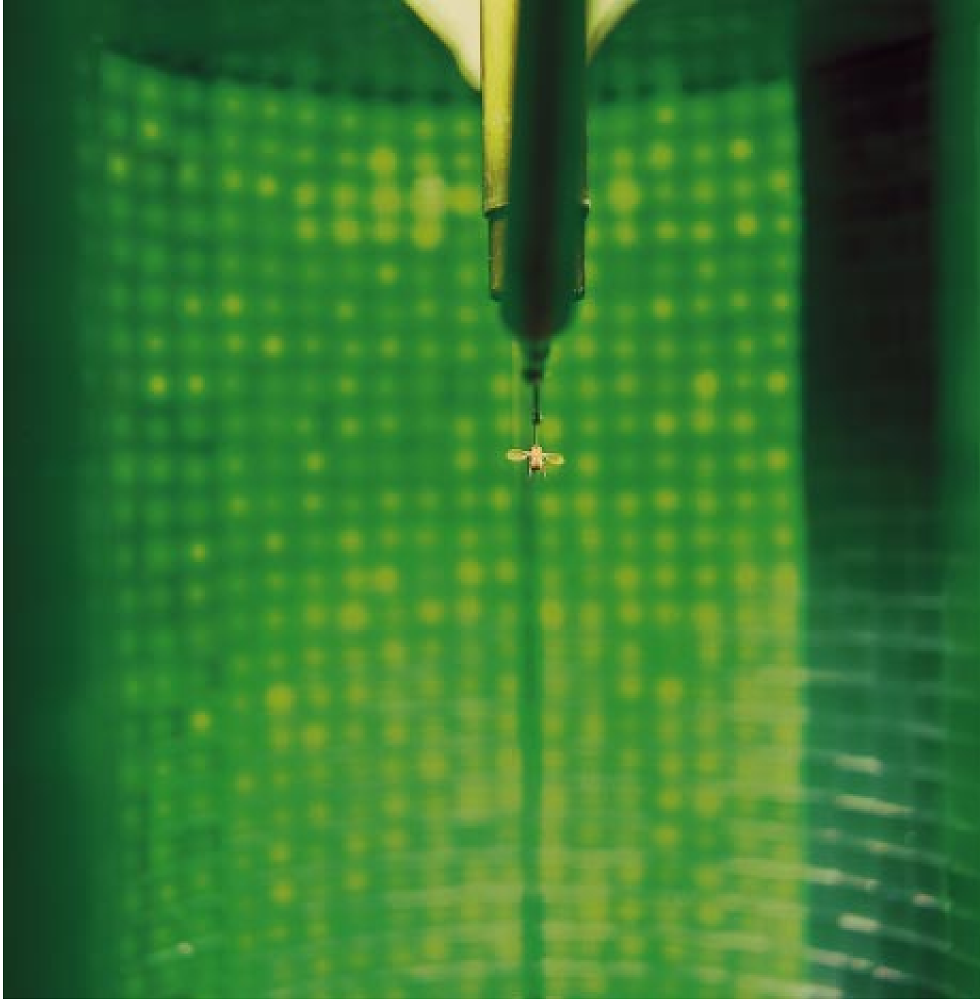
*MICHAEL DICKINSON* began his career as a neurobiologist, focusing on the cellular basis of behavior. His interest in flight developed from an investigation of tiny sensory structures that sense the bending of a wing as it flaps. He now attempts to study behavior in a more integrated fashion, by synthesizing the tools and analyses of biology, physics and engineering. He is a professor in the department of integrative biology at the University of California, Berkeley.

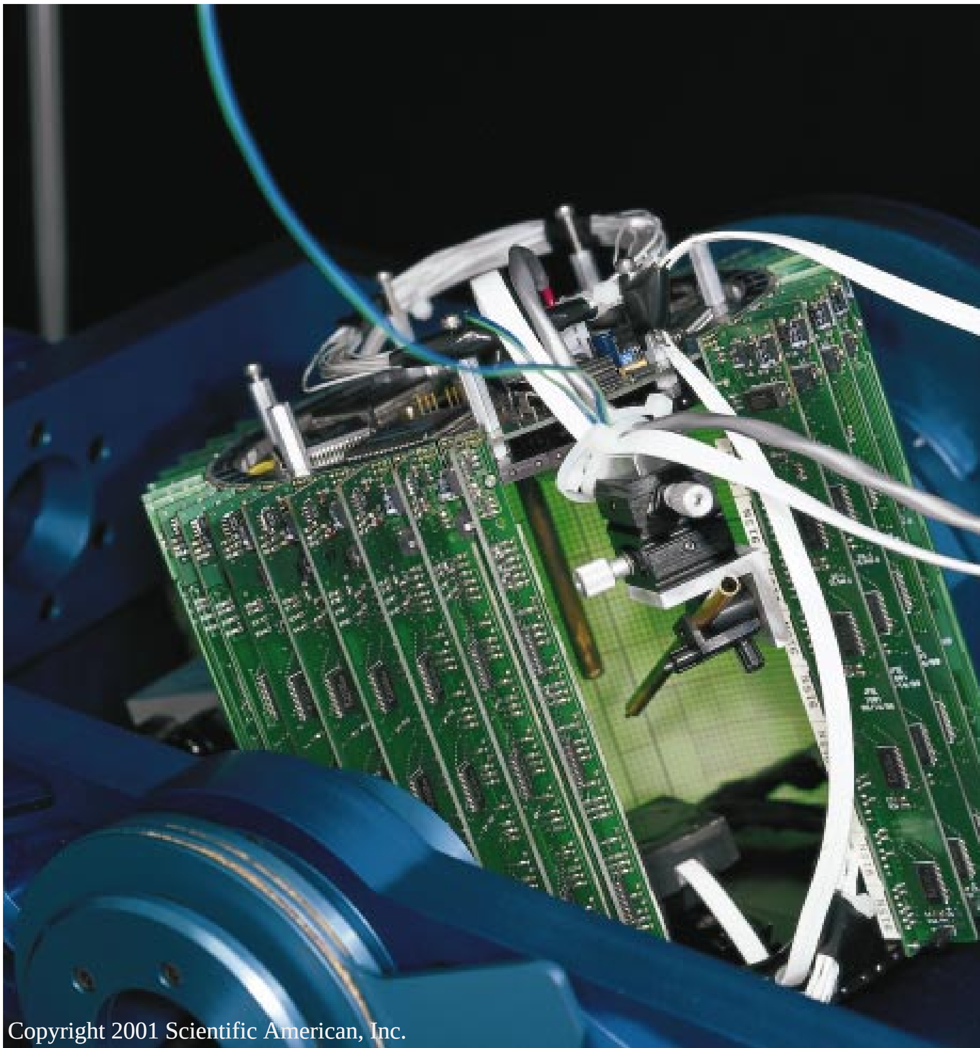
The earliest analyses of insect flight tried to apply conventional steady-state aerodynamics, the approach that works for aircraft wings, to these complex motions. Such attempts are not as naive as the infamous bumblebee computation, because they take into account the changing velocity of the wings as they flap through the air. Imagine freezing the insect's wing at one position in the stroke cycle and then testing it in a wind tunnel with the wind velocity and the wing orientation set to mimic the precise movement of the wing through the air at that instant. In this way, one could measure the aerodynamic force acting on the wing at each moment.

If this steady-state theory were sufficient, the average force, computed by adding up the forces for all the different wing positions throughout the stroke, should point upward and equal the insect's weight. Even in the late 1970s experts disagreed about whether such analysis could explain how insects stay aloft. In the early 1980s Charles Ellington of the University of Cambridge carefully reviewed all available evidence and concluded that the steady-state approach could not account for the forces required. The search for dynamic, "unsteady flow" mechanisms that could explain the enhanced performance of flapping wings took off with renewed vigor.

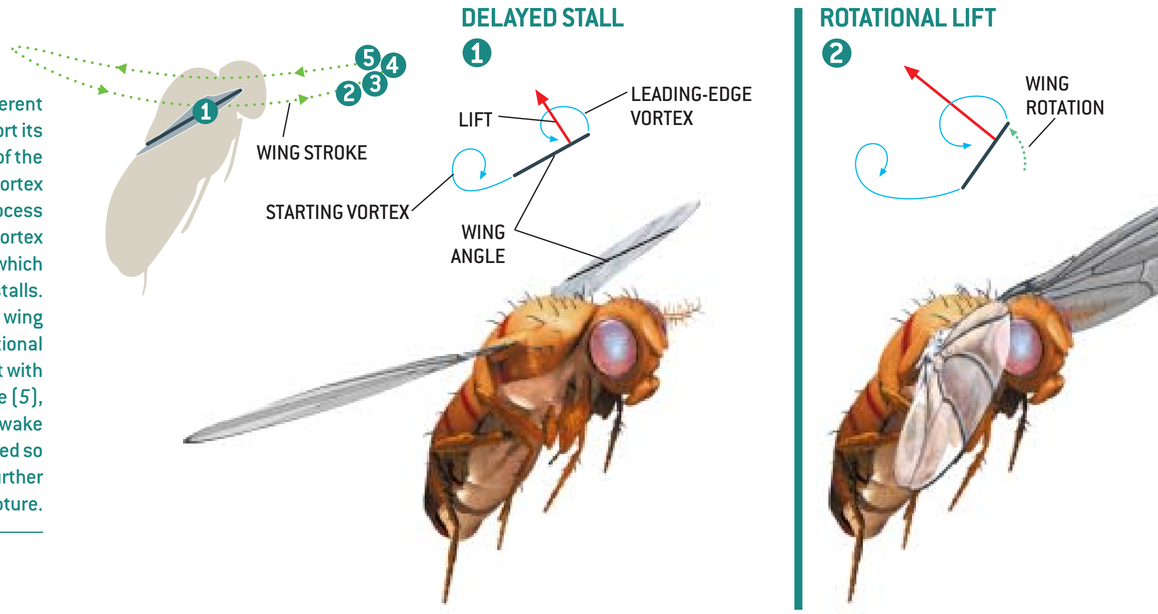
The distribution of velocities and pressures within a fluid is governed by the Navier-Stokes equations, which were formulated in the early 1800s. (For the purpose of analyzing aerodynamics, air is simply a very low density fluid.) If we could solve these equations for a flapping insect wing, we could fully characterize the aerodynamics of the insect's flight. Unfortunately, the complex motion of the wing renders this problem excruciatingly hard to simulate with even the most powerful computers.

If we can't solve the problem by pure

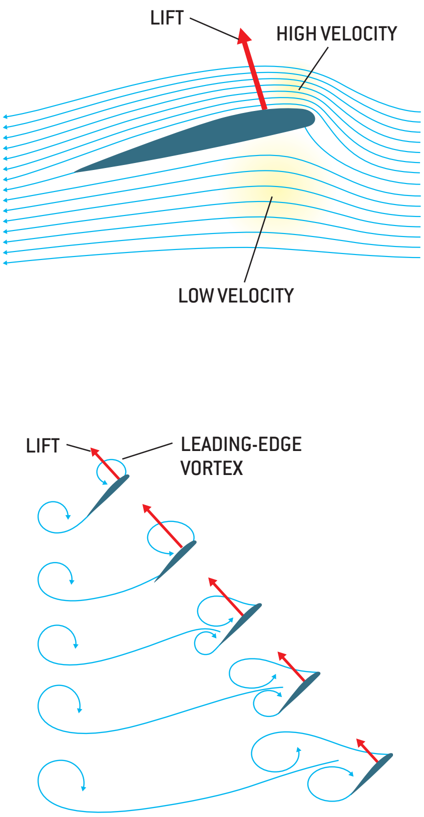




TETHERED FLY is seen against the backdrop of a virtual-reality arena (*top*). A computer controls the thousands of green diodes to produce the illusion (for the fly) of objects moving according to the fly's aerodynamic maneuvers. A similar arena is mounted on a gimble (*bottom*) to simulate the turns, rolls and yaws of free flight.




FRUIT FLY USES three different aerodynamic mechanisms to support its weight in the air. During much of the wing stroke (*1*), a leading-edge vortex forms and increases lift, a process called delayed stall because the vortex does not have time to detach, which is what happens when an aircraft stalls. At the end of a stroke (*2, 3, 4*), the wing rotates, which produces rotational lift analogous to a tennis ball hit with backspin. At the start of the upstroke (*5*), the wing passes back through the wake of the downstroke. The wing is oriented so that this increased airflow adds further lift, a process called wake capture.




AIRCRAFT WING generates lift by steady-flow aerodynamics (*top*). Smooth flow over the top of the wing is faster than that under the wing, producing a region of low pressure and an upward force. If the angle of attack is too great (*bottom*), the wing stalls. When a stall begins, a leading-edge vortex forms with a high flow velocity that momentarily increases lift. The vortex quickly detaches from the wing, however, greatly reducing lift.

theory and computation, can we instead directly measure the forces generated by a flapping insect wing? Several groups have made informative and valiant efforts and are developing imaginative new approaches, but the delicate size and high speed of insect wings make force measurements difficult.

To circumvent these limitations, biologists studying animal locomotion frequently employ scale models—the same trick used by engineers to design planes, boats and automobiles. Engineers scale their vehicles down in size, whereas insect-flight researchers enlarge and slow the wings to a more manageable size and speed. Such models produce meaningful aerodynamic results provided they meet a key condition regarding the two forces that an object encounters within a fluid: a pressure force produced by fluid inertia and a shear force caused by fluid viscosity. The inertial force is essentially that needed to push along a mass of fluid and is larger for denser fluids. Viscosity is more like friction; produced when adjacent regions of fluid move at different velocities, it is what makes molasses hard to stir. The underlying physics of the real and the model animals is identical as long as both have the same ratio of inertial to viscous forces, called the Reynolds number.

The Reynolds number increases in proportion to an object's length and velocity and the density of the fluid; it decreases in proportion to the fluid's viscosity. Being large and fast, aircraft operate at Reynolds numbers of about a million to 100 million. Being small and slow, insects operate at Reynolds numbers of around 100 to 1,000 and under 100 for the tiniest insects, such as thrips, which are a common garden pest.

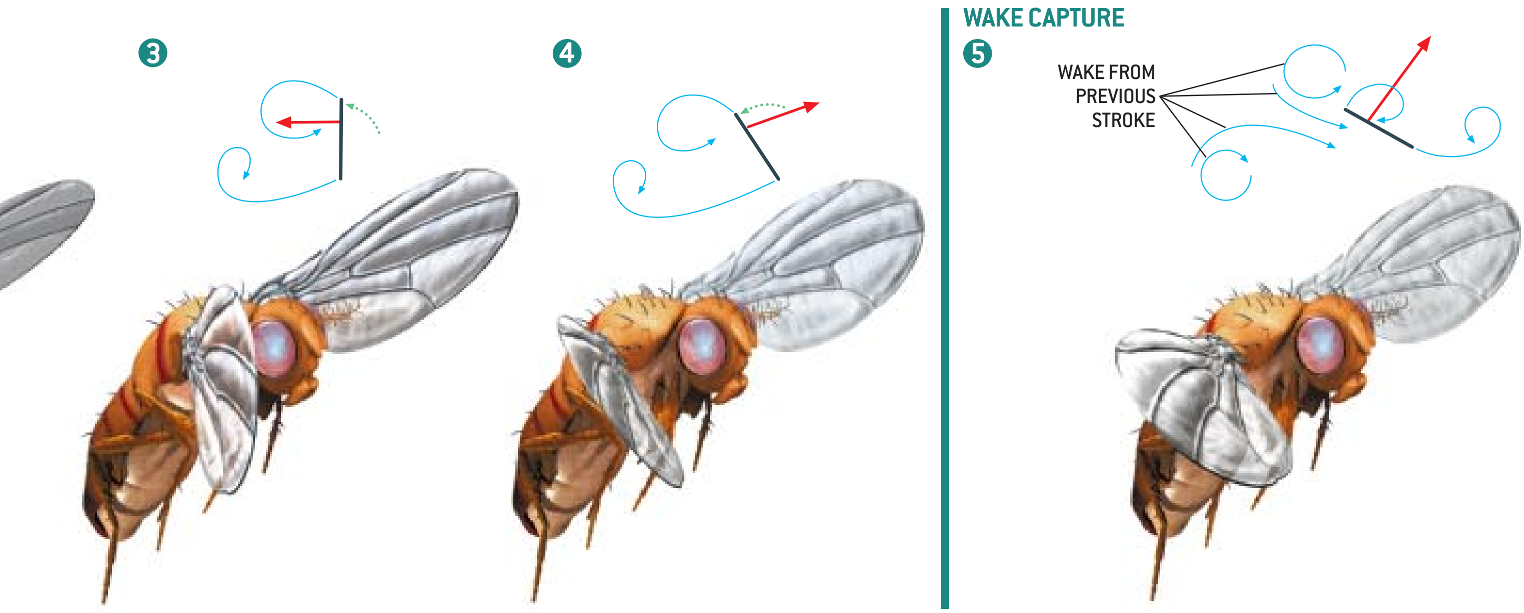
## DELAYED STALL

TO GAIN SOME INSIGHT into how a flapping fruit-fly wing generates aerodynamic force, in 1992 Karl Götz and I, both then at the Max Planck Institute for Biological Cybernetics in Tübingen, Germany, built a model wing consisting of a five-by-20-centimeter paddle connected to a series of motors that moved it within a large tank of thick sugar syrup. That combination of increased size and viscosity, and the slower flapping rate, resulted in the same Reynolds number, and thus the same physics, as a fruit-fly wing that is flapping in air.

We equipped the wing with a force sensor to measure the lift and drag generated as it moved through the sticky fluid. We put baffles at the ends of the wing to inhibit flow along the length and around the edge of the wing. Simple aerodynamic models often use this technique: it effectively reduces the flow from three dimensions to two, which makes the analysis easier but at the risk of missing important effects.

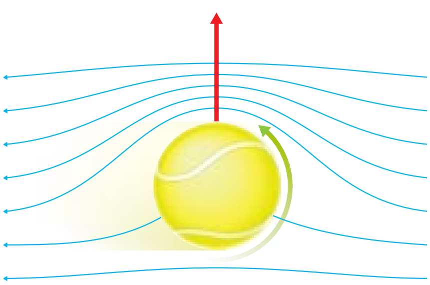
Our experiments with this model wing and work in other laboratories helped to uncover one possible solution to the conundrum of insect flight: de-

ILLUSTRATIONS BY BRYAN CHRISTIE




layed stall. In an aircraft, stall occurs if the angle that the wing cuts through the air—the angle of attack—is too steep. At shallow angles of attack, the air splits at the front of the wing and flows smoothly in two streams along the upper and lower surfaces. The upper flow travels faster, resulting in a lower pressure above the wing, which sucks the wing upward, producing lift. When the angle of attack is too steep, however, the upper flow cannot follow the contour of the upper surface and separates from the wing, resulting in a catastrophic loss of lift.

How can stall, which is disastrous for an airplane, help to lift an insect? The answer lies in the rate at which the wings flap. Wings do not stall instantly; it takes some time for the lift-generating flow to break down after the angle of attack increases. The initial stage of stall actually briefly increases the lift because of a short-lived flow structure called a leading-edge vortex. A vortex is a rotating flow of fluid, as occurs in tornadoes or the little whirlpool in a draining bathtub.



AIRFLOW AROUND a tennis ball that is hit with backspin generates rotational lift. Insects use the same phenomenon by rotating their wings at the end of each stroke.

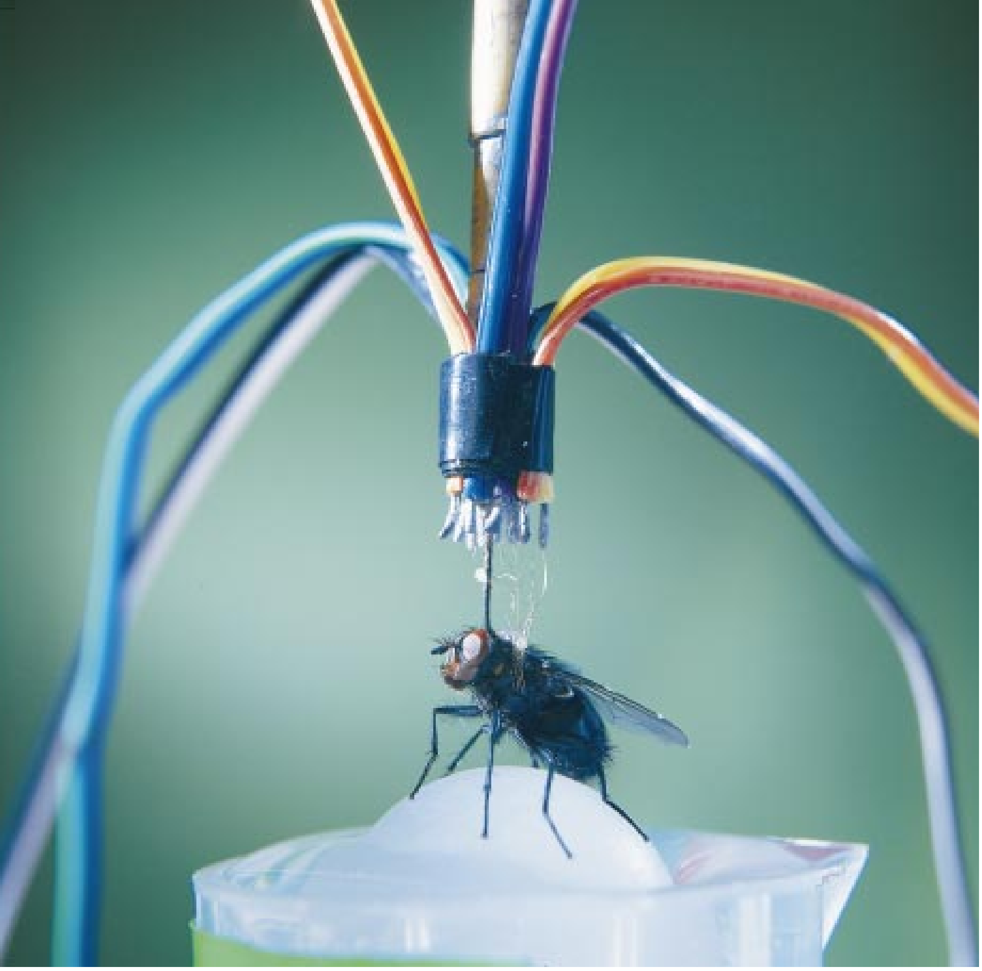
The leading-edge vortex forms just above and behind the wing's leading edge, like a long cylindrical whirlpool turned on its side. The airflow in the vortex is very fast, and the resulting very low pressure adds substantial lift. This effect was first recognized by aeronautics engineers in England in the early 1930s, but it is too brief to be of use to most aircraft. Very quickly, the vortex detaches from the wing and is shed into the aircraft's wake, and lift drops precipitously, as does the plane. The wing strokes of insects, however, are so brief that the wing flips over and reverses direction, producing a new vortex in the opposite direction immediately after the previous one is shed.

These results, obtained with simplified two-dimensional models, were extended to three dimensions in the mid-1990s by Ellington and his co-workers at Cambridge. His group studied the large hawkmoth, *Manduca sexta,* flying tethered in a wind tunnel, as well as a fully three-dimensional robotic moth. Lines of smoke (called a smoke rake) revealed that a vortex is indeed attached to the wings' leading edges during the downstroke. Ellington's team suggested that an axial flow of air from base to tip of the wings enhanced the effect by reducing the strength of the vortex but increasing its stability and allowing it to remain attached to the wings throughout the stroke. Such axial

The first animals to evolve active flight were insects.

Most insects have two pairs of wings. The hind wings of flies, however, have evolved into tiny sensory organs that function as gyroscopes, monitoring the orientation of the fly's body.

Per second, flying expends about 10 times more energy than locomotion on the ground. On the other hand, per kilometer traveled, flying is four times more energy-efficient than ground locomotion. Thus, flying is very hard to achieve but has great value for organisms that can do it.



BLOWFLY IS WIRED for studies that relate the electrical activity in steering muscles to changes in wing motion that occur during steering maneuvers.

flow might be especially important for large insects such as hawkmoths and dragonflies that flap their wings over a great distance during each stroke.

Although identifying this effect solved a major piece of the puzzle, various lines of evidence suggested that insects harnessed other mechanisms in addition to delayed stall. First, the extra force produced by delayed stall is enough to explain how an insect remains airborne but insufficient to explain how many insects can lift almost twice their body weight. Second, several investigators have attempted to measure the forces an insect creates by tethering it to a sensitive force transducer. Such experiments must be viewed cautiously, because tethered animals may not behave identically to freely flying animals, but the precise timing of the forces is not easily explained by delayed stall. For example, when Götz used a laser diffraction technique to measure the forces generated by a fruit fly, he found that the greatest forces occurred during the upstroke—at a time when the forces resulting from delayed stall are expected to be weak.

To search for additional unsteady mechanisms, in 1998 Fritz-Olaf Lehmann, Sanjay P. Sane and I constructed a large model of a flapping fruit fly, *Drosophila melanogaster*—the Robofly described earlier. The viscous mineral oil within the tank makes the 25-centimeter robot wings flapping once every five seconds dynamically similar to 2.5-millimeter fruit-fly wings flapping 200 times a second in air. We measured two critical properties—the aerodynamic forces on the wings and the fluid flow around them—that are nearly impossible to determine on real fly wings. Although Robofly is designed to mimic a fruit fly, by programming the six motors that drive the two wings, we can re-create the wing motion of numerous insect species. In addition, we can make Robofly flap its wings in any way required to test specific hypotheses—a luxury not afforded by real animals, which tend to get temperamental under laboratory conditions.

## ROBOFLY'S RESULTS

WHEN ROBOFLY FLAPPED like a fruit fly, we measured a curious pattern of forces. The wings generated momentary strong forces at the beginning and end of each stroke that could not be easily explained by delayed stall. These force peaks occurred during stroke reversal, when the wing slows down and rapidly rotates, suggesting that the rotation itself might be responsible.

Rotating objects moving through the air produce flows similar to those that lift a conventional wing. A tennis ball hit with backspin pulls air faster over the top, causing the ball to rise. Conversely, topspin pulls air faster underneath, pushing the ball down. A flat wing is different from a spherical ball, but rotation of a wing should produce some lift by the same general mechanism.

We tested our hypothesis by modifying the precise moment in the stroke cycle when the wing flips. If a wing rotates at the end of one stroke, as in a normal fly stroke, the wing's leading edge rotates backward relative to the direction in

Insects possess the most diverse wing structure and kinematics of all flying animals.

Flight muscle of insects exhibits the highest-known metabolic rate of any tissue.

Air is more kinematically viscous than water: its ratio of viscosity to density is higher. That ratio is what matters for fluid dynamics.

PROTOTYPE MICROMECHANICAL flying insect is being developed by the Robotics and Intelligent Machines Laboratory at the University of California at Berkeley. The design parameters are based on the blowfly *Calliphora*.

which the wing is moving and the wing should develop some upward force—analogous to a tennis ball hit with backspin. If the wing rotates late, at the beginning of the next stroke, the leading edge moves forward relative to the direction of motion, and the wing will develop a downward force analogous to topspin. Robofly's data were in complete agreement with these expectations, indicating that flapping wings develop significant lift by rotational circulation.

There remained, however, another significant force peak in Robofly's data, occurring at the start of each downstroke and upstroke, that rotational circulation could not easily explain. Several sets of experiments indicated that this peak was caused by a phenomenon called wake capture—the collision of the wing with the swirling wake of the previous stroke.

Each stroke of the wing leaves behind a complicated wake consisting of the vorticity it produced by traveling and rotating through the fluid. When the wing reverses direction, it passes back through this churning air. A wake contains energy lost from the insect to the fluid, so wake capture provides a way for the insect to recover some of that energy—to recycle it, one might say. We tested the wake-capture hypothesis by bringing Robofly's wings to a complete stop after flapping back and forth. The stationary wings continued to generate force because the fluid around them was still moving.

Although wake capture must always occur at the start of each stroke, as with rotational circulation the fly can manipulate the size and direction of the force produced by changing the timing of wing rotation. If the wing rotates early, it already has a favorable angle of attack when it collides with the wake, producing a strong upward force. If the wing rotates late, collision with the wake generates a downward force.

Together wake capture and rotational circulation also help to explain the aerodynamics of flight control—how flies steer. Flies are observed to adjust the timing of wing rotation when they turn. In some maneuvers, the wing on the outside of a turn rotates early, producing more lift, and the wing on the inside of a turn rotates late, generating less lift; the net force tilts and turns the fly in the desired direction. The fly has at its disposal an array of sophisticated sensors, including eyes, tiny hind wings that are used as gyroscopes, and a battery of mechanosensory structures on the wings that it can use to precisely tune rotational timing, stroke amplitude and other aspects of wing motion.

## BRIDE OF ROBOFLY

THE WORK of numerous researchers is beginning to coalesce into a coherent theory of insect flight, but many questions remain. Insects have a vast array of body forms, sizes and behaviors, ranging from tiny thrips to large hawkmoths; from two-winged flies such as fruit flies to lacewings that flap two pairs of wings slightly out of sync and tiger beetles that have two large stationary wings (their elytra, which form their carapace when on the ground) in addition to the two wings that flap. To what extent do the results for fruit flies apply to these myriad cases?

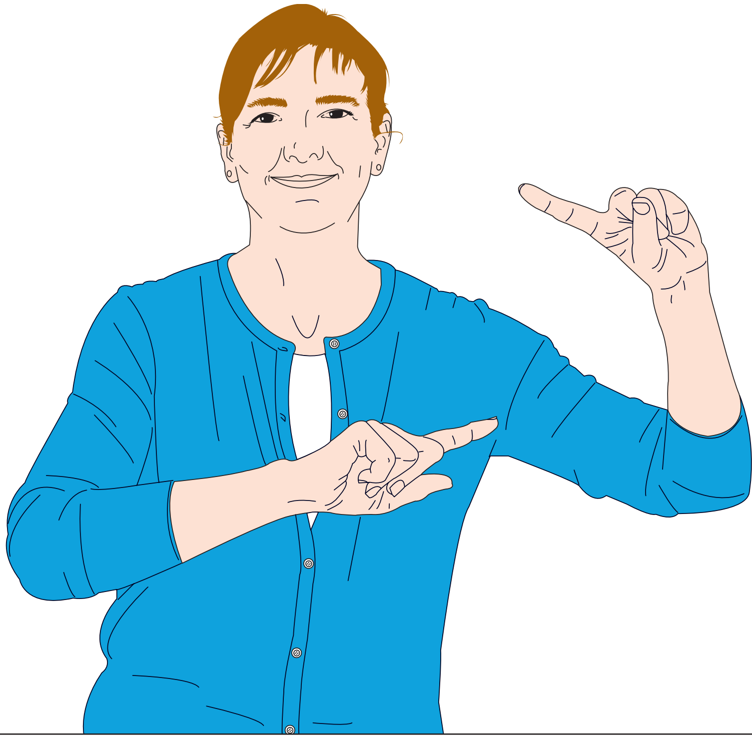
Also, the studies so far have focused on hovering flight, which is the hardest case to explain because the insect can gain no benefit from onrushing air. But do insects use other significant mechanisms to produce lift when they are moving? Many researchers are preparing to study these challenging questions. My group, for example, is building "bride of Robofly," which will live in a tank large enough for it to fly forward and make turns, to test, for instance, our hypotheses about how flies make their characteristic remarkably sharp turns by adjusting the timing of their wing strokes. After uncovering the basic set of tricks that insects use to stay in the air, the real fun now begins. SA

### MORE TO EXPLORE

**The Biomechanics of Insect Flight: Form, Function, Evolution.** Robert Dudley. Princeton University Press, 2000.

The Web site of the author's research group is available at **http://socrates.berkeley.edu/~flymanmd/**

An account of the origins of the bumblebee myth is online at **www.math.niu.edu/~rusin/known-math/98/bees**



# How does the human brain process language? New studies of deaf signers hint at an answer

ONE OF THE GREAT MYSTERIES of the human brain is how it understands and produces language. Until recently, most of the research on this subject had been based on the study of spoken languages: English, French, German and the like. Starting in the mid-19th century, scientists made large strides in identifying the regions of the brain involved in speech. For example, in 1861 French neurologist Paul Broca discovered that patients who could understand spoken language but had difficulty speaking tended to have damage to a part of the brain's left hemisphere that became known as Broca's area. And in 1874 German physician Carl Wernicke found that patients with fluent speech but severe comprehension problems typically had damage to another part of the left hemisphere, which was dubbed Wernicke's area.

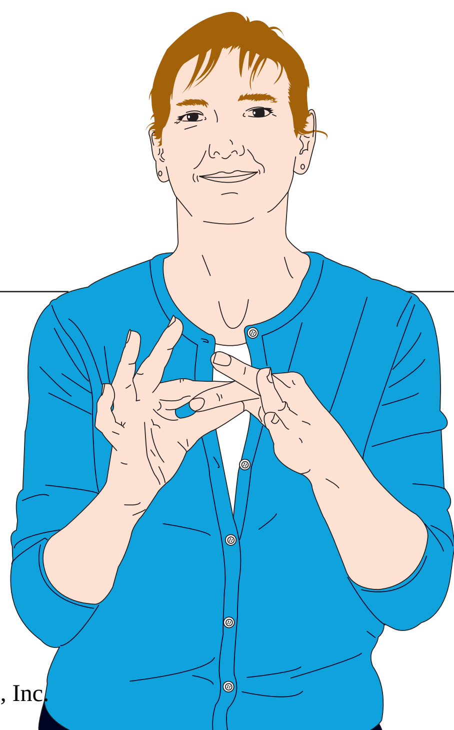
Similar damage to the brain's right hemisphere only very rarely results in such language disruptions, which are called aphasias. Instead right hemisphere damage is more often associated with severe visual-spatial problems, such as the inability to copy a simple line drawing. For these reasons, the left hemisphere is often branded the verbal hemisphere and the right hemisphere the spatial hemisphere. Although this dichotomy is an oversimplification, it does capture some of the main clinical differences between individuals with damage to the left side of the brain and those with damage to the right.

But many puzzles remain. One that has been particularly hard to crack is why language sets up shop where it does. The locations of Wernicke's and Broca's areas seem to make sense: Wernicke's area, involved in speech comprehension, is located near the auditory cortex, the part of the brain that receives signals from the ears. Broca's area, involved in speech production, is located next to the part of the motor cortex that controls the muscles of the mouth and lips [*see illustration on page 60*]. But is the brain's organization for language truly based on the functions of hearing and speaking?

One way to explore this question is to study a language that uses different sensory and motor channels. Reading and writing, of course, employ vision for comprehension and hand movements for expression, but for most people these activities depend, at least in part, on brain systems involved in the use of

# SIGN language in the BRAIN

by Gregory Hickok, Ursula Bellugi and Edward S. Klima



Illustrations by Peter Stemler

TRANSLATION of the phrase "Sign Language in the Brain" into American Sign Language is shown in these artist's renderings, which are based on photographs of a deaf signer.

a spoken language. The sign languages of the deaf, however, precisely fit the bill. Over the past two decades, we have examined groups of deaf signers who have suffered damage to either the right or the left hemisphere of their brains, mostly as a result of strokes. By evaluating their proficiency at understanding and producing signs, we set out to determine whether the brain regions that interpret and generate sign language are the same ones involved in spoken language. The surprising results have illuminated the workings of the human brain and may help neurologists treat the ills of their deaf patients.

## The Signs of Language

MANY PEOPLE MISTAKENLY BELIEVE that sign language is just a loose collection of pantomime-like gestures thrown together willy-nilly to allow rudimentary communication. But in truth, sign languages are highly structured linguistic systems with all the grammatical complexity of spoken languages. Just as English and Italian have elaborate rules for forming words and sentences, sign languages have rules for individual signs and signed sentences. Contrary to another common misconception, there is no universal sign language. Deaf people in different countries use very different sign languages. In fact, a deaf signer who acquires a second sign language as an adult will actually sign with a foreign accent! Moreover, sign languages are not simply manual versions of the spoken languages used in their surrounding communities. American Sign Language (ASL) and British Sign Language, for example, are mutually incomprehensible.

Sign and spoken languages share the abstract properties of language but differ radically in their outward form. Spoken languages are encoded in acoustic-temporal changes—variations in sound over time. Sign languages, however, rely on visual-spatial changes to signal linguistic contrasts [*see box on opposite page*]. How does this difference in form affect the neural organization of language? One might hypothesize that sign language would be supported by systems in the brain's right hemisphere because signs are visual-spatial signals. Accordingly, one could contend that the sign-language analogue of Wernicke's area in deaf signers would be near the brain regions associated with visual processing and that the analogue of Broca's area would be near the motor cortex controlling hand and arm movements.

When we began to test this hypothesis in the 1980s, two fundamental questions needed to be answered: Did deaf signers with brain damage have sign-language deficits? And if so, did the deficits resemble either Wernicke's aphasia (comprehension problems and error-prone speech) or Broca's aphasia (good comprehension but difficulty in producing fluent speech)? The answer to both questions was a resounding yes. One of the first patients studied by our group signed fluently, using all the proper grammatical markers of ASL, but the message conveyed by his signing was often incoherent. An English gloss of one of his utterances reads:

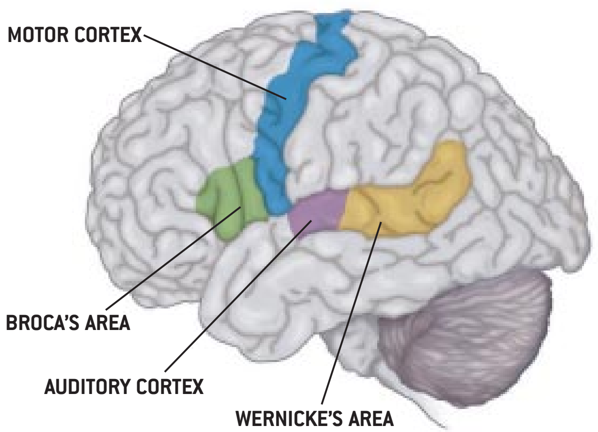
> And there's one (way down at the end) [unintelligible]. The man walked over to see the (disconnected), an extension of the (earth) room. It's there for the man (can live) a roof and light with shades to (keep pulling down).

The patient's disorganized signing and apparent lack of comprehension of others' signs were very similar to the symptoms of hearing patients with Wernicke's aphasia. Another deaf patient we studied early in the research program had extreme difficulty producing signs. She had to struggle to shape and orient her hands to perform the proper movement for virtually every sign she attempted. Most of her utterances were limited to isolated signs. This was not merely a motor control problem: when asked to copy line drawings of objects such as an elephant or a flower, she did so accurately. Also, in contrast to her severe sign-language production problems, her comprehension of sign language was excellent. This profile of language abilities parallels the symptoms of Broca's aphasia.

But where was the brain damage that caused these sign aphasias? The answer was surprising. Both patients had lesions in their left hemispheres. And the lesions were located just about where you'd expect to find them in hearing patients with

## Where Language Lives

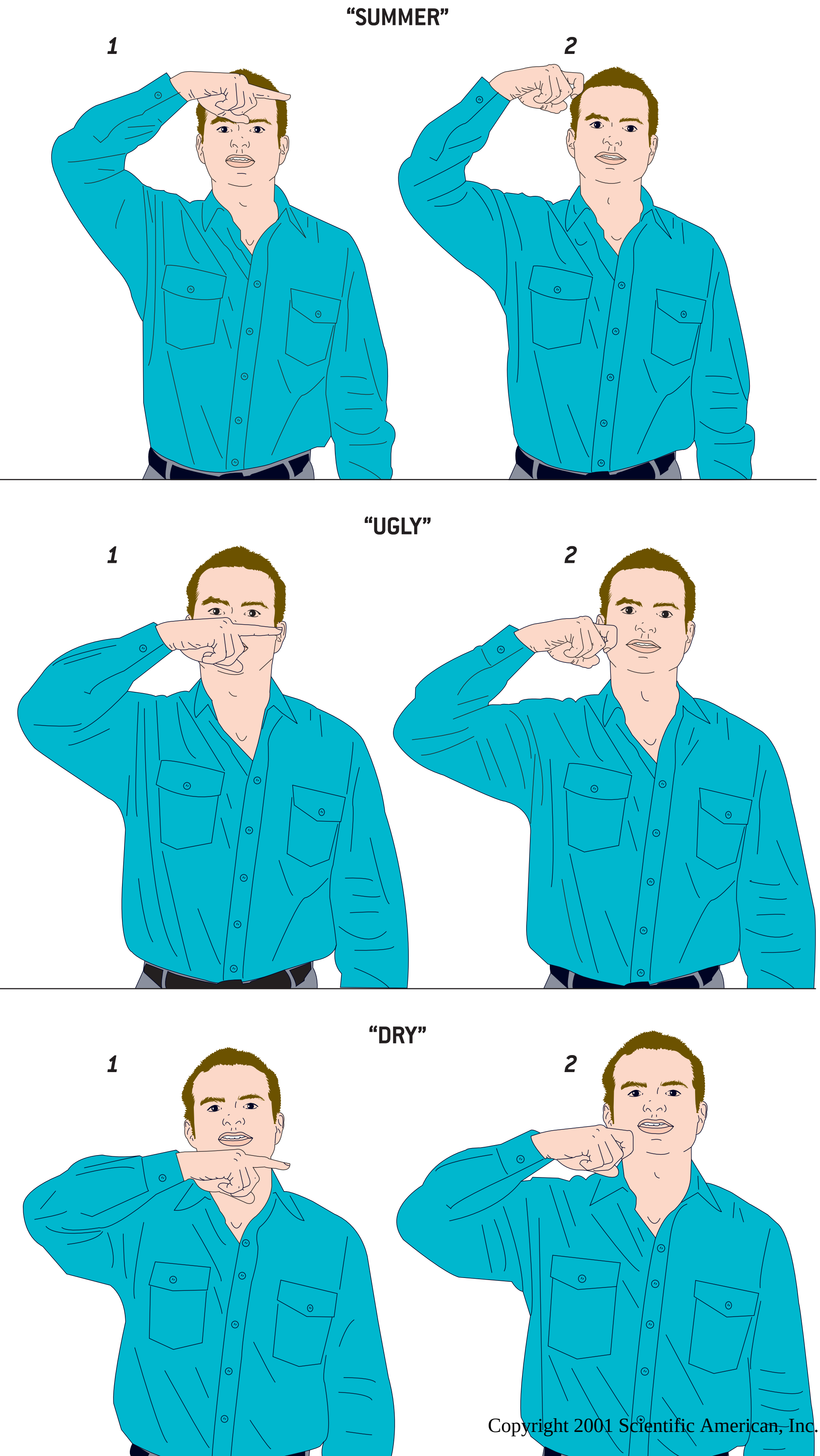
TWO OF THE REGIONS of the brain's left hemisphere that play important roles in language processing are Broca's area and Wernicke's area (there are several others). Broca's area is activated in hearing individuals when they are speaking and in deaf people when they are signing. Wernicke's area is involved in the comprehension of both speech and signs.




THE AUTHORS

*GREGORY HICKOK, URSULA BELLUGI* and *EDWARD S. KLIMA* have worked together on sign language aphasia for a decade. Hickok is associate professor in the department of cognitive sciences at the University of California, Irvine, and director of the Laboratory for Cognitive Brain Research, where he studies the functional anatomy of language. Bellugi is director of the Salk Institute's Laboratory for Cognitive Neuroscience in La Jolla, Calif., where she conducts research on language and its biological foundations. Much of her research is in collaboration with Klima, who is professor emeritus at the University of California, San Diego, and a research scientist at Salk.

# The Building Blocks of Sign Language




Sign languages, like spoken languages, have several kinds of linguistic structure, including phonological, morphological and syntactic levels. At the phonological level, signs are made up of a small set of components, just as spoken words are composed of a small set of consonants and vowels. The components of signs include hand shapes, the locations around the body where signs are made, the movements of the hands and arms, and the orientation of the hands (for example, palm up versus palm down). In American Sign Language (ASL) the signs for "summer," "ugly" and "dry" have the same hand shape, movement and orientation but differ in location [*see illustrations at left*]. Likewise, signs such as "train," "tape" and "chair" share hand shape, orientation and location but differ in movement.

At the morphological level, ASL has grammatical markers that systematically change the meaning of signs. Morphological markers in English include fragments like "-ed," which can be added to most verbs to indicate past tense ("walk" becomes "walked"). Whereas in English the markers are added to the beginning or end of a word, in ASL the signs are modified using distinctive spatial patterns. For example, adding a rolling movement to the sign "give" (and to most ASL verb signs) changes the sign's meaning to "give continuously." Signers can use different patterns to modify the verb to mean "give to all," "give to each," "give to each other" and many other variations.

At the syntactic level, ASL specifies the grammatical relations among signs (that is, who is doing what to whom) in ways that do not occur in spoken languages. In English the order of the words provides the primary cue for the syntactic organization of a sentence such as "Mary criticized John." Reverse the order of the nouns, and you reverse the meaning of the sentence. Signers of ASL can use word-order cues as well, but they need not. Instead signers can point to a distinct position in space while signing a noun, thus linking the word with that position. Then the signer can move the verb sign from Mary's position to John's to mean "Mary criticized John" and in the other direction to mean the reverse.

**LOCATION of a sign is a critical element in conveying meaning. In American Sign Language, "summer" is articulated near the forehead, "ugly" near the nose and "dry" near the chin.**

COMMON PROBLEM experienced by left hemisphere–damaged (LHD) deaf signers is the production of paraphasias—slips of the hand—analogous to the slips of the tongue experienced by LHD hearing patients. The illustration at the right shows the correct form of the sign for "fine," whereas the drawing on the opposite page shows an error often made by LHD signers. In the latter figure, the signer articulated the location and movement of the sign correctly but used the wrong hand shape, resulting in something that has no meaning in ASL—a nonsense sign, equivalent to "bline" or "gine" in English.

Although the hand shape in this paraphasia is incorrect for "fine," it is used in many other ASL signs, such as "play" and "California." Similar paraphasias include errors in producing the proper location, movement and hand orientation of a sign, as well as mistakes in rendering the morphological and syntactic structure of the language.


**The brain's left hemisphere is dominant for sign language, just as it is for speech.**

similar problems. The deaf signer with comprehension difficulties had damage that included Wernicke's area, whereas the patient who had trouble making signs had damage that involved Broca's area.

These observations showed that the left hemisphere plays a crucial role in supporting sign language. But what about the right hemisphere? One would think that damage to the right hemisphere, which appears to be critically involved in many visual-spatial functions, would have a devastating effect on sign-language ability as well. But this assumption is apparently wrong. Signers with damage to the right hemisphere were fluent and accurate in their production of signs, used normal grammar and comprehended signs with ease. This held true even in patients whose nonlinguistic visual-spatial abilities had been severely compromised by their brain damage. One signer with damage to the right hemisphere , for example, could not create or copy recognizable drawings and failed to notice objects in the left part of his visual field (a condition known as hemispatial neglect). Yet he could communicate very efficiently in sign language.

Subsequent research using larger groups of deaf signers confirmed the early case studies. A study published by our team in 1996 compared the sign-language abilities of 13 left hemisphere–damaged (LHD) signers with those of 10 right hemisphere–damaged (RHD) signers. As a group, the LHD signers performed poorly across a wide range of sign-language measures: They had trouble comprehending isolated signs and signed sentences and were likely to have problems with fluency as well. They also had difficulty with picture-naming tasks and frequently made paraphasic errors—slips of the hand—in which they inadvertently substituted one sign for another or one component of a sign, such as hand shape, for another. In contrast, the RHD signers performed well on all these tasks. The study also showed that difficulties with sign-language fluency were not caused by more general problems in controlling voluntary hand or arm movements: patients who had trouble making signs were often capable of producing nonmeaningful hand and arm gestures.

We obtained similar results in another study, this one focusing on sign-language comprehension in 19 lifelong signers with brain lesions, 11 with damage to the left hemisphere and eight with damage to the right. The LHD group performed significantly worse than the RHD group on three tests that evaluated their understanding of single signs, simple sentences and complex sentences. The most impaired signers were those with damage to the brain's left temporal lobe, where Wernicke's area is located.

Taken together, these findings suggest that the brain's left hemisphere is dominant for sign language, just as it is for speech. The organization of the brain for language does not appear to be particularly affected by the way in which language is perceived and produced.

## The Story Gets Complicated

As we noted at the beginning of this article, the assumed left-right dichotomy of the brain—with verbal abilities concentrated in the left hemisphere and visual-spatial abilities clustered in the right—is an oversimplification. Research over the past few decades has shown that most cognitive abilities can be divided into multiple processing steps. At some levels, brain activity may be lateralized (taking place primarily in one hemisphere), whereas at others the activity may be bilateral (occurring in both).

Language ability, for instance, has many components. A hearing person must be able to perceive and produce individual speech sounds and the words they make up; otherwise, one could not distinguish "cup" from "pup." In addition, one must be able to recognize morphological additions ("walking" vs. "walked"), syntactic constructions ("the dog chased the cat" vs. "the dog was chased by the cat"), and melodic intonations ("the *White* House" vs. "the white *house*"). Finally, to conduct an extended discourse one must be able to establish and maintain a coherent connection between characters and events over the course of many sentences.

Of all these aspects of linguistic ability, the production of language is the one most sharply restricted to the brain's left hemisphere. Damage to the left hemisphere often interferes with the ability to select and assemble appropriate sounds and words when speaking. Right hemisphere damage rarely does. One exception to the left hemisphere's monopoly on language production is the creation of a coherent discourse. Patients with right hemisphere damage may be able to construct words and sentences quite well, but they frequently ramble from one subject to the next with only a loose thread of a connection between topics.

The perception and comprehension of language appear to be less confined to the left hemisphere than language production is. Both hemispheres are capable of distinguishing individual speech sounds, and the right hemisphere seems to have a role in the comprehension of extended discourse. But deciphering the meaning of words and sentences seems to take place primarily in the left hemisphere. This may explain why language was originally considered to be the exclusive province of the left hemisphere: the most common tests for aphasia evaluated the comprehension and production of words and sentences, not longer discourses.

Nonlinguistic spatial abilities can also be broken down into components with differing patterns of lateralization. Although the most severe impairments of spatial abilities occur more commonly following damage to the right hemisphere (both in deaf and hearing populations), researchers have observed some visual-spatial deficits in LHD hearing people. The symptoms typically involve difficulties in perceiving or reproducing the local-level features of a visual stimulus—such as the details in a drawing—even though the LHD patients can correctly identify or reproduce the drawing's overall configuration. RHD hearing people tend to show the opposite pattern. Thus, it has been suggested that the left hemisphere is important for local-level spatial perception and manipulation, whereas the right hemisphere is important for global-level processes.

This more sophisticated picture of the brain raises an interesting question: Is the division of visual-spatial abilities between the two hemispheres—local level in the left, global level in the right—related to the division of sign-language abilities? Individual signs and signed sentences can be thought of as pieces of the language, whereas an extended discourse can represent how those pieces are put together. Perhaps the left hemisphere is dominant for producing and comprehending signs and signed sentences because those processes are dependent on local-level spatial abilities. And perhaps the right hemisphere is dominant for establishing and maintaining a coherent discourse in sign language because those processes are dependent on global-level spatial abilities.

We set out to test this hypothesis. Our research confirmed that many RHD signers have trouble with extended discourse: their narratives are full of tangential utterances and even confabulations—just the kind of difficulties that hearing RHD patients often have. But some RHD signers face another type of problem. Discourse in sign language has a unique spatial organization: when telling a story with many characters, the signer identifies each one using a different location. The space in front of the signer becomes a sort of virtual stage on which each character has his or her own spot. Our studies found that some RHD signers were able to stay with a topic in their discourse but failed to maintain a consistent

INCORRECT SIGN FOR "FINE" TYPICALLY PRODUCED BY A SIGNER WITH LEFT HEMISPHERE DAMAGE

## The brain is a highly modular organ, with each module organized around a particular computational task.

spatial framework for the characters in their narratives.

Is either of these types of discourse problems in RHD deaf signers causally connected to deficits in their nonlinguistic spatial abilities? It would appear not. We studied one RHD signer whose spatial abilities were severely impaired yet who had no trouble signing a coherent story. Another RHD patient had only mild visual-spatial problems yet could not sustain a proper spatial framework for the characters in the narrative. Clearly, the cognitive systems in the right hemisphere that support nonlinguistic spatial abilities are different from the ones that support extended discourse.

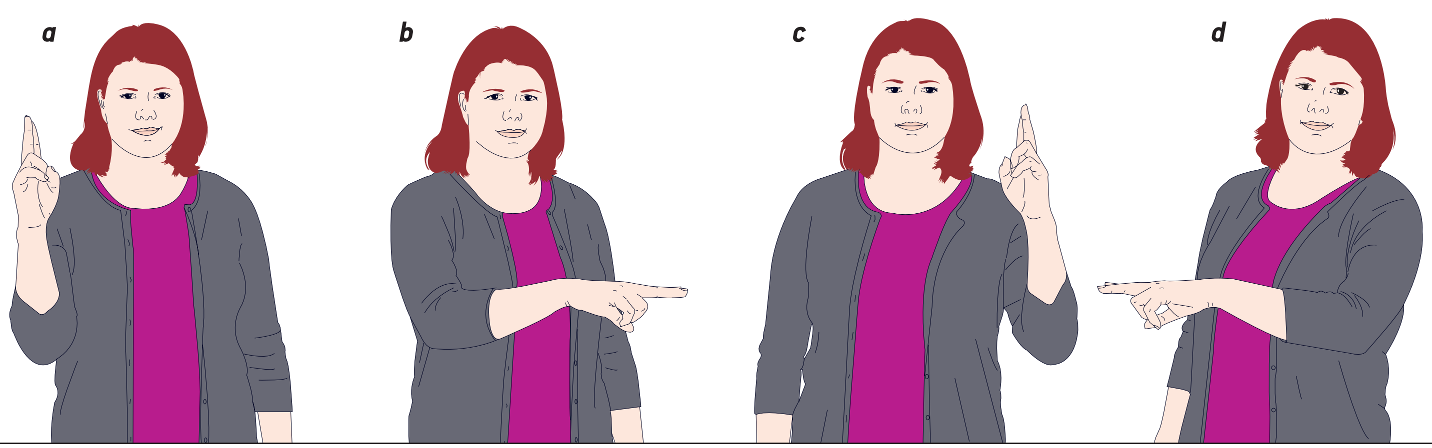
What about deaf signers with damage to the left hemisphere? Are their sign-language aphasias caused by impairments in local-level spatial abilities? To address this issue, we asked a group of deaf signers to reproduce line drawings and hierarchical figures, which have recognizable local and global features. (An example would be the letter "D" fashioned out of a constellation of small "y"s.) Just like hearing patients with left hemisphere damage, the LHD deaf subjects tended to reproduce the global configuration of the drawings correctly but often left out some of the details. (The RHD deaf subjects exhibited the reverse pattern, drawing pictures with lots of detail but a disorganized whole.) We found no correlation between the severity of the local-level spatial deficits in the LHD subjects and the severity of their sign-language aphasias. Contrary to all expectations, the sign-language abilities of lifelong deaf signers appear to be independent of their nonlinguistic spatial skills.

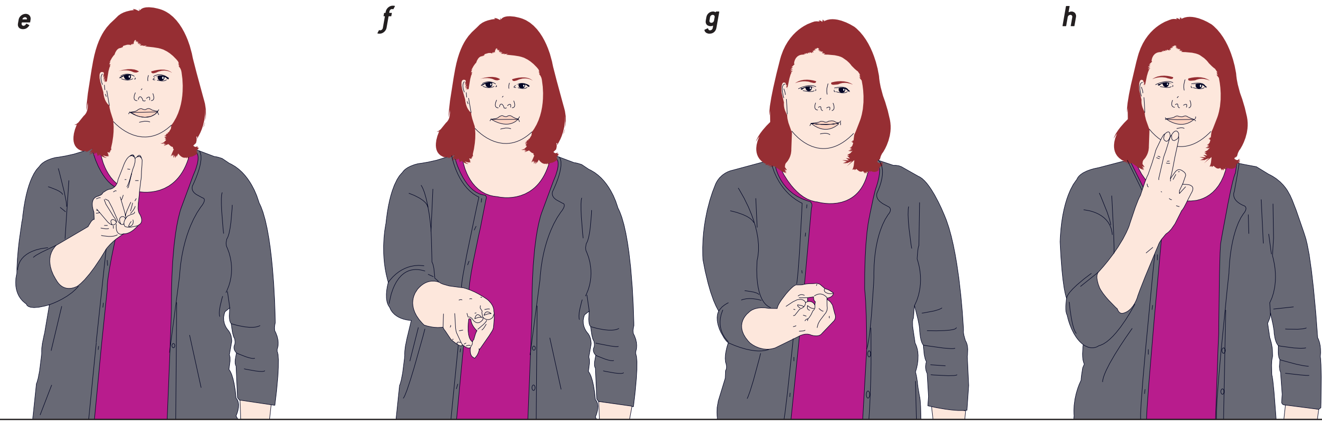
It is possible that we have missed some fine distinctions in the organization of the brain for language in hearing patients and signers. Studies of patients with brain lesions are limited in their precision: to ascertain exactly which parts of the brain are involved in sign language, researchers would need to examine dozens of deaf signers with lesions in just the right places, and it would take decades to find them all. But the introduction of noninvasive brain imaging techniques—functional magnetic resonance imaging (fMRI) and positron-emission tomography (PET)—has given scientists new tools for probing the neural roots of language.

Researchers have employed these techniques to investigate the role of Broca's area in speech and sign production. Imaging results have shown that Broca's area is indeed activated in hearing patients when they are speaking and in deaf patients when they are signing. Brain imaging has also confirmed that the regions that play a role in sign-language comprehension are much the same as those involved in the understanding of spoken language. In a 1998 study researchers used fMRI methods to observe the brain activity of lifelong deaf signers who were watching videotapes of sentences in ASL. The investigators found regions of activity in several parts of the left temporal lobe, including parts of Wernicke's area, and in several regions of the left frontal lobe, including Broca's area.

The study also found regions of activity in the right temporal lobe and right frontal lobe. This result has led some researchers to suggest that sign-language

SEQUENCE OF DRAWINGS below shows the correct maintenance of a spatial framework for an extended discourse in American Sign Language. The signer is describing a series of pictures that show two children painting each other's faces as they sit side by side at a table. At the start of the discourse, the signer linked each child to a particular location in space: Alice on the signer's right and Bob on the signer's left (*not shown*). Subtle shifts in the signer's body position and the direction of the movement of the sign for "paint" (from Alice's location on her right to Bob's location on her left) indicate that Alice is painting Bob (*a, b*). The reverse movements (*c, d*) indicate that Bob is painting Alice.






MANY SIGNERS with right hemisphere damage make mistakes in their spatial organization of a discourse. They can correctly link the characters in the narrative to positions in space, but they often fail to reference these positions consistently. In the drawings above, the signer does not link the sign for "paint" to the positions of Alice and Bob. An English equivalent of this lack of specificity might be: "Alice and Bob were sitting at a table, painting. Suddenly someone painted on someone's face (*e, f*), and then someone painted on someone's face (*g, h*)."

comprehension may be more bilaterally organized than spoken-language comprehension. But bilateral activity has also been detected in studies of hearing subjects listening to speech. More research is needed to clarify the role of the right hemisphere in sign-language processing. In any case, the studies of brain lesions make it clear that if differences exist between spoken and sign language, they are likely to be subtle.

## Lessons from Sign Language

SIGN LANGUAGE involves both linguistic and visual-spatial processing—two abilities that are supported by largely distinct neural systems in hearing individuals. But contrary to all expectations, the neural organization of sign language has more in common with that of spoken language than it does with the brain organization for visual-spatial processing. Why should this be the case?

The answer suggested by our line of research, as well as the work of others, is that the brain is a highly modular organ, with each module organized around a particular computational task. According to this view, the processing of visual-spatial information is not confined to a single region of the brain. Instead different neural modules process visual inputs in different ways. For example, visual inputs that carry linguistic information would be translated into a format optimized for linguistic processing, allowing the brain to access the meanings of signs, extract grammatical relations, and so on. But visual stimuli that carry a different kind of information—such as the features and contours of a drawing—would be translated into a format that is optimized for, say, carrying out motor commands to reproduce that drawing. The computational demands of these two kinds of processing tasks are very different, and thus different neural systems are involved.

Viewed in this way, it is not so surprising that comprehending and producing sign language appear to be independent of visual-spatial abilities such as copying a drawing. Although they both involve visual inputs and manual outputs, the tasks are fundamentally different. Consequently, we would expect them to share brain systems to some extent at the peripheral levels of processing—for instance, at the primary visual cortex that receives signals from the optic nerve—but to diverge in more central, higher-level brain systems.

The situation with spoken and sign languages is just the opposite. These two systems differ radically in their inputs and outputs but appear to involve very similar linguistic computations. We therefore expect that spoken and sign languages will share a great deal of neural territory at the more central, higher-level brain systems but diverge at the more peripheral levels of processing. At the sensory end, for example, the peripheral processing of speech occurs in the auditory cortices in both hemispheres, whereas the initial processing of signs takes place in the visual cortex. But after the first stages of processing, the signals appear to be routed to central linguistic systems that have a common neural organization in speakers and signers.

These findings may prove useful to neurologists treating deaf signers who have suffered strokes. The prognosis for the recovery of the signers' language abilities will most likely be similar to that of hearing patients with the same brain damage. Furthermore, when neurosurgeons remove brain tumors from deaf signers, they must take the same precautions to avoid damaging the language centers as they do with hearing patients.

A major challenge for future research will be to determine where the peripheral processing stages leave off and the central stages begin (or even if there is such a sharp boundary between the two). More study is also needed to understand the nature of the computations carried out at the various levels of linguistic processing. The similarities and differences between spoken and sign languages are ideally suited to answering these questions. SA

### MORE TO EXPLORE

**The Signs of Language.** Edward S. Klima and Ursula Bellugi. Harvard University Press, 1979. Reprinted 1988.

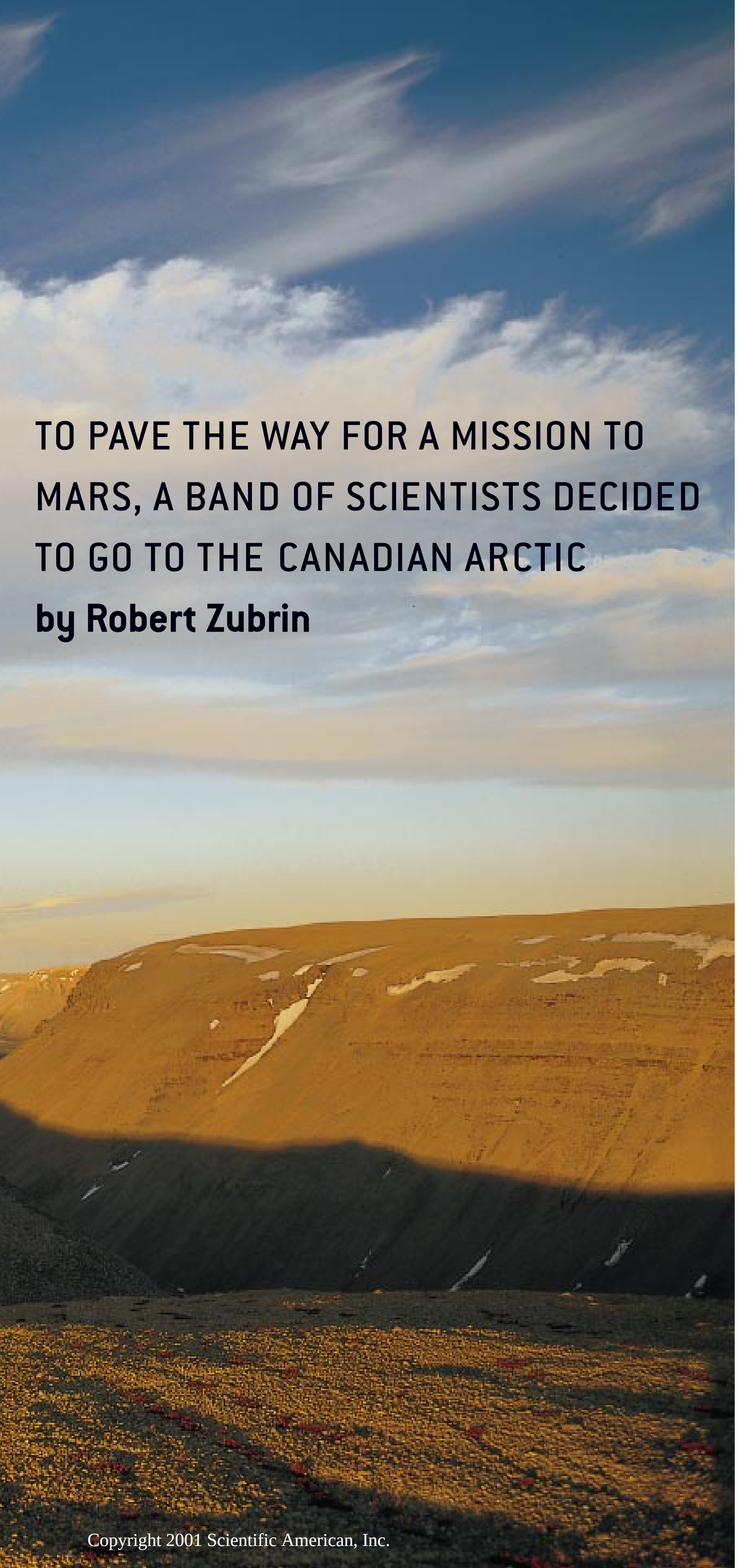
**What the Hands Reveal about the Brain.** H. Poizner, Edward S. Klima and Ursula Bellugi. MIT Press, 1987. Reprinted by Bradford Books, 1990.

**The Neural Organization of Language: Evidence from Sign Language Aphasia.** G. Hickok, U. Bellugi and E. S. Klima in *Trends in Cognitive Sciences,* Vol. 2, No. 4, pages 129–136; April 1998.

**The Signs of Aphasia.** G. Hickok and U. Bellugi in *Handbook of Neuropsychology,* Vol. 3. Second edition. Edited by R. S. Berndt. Elsevier, 2001.

# NORTH TO MARS!

ALIEN LANDSCAPE
of Canada's Devon Island is the setting for a simulated Mars base.



# TO PAVE THE WAY FOR A MISSION TO MARS, A BAND OF SCIENTISTS DECIDED TO GO TO THE CANADIAN ARCTIC

**by Robert Zubrin**

DEVON ISLAND IS A BARREN but weirdly beautiful place in the Canadian Arctic, only 1,500 kilometers from the North Pole. About 23 million years ago a meteorite struck there with the force of 100,000 hydrogen bombs, gouging out the 20-kilometer-wide Haughton Crater. The impact killed every living thing on the island and destroyed its soil, leaving a bizarre landscape of condensed powder ridges and shock-fractured stones. Because most of the island is devoid of trees, bushes and grasses, it looks and feels like an alien world. In fact, for the past four years a team of scientists from the National Aeronautics and Space Administration has been studying the island's geology to learn about Mars [*see box on next page*].

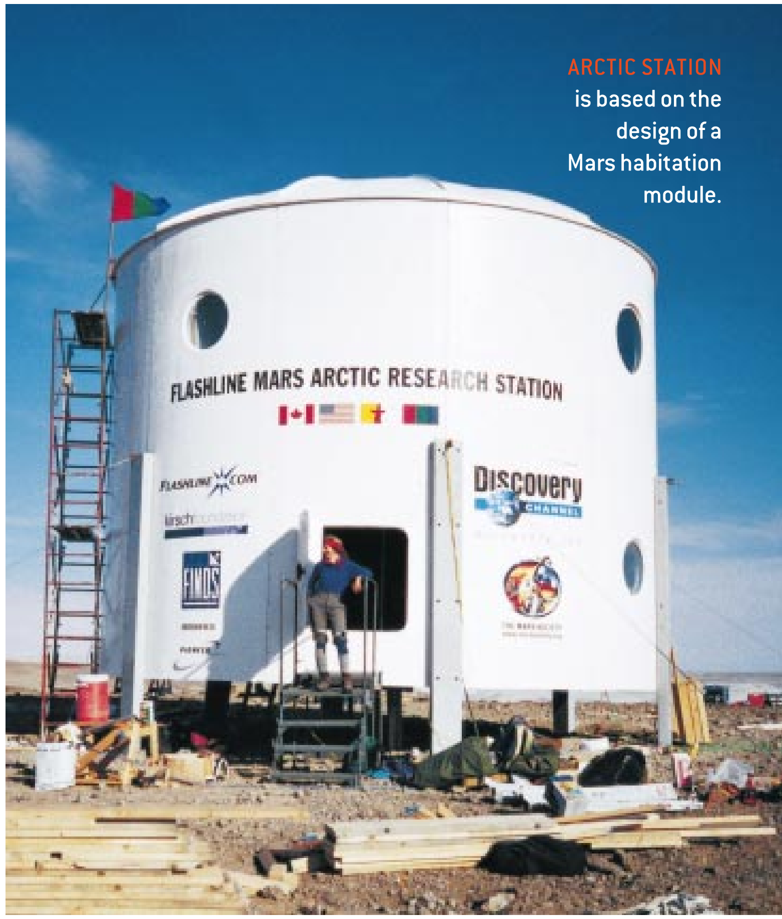
In 1998 I founded the Mars Society, an organization dedicated to promoting the exploration of the Red Planet. Pascal Lee, the geologist who headed NASA's Devon Island team, proposed that the society build a simulated Mars base at Haughton Crater. Researchers at this station could explore Devon under many of the same conditions and constraints that would be involved in a human mission to Mars. The things we could learn from such a program would be invaluable. For example, the crew at the Devon Island station could try out equipment intended for a Mars mission, such as water-recycling systems and spacesuits, putting the gear through months of rough treatment in the field instead of merely testing it in the laboratory. While studying Devon Island's geology and microbiology, the researchers could find out how much water an active Mars exploration team would really need. They could also investigate key issues of crew psychology, such as the effects of isolation and close confinement, team dynamics and how the layout of the station would affect the astronauts' performance.

In addition, the Devon Island crew could determine which operational procedures would work well on the Red Planet and which would simply hamstring future astronauts. And they could develop the art of combined operations—that is, coordinating the mission's human, robotic and vehicular elements to maximize their effectiveness. In short, the Devon Island crew could learn how to live and work on Mars.

The Mars Society raised $600,000 in private funds for the project and in January 2000 contracted the manufacturing of the station to Infrastructure Composites International (Infracomp). The company had invented a honeycomb-like fiberglass that was originally intended for building floating cities on the sea. This ultrastrong and relatively lightweight material proved perfect for our Mars habitat. The shape of the structure—a domed cylinder with a diameter of about eight meters, containing two decks with about three meters of headroom each—mirrored the design proposed by NASA for a six-person Mars habitation module.

## Look Out Below!

THE PLAN WAS TO DELIVER the large fiberglass components to Devon Island by parachuting them from U.S. Marine Corps C-130 transport planes. On July 5 the first five airdrops,




**ARCTIC STATION** is based on the design of a Mars habitation module.

ANDY ANDERSON (*preceding and opposite pages*); ROBERT ZUBRIN (*above*)

which contained the walls, legs and some of the dome sections of the habitat, delivered the payloads safely to the ground, although gusty winds caused most of them to fall several hundred meters from the construction site. The sixth drop, on July 8, carrying the remaining dome sections and other equipment, also went well. The final drop that day, however, was a disaster. The payload separated from the parachute at an altitude of 300 meters and plunged to the ground. The habitat's fiberglass floors were completely destroyed, along with the trailer needed to move the 360-kilogram wall panels and the crane needed to lift them.

With the loss of the trailer, the floors and the crane, the construction crew that the Mars Society had hired to assemble the station declared the task impossible and fled the island. At this point, the project seemed doomed. Indeed, one journalist asked me if I saw a parallel between the failure of the airdrop and that of the Mars Polar Lander, the unmanned spacecraft that apparently crashed on the Martian surface in December 1999. I replied: "There's a parallel in that we both hit a rock. But the difference is that we have a human crew here, and we are going to find a way out of this."

Lee and I assembled a new, makeshift construction team consisting of Mars Society scientists and volunteers, Inuit youth hired from the town of Resolute Bay (about 170 kilometers away) and a few journalists. Frank Schubert, a gener-

## Devon Island *vs. Mars*

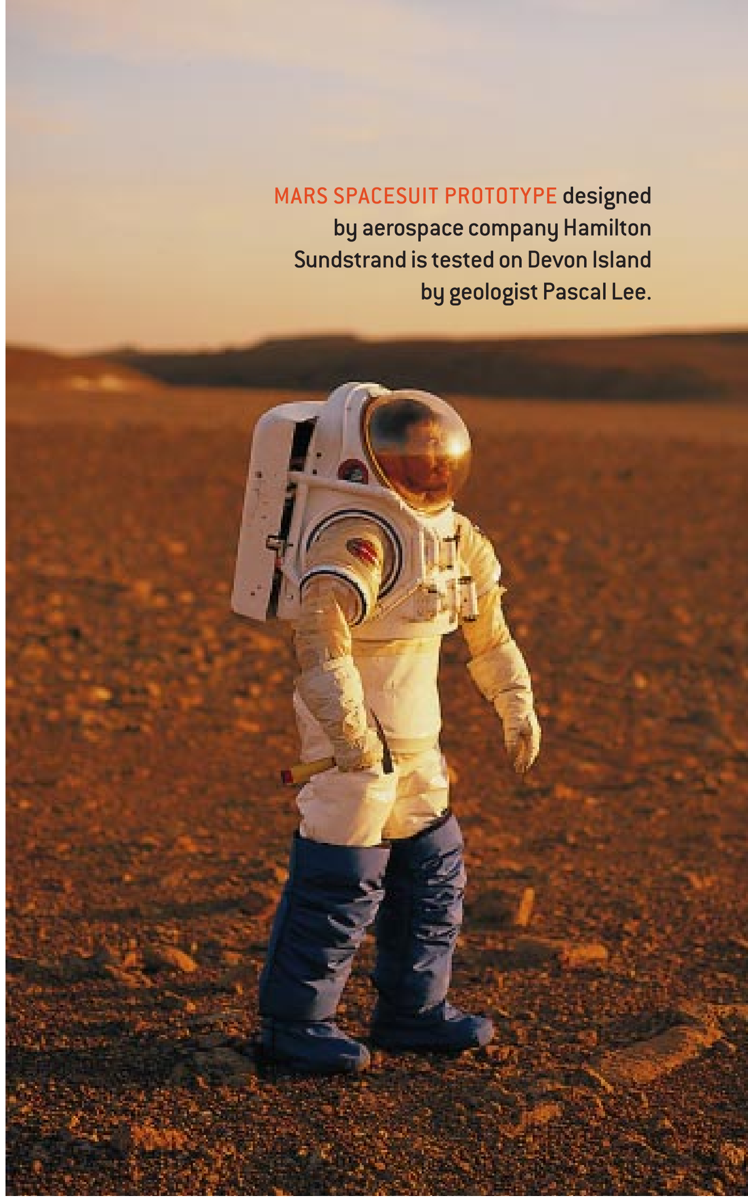
**A list of similarities and differences, compiled by Pascal Lee of the SETI Institute and the NASA Ames Research Center:**

**SIMILARITIES** **ENVIRONMENT:** Devon Island and Mars are polar deserts: cold, dry, windy, rocky and dusty. **GEOLOGY:** Haughton Crater's thick deposits of impact breccia—rock fragments created by the meteorite strike—may be similar to the rubble on the surface of Mars. Also, the valley systems created by erosion of Devon's terrain look like many of the valleys and gullies observed on the Red Planet. **BIOLOGY:** Some types of microbes on Devon Island live inside impact-damaged rocks. Researchers have also found stromatolites—fossils of colonies of primitive microorganisms. Similar life-forms or their fossils might exist on Mars.

**DIFFERENCES** **GRAVITY:** Martian gravity is only about one third as strong as Earth's. **TEMPERATURE:** On Devon Island the average temperature is about –15 degrees Celsius, compared with –55 degrees C on Mars. **ATMOSPHERE:** Whereas Earth's atmosphere is mostly nitrogen and oxygen, the Martian atmosphere is 95 percent carbon dioxide, and the surface pressure is less than 1 percent of Earth's. **RADIATION:** Ultraviolet radiation on Mars is about 800 times more intense than it is on Devon Island in the summer.

al contractor from Denver and a founding member of the Mars Society, flew in to direct the construction, with the assistance of his foreman, Matt Smola, and Infracomp vice president John Kunz. A new trailer, "the Kunzmobile," was constructed out of wood and parts of a wrecked baggage cart from the Resolute Bay airport. Over three days of freezing rain we used this trailer to haul all the scattered habitat components to the construction site.

Next we designed wooden floors to replace the ruined fiberglass decks, using timber transported by small aircraft from Resolute Bay. To erect the 20-ton habitat without a crane, we had to resort to construction techniques that have been in use since the time of the ancient Romans. A 12-person crew would have to lift each six-by-two-meter wall panel into place using a winch, a scaffold, bracing timbers and guy ropes. We knew it would be too risky to try this method if Devon's frequent 40-knot winds came up. But on the evening of July 19 the weather cleared, leaving us with sunny skies, negligible winds and temperatures in the low 40s. On Devon Island, it doesn't get any better than that. That night we held a council of war in the mess tent at the base camp. We decided to go for it.



MARS SPACESUIT PROTOTYPE designed by aerospace company Hamilton Sundstrand is tested on Devon Island by geologist Pascal Lee.

## Arctic Overtime

BECAUSE WE DID NOT KNOW how long the good weather would last, we raced against the clock. We took advantage of the Arctic's perpetual summer daylight to institute 14-hour workdays. In three incredible days, we got the walls up. The weather was still clear. We partly installed the wooden floors, then used block-and-tackle gear to haul the first two 160-kilogram dome sections onto the upper deck. Then we constructed a scaffold and erected the two sections over a central core to create an arch.

Now the task before us was to lift the other dome sections into place. By this time, however, the long workdays had started to take their toll. Near exhaustion, the crew made mistakes. We had two close calls when improperly guyed scaffolds came crashing down. But we pressed on. On the evening of July 26, with the wind finally beginning to rise and rain threatening, we heaved the last dome section into place. The only remaining task was to build the bunks, airlock and toilet area inside the habitat. The freezing rain was back, but it didn't matter. We could do our work inside the best house on Devon Island.

On July 28 we held a ceremony to mark the completion of the habitat. Because of the construction delays, we had time for only a four-day mission simulation. Commanded by Carol Stoker of the NASA Ames Research Center, the six crew members lived and worked in the habitat, supporting a series of exploration traverses and the field-testing of a Mars spacesuit prototype. The team maintained radio contact with a simulated mission control based in Denver; 20-minute delays were inserted between the transmissions to duplicate the time lags that would ordinarily occur in radio communications between Earth and Mars.

On August 4 the habitat was sealed for the winter. The Mars Society is now preparing for the summer of 2001, when the station will support eight weeks of research under strict mission-simulation protocols. Everyone who leaves the habitat will have to wear a simulated spacesuit and spend 20 minutes in the airlock exiting and returning. Under these and similar constraints, we will attempt to conduct a sustained program of geology and microbiology field exploration. We are certain to run into operational problems—but those problems are exactly what we are trying to uncover.

Many things did not go right on Devon Island. In all likelihood, many things will also go awry when astronauts make their first journey to Mars. When venturing into the unknown, one can expect the unexpected. But as we learned from our Arctic experience, a resourceful crew can overcome nearly any obstacle. On the first human mission to Mars, the crew will be the strongest link in the chain. SA

THE AUTHOR

*ROBERT ZUBRIN,* author of *The Case for Mars* (Simon & Schuster, 1996) and *Entering Space* (Tarcher Putnam, 1999), is president and founder of the Mars Society (www.marssociety.org). He is also the founder of Pioneer Astronautics, which is involved in the research and development of space exploration technology. Readers who wish to express their opinions on the Mars Society's Devon Island project can send their comments to editors@sciam.com

Scientists are rapidly discovering the molecules that control hair production. In so doing, they could be unearthing the key to combating both baldness and excessive hair growth

# HAIR

## Why it grows Why it stops

By Ricki L. Rusting • Photographs by Jeff Mermelstein

BY AGE 50, about half of all men and women are grappling with hair loss, typically a receding hairline and a balding crown in men and diffuse thinning in women. Countless people also fret over having too much hair where they don't want it.

Remedies exist but could certainly stand improvement. One logical way to correct hair disorders would be to deliver drugs designed specifically to influence the molecules that normally orchestrate hair production. To develop such targeted drugs, however, pharmaceutical makers would need to know the identities of those hair-regulating molecules.

Five years ago biologists were still very much in the dark. Now several research groups are beginning to uncover the molecular controls on hair development. Once the picture is complete, they should be in good position to determine which ones go awry in specific hair conditions and how to bring the defective regulatory system back into line.

Surprising as it may seem, people suffering from serious disorders unrelated to hair may also benefit from the recent research on hair production. Earlier this year investigators pinpointed the hiding place of the unspecialized stem cells that replace lost hair-producing cells and constantly rejuvenate the epidermis at the skin surface. If scientists can turn these malleable cells into other kinds of tissue, particularly nerves and muscles, they will have a readily accessible source of stem cells for potentially treating Alzheimer's, Parkinson's and other diseases, while avoiding the complex ethical issues raised by harvesting stem cells from embryos.

## Overview / *Hair Growth*

- Biologists now understand many of the steps leading to the development of hair follicles in embryos and to hair production throughout life.
- Signaling proteins in a family known as Wnt play a role in directing many of those steps. Researchers are uncovering additional regulatory molecules as well.
- Baldness often arises not because follicles die but because they shrink and malfunction. Drugs that manipulate Wnts or other regulatory proteins might one day protect threatened follicles and prod shrunken ones into producing hair normally again.
- Knowledge of the controls on hair production could also lead to new ways of eliminating unwanted hair.

## Fashioning a Follicle

TO TRACE THE MOLECULAR CONTROLS over any given process, scientists first need to know the basic outlines of the process itself. By 1995 microscopists and others had developed a good sketch of the incredible steps that lead to the formation of hair follicles (the tiny bulbs that produce the hair shaft) in the developing embryo. They had also described the hair cycle—the periodic phases during which follicles produce or stop producing hair; follicles undergo this cycle repeatedly in a lifetime.

Hair follicles develop during gestation in response to cross talk between the ectoderm, or top layer of cells, composing a young embryo and the mesoderm underneath. First, a patch of the mesoderm signals the overlying ectoderm to make an appendage. In response, the ectoderm cells organize, proliferate and invade the mesoderm, becoming an elongated structure called a hair germ.

Next, the hair germ directs the underlying mesoderm cells to cluster together to form the dermal papilla of the hair follicle. This structure becomes a kind of command central: it instructs the germ cells to multiply further and develop into a full-fledged hair follicle. In the end, the upper, permanent section of the follicle contains an oil-producing sebaceous gland and a bulge—a swelling now known to be the home of most or all of the stem cells that replenish the hair, the sebaceous gland and the epidermis throughout life. The lower segment of the follicle, below the bulge, becomes the hair-producing region and is the part that cycles through different stages after embryonic development is complete.

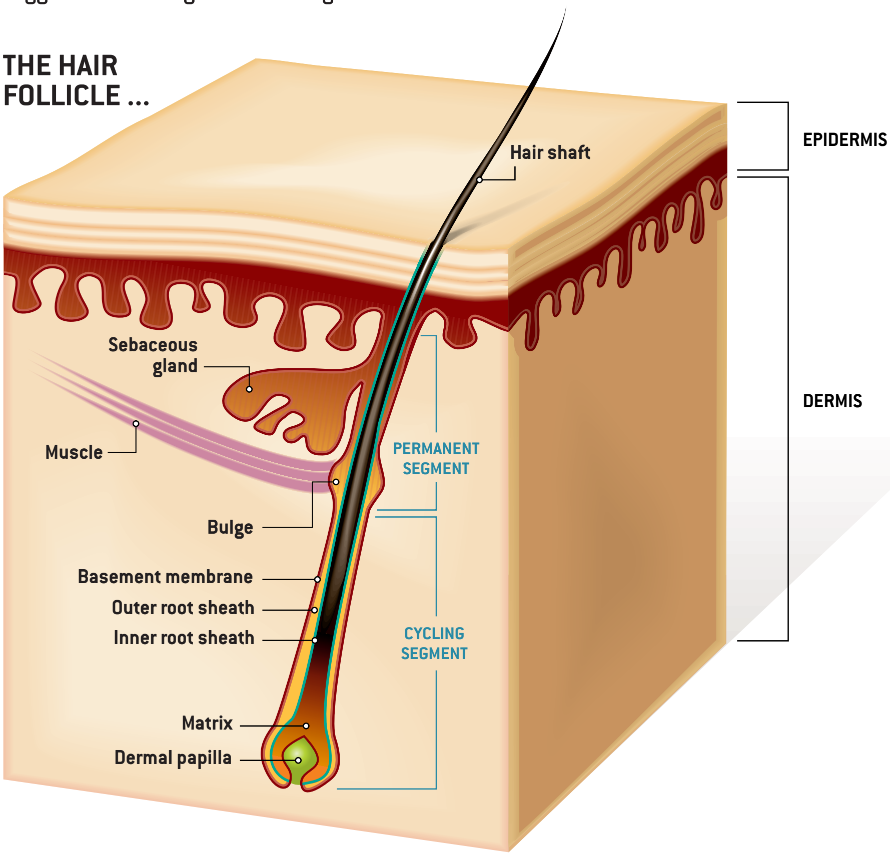
During development, this bottom section arises as cells from the hair germ spread downward, like a growing root, deep into the dermis of the skin, where they form a bulb-shaped matrix of cells surrounding the dermal papilla. The dermal papilla prods the matrix cells into dividing. As matrix cells get pushed upward and lose their contact with the dermal papilla, they stop dividing and mature, a process known as terminal differentiation.

The matrix cells sitting directly over the apex of the dermal papilla mature into hair cells—that is, they produce the fibrous keratin proteins characteristic of hair. More peripheral matrix

# THE HAIRY DETAILS

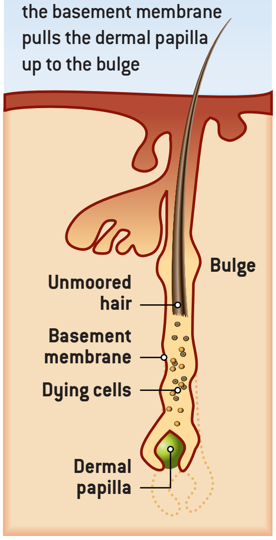
THE MATURE HAIR FOLLICLE consists of a bulbous, vaselike structure that produces the hair shaft. Throughout life, follicles cycle through hair-growing and nongrowing phases. Many molecules involved in controlling cycling have now been identified. These discoveries suggest new strategies for treating hair disorders.

## THE HAIR FOLLICLE ...

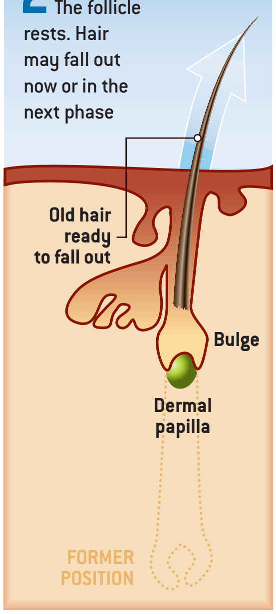



## ... AND ITS THREE-PART LIFE CYCLE

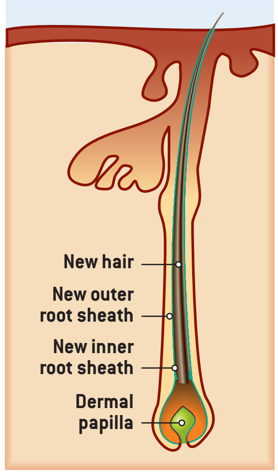
**1 CATAGEN** Cells in the cycling segment die, and the shaft loses its mooring. Meanwhile the basement membrane pulls the dermal papilla up to the bulge




**2 TELOGEN** The follicle rests. Hair may fall out now or in the next phase

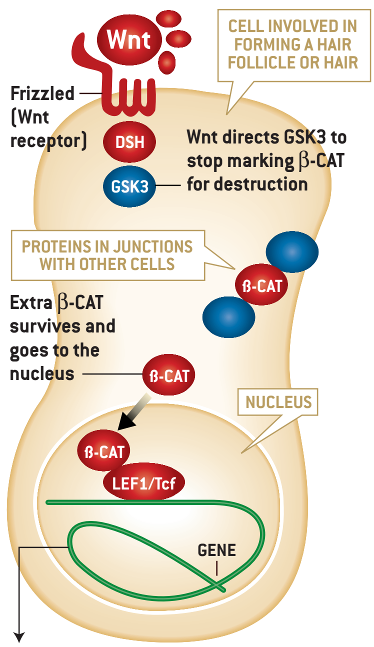



**3 ANAGEN** On instructions from the dermal papilla, the lower part of the follicle rebuilds and begins producing hair again




## MOLECULAR CONTROLS ON HAIR PRODUCTION

Recent studies suggest that Wnt proteins play a major role in inducing embryonic skin cells to make hair follicles and, later, in prodding follicle cells to make hair throughout life. Wnts instruct cells to stop breaking down another protein, beta-catenin (β-CAT), which joins with LEF1 or a related protein to help activate specific genes. Those genes, in turn, give rise to proteins that cause the cells to specialize and contribute to follicle or hair formation. Molecules in, or interacting with, the Wnt signaling pathway could one day serve as targets for drugs aimed at enhancing or diminishing hair production.




Proteins are produced, such as cyclin D (in embryonic skin cells) and hair keratins (in follicle cells that become hair cells)

## PROTEINS THAT MAY INTERACT WITH THE Wnt SIGNALING PATHWAY IN THE SKIN

- Bone morphogenic protein
- Fibroblast growth factor
- Noggin
- Sonic hedgehog
- Sox
- Transforming growth factor-beta
- Winged-helix *nude*

JOE ZEFF

**JULIUS CAESAR** reportedly combed his "scanty locks" forward to cover his baldness; he also had "superfluous" hairs plucked out

**GOOSE BUMPS FORM**, and hair stands on end, when tiny muscles that are linked to hair follicles contract in unison

**COMMON BALDNESS** in men can be inherited from either side of the family; many genes appear to be involved

**BODILY STRESS**, such as severe infection or surgery, can cause hair to fall out, but the loss may be delayed for up to six months

**SMOKING** can hasten hair loss

**HAIR-REPLACEMENT SURGERY** moves follicles from the sides and back of a man's head to the bald areas

**SOME WOMEN LOSE HAIR** after giving birth or discontinuing birth-control pills

**THE AVERAGE SCALP FOLLICLE** can generate more than 30 feet of hair in a lifetime

**FOLLICLES** with round cross sections yield straight hair; flatter follicles yield curlier locks

cells differentiate to form the inner root sheath, which serves as a vase for the hair. An outer root sheath arises, too, and encases the inner sheath. As new hair cells push the older ones upward, causing them to break through the skin surface, the older cells die, forming a shaft of dead, keratin-rich cells. These dead cells are virtually indestructible, persisting to decorate our heads and blanket our bodies with hair.

At the end of gestation, a newborn human enters the world with five million to six million hair follicles distributed in a genetically determined pattern over the body. No new ones form thereafter. The palms of the hands and the soles of the feet are pretty much the only places that truly lack follicles; other areas that seem to be hair-free actually produce short, thin hairs.

## Born to Cycle

FOLLICLES BEGIN CYCLING within two or three years after birth. The cycle has been shown to have three main stages. In catagen, the epithelial cells below the bulge essentially commit suicide, leaving behind only the dermal papilla and a membrane (the basement membrane) that formerly encased the now dying region. As the cells die, this membrane contracts and draws the dermal papilla up to the bulge. (In the scalp, this trip takes about two weeks.) Meanwhile the hair shaft loses its anchor deep in the dermis. It therefore becomes prone to shedding in the next two stages.

When the dermal papilla reaches the bulge, follicles enters telogen, the resting phase. Telogen can last about three months in the human scalp, but its duration can be modulated by a range of factors. Plucking hair or wounding the follicles can shorten it, for instance.

Anagen follows telogen. Early on some of the stem cells from the bulge divide and travel down along the basement membrane to become matrix or outer root sheath cells. Once formed, the matrix cells proliferate and ultimately give rise to the hair cells and the inner root sheath, repeating the steps that occur during embryonic development. This repetition implies that the events of anagen are probably controlled by a number of the same signaling molecules that operate during development.

The reconstituted anagen follicles produce an inch of hair every two months or so in the scalp and usually keep this up for six to eight years. The length of anagen determines how long a single hair can grow. On any given day in the life of a typical 20-year-old, about 90 percent of the scalp follicles are in the productive, hair-growing phase, and about 10 percent are decaying or inactive; approximately 50 to 100 hairs are shed.

Hair thinning generally happens not because follicles disappear but because the ratio of follicles in the growing and nongrowing phases shifts unfavorably. Also, many follicles in balding people shrink progressively, ultimately producing only small, colorless hairs.

As is true during follicle development in the embryo, during anagen signals from the dermal papilla instruct the matrix cells to divide and subsequently differentiate into hair cells. For this reason, scientists have become very interested in uncovering the nature of the signals issued by the dermal papilla dur-

**SOME DRUGS** that can cause hair loss include blood thinners, antidepressants, high blood pressure pills and anabolic steroids

**CUTTING HAIR** does not make it grow faster or get thicker

**THE AVERAGE ADULT SCALP** sports about 100,000 follicles

**CANCER DRUGS** cause balding because they kill rapidly dividing cells, including ones that multiply transiently during hair production. Hair grows back eventually because the drugs usually do not harm the stem cells that replenish lost hair cells

**BRISTLES** are the only hairs on whales, elephants and rhinoceroses

**HAIR CAN BE STRETCHED** by about a third its length in water without being harmed

ing development and cycling. They don't have the answer yet, but in the past few years Elaine Fuchs and her colleagues at the University of Chicago have discovered that the dermal papilla's signals probably convey their directives largely by activating still other signaling molecules—members of the Wnt family of proteins. Wnt proteins have long been recognized as key regulators of varied developmental processes in mammals and other organisms.

## The Hand on the Helm

FUCHS STUMBLED ACROSS the first clues to the importance of Wnts to hair about six years ago. At the time, for reasons unrelated to treating human hair disorders, she wanted to identify the signaling molecules that instruct certain matrix cells to begin producing hair keratins.

Often a cell will initiate a behavior, such as making new proteins, after a molecule from the outside binds to a receptor on the cell surface and triggers a cascade of molecular interactions on the inside. These signaling cascades frequently lead to the activation of specific genes in the nucleus, culminating in the production of the proteins the genes encode. Knowing this, Fuchs began her search for the molecules that dictate the conversion of matrix cells to hair cells by trying to identify the molecules in the nucleus that switch on the hair keratin genes.

In 1995 her group discovered that a regulatory protein called lymphocyte enhancer factor 1 (LEF1) participated in activating the hair keratin genes. It was also present during hair follicle formation in the embryo, where it appeared in the earliest clusters of ectoderm cells as well as in the cells destined to form the dermal papilla. Presumably on orders from some outside signal, LEF1 became active and helped to turn on genes needed for follicle formation or hair growth. Consistent with this conclusion, Rudy Grosschedl and his co-workers, then at the University of California at San Francisco, discovered that without LEF1, mice fail to make a furry coat. And when Fuchs's team engineered mice that produced excess LEF1 in the skin, the animals produced more hair follicles than normal.

At about the same time, other groups demonstrated that LEF1 cannot activate genes on its own; rather it must first couple with a second protein, beta-catenin. The only mechanism known to trigger this coupling was the activation of the signaling cascade that begins with the binding of a Wnt molecule to the cell surface. Beta-catenin normally helps to form junctions with neighboring cells. In the absence of Wnt signaling, an enzyme inside the cells marks any unused beta-catenin for destruction. Wnts instruct cells to handcuff that enzyme. With the enzyme out of commission, beta-catenin becomes free to accumulate and to pair with LEF1 or one of its relatives.

Combined with Fuchs's discoveries, these results suggested that Wnts and rescued beta-catenin molecules might be central in both follicle formation and hair production. Subsequent studies in mice added support to that notion. For instance,

## SAVE THE HAIRS! by Mia Schmiedeskamp

*Drug companies are busy searching for the next generation of hair-promoting compounds*

FEW PEOPLE ACCEPT hair loss with equanimity. "People often say to me they can deal with the loss of a kidney ... but not with hair loss," says Vera H. Price, director of the Hair Research Center at the University of California at San Francisco. So how can science help?

The good biological news is that in the most common types of thinning, hair follicles don't die. In classic male- and female-pattern hair loss (androgenetic alopecia), for instance, follicles become miniaturized and their growing phase abbreviated; they then produce extremely short, fine hairs. "Even guys who are bald still have little hairs on the top of their head," explains Bruce A. Morgan of Harvard's Cutaneous Biology Research Center. In a rarer condition, alopecia areata (affecting nearly 2 percent of people), the follicles' growth phase ends prematurely under autoimmune attack, causing hair to fall out in patches or, in extreme cases, all over the body. But, again, the follicles survive.

Treatment for alopecia areata typically focuses on quelling the wayward immune system, but treatment for male- and female-pattern hair loss must increase the size of Lilliputian follicles as well as hair length. Minoxidil—introduced as Rogaine in 1988—was the first drug approved by the U.S. Food and Drug Administration for this purpose and is the only one licensed for use in both sexes. Scientists still debate how minoxidil, which is applied topically, produces thicker, longer hairs: perhaps it increases blood supply, better nourishing the follicles, or perhaps it alters cellular concentrations of substances that regulate hair growth.

The mechanism of the second approved drug, finasteride, is clearer. This compound, marketed as Propecia for male hair loss (and as Proscar in a higher-dose formulation for prostate enlargement) is taken orally. In the body, it inhibits an enzyme that converts testosterone to a hormone called dihydrotestosterone (DHT) and thus reduces DHT production. DHT is critical to the development of male fetuses, but later it can be a troublemaker. It stimulates some folli-

Fuchs's group devised a way to flag cells that activated LEF1 binding genes in response to a Wnt signal in a developing embryo. Those experiments implied that Wnt is the mesoderm-issued signal that instructs the overlying ectoderm to begin forming an appendage and is likewise the ectodermal signal that tells the underlying mesoderm to form the dermal papilla. What is more, much later in development, after follicles have formed, Wnt appears to be the message that directs matrix cells above the dermal papilla to differentiate into hair cells.

Even more dramatic evidence for the central importance of Wnts came when Fuchs's group created mice that, after birth, could not degrade beta-catenin in their epidermal cells, a feature that made the cells behave as if they were endlessly receiving a Wnt signal. As adults, these rodents acquired an unusucles to produce thick, long hair (on the cheek and chin, for example), and it induces scalp hair thinning in susceptible people, sometimes as early as the preteen years. Some researchers suspect that DHT disrupts hair follicles by acting on a region called the dermal papilla, altering its production of substances that influence hair growth.

In a study published in 1998 of more than 1,200 men between the ages of 18 and 41 with mild to moderate hair loss, about 83 percent maintained the hair they had on the top of their head after two years of finasteride use. More than half had at least mild regrowth. But Jerry Shapiro, director of the University of British Columbia Hair Research and Treatment Center, cautions, "I think the big job is to keep patients' expectation levels appropriate, so that they know it's not going to be luxuriant hair. The emphasis should be on prevention. Regrowth is also a possibility but shouldn't be stressed, especially in men with more advanced hair loss."

Men can expect similar results with 5 percent minoxidil, advises Marty E. Sawaya of ARATEC, which conducts clinical trials for various companies. She estimates that 25 to 30 percent of men gain moderate-to-dense regrowth with either product. Some men hedge their bets by using both over-the-counter minoxidil and prescription finasteride. In stumptailed macaques, at least, the two drugs together worked better than either one alone.

Shapiro and Price advise their patients to allow about a year to see whether hair-growth drugs work—and to commit to using them correctly. Minoxidil solution is applied directly to the scalp twice daily; Propecia is a once-daily pill. To maintain results, either drug must be used consistently and indefinitely. "Nothing reverses thinning completely," Price says. "But do these drugs work? Yes, they work."

For female-pattern hair loss, only 2 percent minoxidil has FDA approval. About 60 percent of women achieve maintenance of hair and some regrowth with this option. Those with the opposite woe of unwanted facial hair now have an FDA-approved option, too: topical eflornithine cream, marketed as Vaniqa, inhibits an enzyme necessary for cell proliferation, thus retarding hair growth. But experts once more caution patients to keep their expectations reasonable. About 58 percent of women see slight improvement or better, usually after a couple of months. The cream slows hair growth but does not stop it, so treated women do continue to tweeze or remove hair by other means.

## Looking Ahead

MUCH RESEARCH done by companies is kept secret until drug candidates reach clinical trials. Probably, though, the next hair-loss treatments to come down the road will work on familiar principles. Several companies have developed molecules that inhibit the same enzyme as finasteride. Hoechst AG has done some laboratory testing of a drug that would be applied to the scalp to block DHT from binding to hair follicle cells. And Bristol-Myers Squibb has a drug in early clinical studies that is thought to function similarly to minoxidil.

Perhaps the most promising compound to enter human trials is called dutasteride, from GlaxoSmithKline. Like finasteride, it inhibits the enzyme that produces DHT, but it blocks two forms of the enzyme instead of just one. Sawaya says the preliminary results suggest that dutasteride is more effective at increasing hair count than finasteride, even at a lower dose.

"We don't have a product yet that's going to be 'wow!' for over 50 percent of people," she notes. "I do think dutasteride will be that product if the company goes forward." When or if FDA approval might be sought for using dutasteride against hair loss remains uncertain, however. Gaining approvals is time-consuming and costly, and GlaxoSmithKline may choose to pursue it first as a prostate drug, as happened with finasteride.

Scientists are on the prowl for new drugs all the time. Morgan's Harvard colleague Michael Detmar discovered earlier this year that abundant amounts of a growth factor that increases the blood supply make mice grow hair faster and thicker. Now, Morgan says, the hunt is on for small molecules that will either mimic or activate the factor. But drugs like that or ones intended to interact with molecules that directly regulate hair growth—such as Wnt or beta-catenin—are a long way off. Much more research needs to be done before the right targets can be manipulated without risking such consequences as cancer.

A fundamental understanding of hair biology may someday let physicians replace a defective gene in hair follicles through gene therapy or grow hairs in a petri dish for use in graft surgery. "The complexity of the question is like understanding how a limb forms. It's ambitious. But we are discovering a lot and discovering a lot quickly," muses Kurt S. Stenn, chief scientific officer of Juvenir Biosciences, a company recently spun off from Johnson & Johnson to focus predominantly on hair research. "This is a wonderful time to be working in hair biology. So many breakthroughs are coming."

"This is a wonderful time to be working in hair biology. So many breakthroughs are coming."

*—Kurt S. Stenn, Juvenir Biosciences*

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*Mia Schmiedeskamp is a science writer based in Seattle.*

ally lush coat by forming new hair follicles between the ones that were laid down during embryonic development.

The production of new follicles is certainly exciting, but a couple of other findings from the mouse studies might make balding readers think twice before tracking down Fuchs and begging her for vials of Wnt to pour on their heads. As the furry rodents aged, they acquired benign lumps that resembled a common human scalp tumor called pilomatricoma. Fuchs's laboratory subsequently demonstrated that in humans these tumors arise when a mutation in the beta-catenin gene prevents the protein's breakdown. Wnts and extra beta-catenin have also been implicated in cancers of the colon, liver, breast and reproductive tract.

To Fuchs, all these results, including the unfortunate mouse

## TAKING HAIR LOSS TO HEART

### *Shiny domes may signify an elevated susceptibility to heart attacks*

IN THE PAST 10 years several studies have hinted that baldness is more than an embarrassment: it can be a visible warning of increased risk for heart disease. Last year the largest study yet conducted confirmed that notion.

The investigation, headed by JoAnn E. Manson of Harvard Medical School's Brigham and Women's Hospital, looked at participants in the Physicians' Health Study, a long-term project that examined the risks for heart disease in some 22,000 male physicians. Eleven years into the project, the doctors, who were then between the ages of 51 and 95, indicated which of five pictures most closely approximated their hair pattern when they were 45. Most men who go bald lose their hair in a standard sequence, although at different rates. First, the hairline recedes near the temples. Next, the hair at the crown, or vertex, begins to go. Then the hairline rises farther and the bald spot at the crown grows, until the two areas meet.

Manson and her colleagues correlated the hair patterns with heart problems that had arisen in 19,112 subjects who had no cardiovascular problems at the start of the Physicians' Health Study. Physicians who died during the 11-year period were not evaluated, so the link between baldness and fatal heart attacks could not be assessed. But the researchers could look at the connection between hair loss and other "coronary events," namely nonfatal heart attacks, angina or treatment for heart disease (bypass surgery or angioplasty).

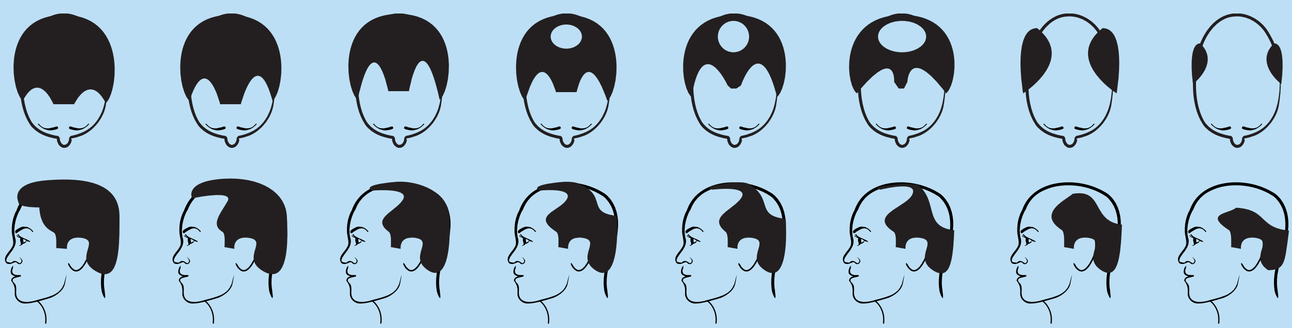
When potential confounding influences were eliminated, the results showed that, regardless of age, men with frontal baldness alone were only slightly more likely (9 percent) to face heart problems than were men who retained all their hair. But those with mild thinning at the crown had a 23 percent higher risk of heart disease, and those with moderate or severe balding at the crown had more than a 30 percent higher risk.

Worst off were severely bald men with high cholesterol levels or high blood pressure. Those with elevated cholesterol were almost three times more likely to have heart disease than were men with high cholesterol and hair on their pates. Bald subjects with raised blood pressure faced almost twice the risk encountered by their counterparts with lusher hair.

Researchers can only speculate about why bald men would be more susceptible to heart disease. Genetic inheritance could be at fault, or high levels of male hormones (androgens) or increased sensitivity to them could be the common denominator. Androgens, Manson notes, play a part in male-pattern baldness and appear to contribute to atherosclerosis and increased blood clotting, both of which promote heart disease.

Obviously, baldness does not cause heart attacks. It can, however, serve as a daily reminder to take preventive measures. The drill should be familiar by now: avoid smoking, get regular exercise, eat right and keep blood pressure and cholesterol levels in the normal range.

Will taking drugs aimed at preventing hair loss also protect against heart disease? Manson received a flood of e-mails last year asking that very question. Sorry, she says. No evidence suggests it will. *—R.L.R.*



STANDARD CLASSIFICATION SCHEME for the progression of male-pattern baldness, the Norwood-Hamilton scale, includes the heads depicted here. In a less typical pattern (not shown), the hairline rises progressively to the back of the head but a discrete bald spot never forms. The heart study described above presented a simplified version of the scale.

JOE ZEFF; SOURCE: O'TAR T. NORWOOD

tumors, provide useful information for scientists interested in treating hair disorders. They teach that Wnts are major regulators of follicle development and cycling but that simply delivering Wnts by constant application would not be feasible as a human therapy, because of the tumor risk. The trick to correcting hair maladies, Fuchs contends, may be to deliver Wnts in a pattern that mimics nature better or to manipulate other steps in the Wnt signaling cascade.

To do that, scientists need still more information about the Wnt signaling pathway and about other factors in the skin that influence it. Which Wnts, and which of their numerous receptors, are involved at different steps of the hair cycle and in follicle development, and what molecules control their production? And which molecules inside Wnt target cells determine how those cells respond to Wnts, such as whether they become hair cells or other parts of a follicle?

**HAIRS DETECT MECHANICAL STIMULI** and relay the information to the nervous system

**AN EYEBROW HAIR** grows for about two months before falling out

**CONTINUALLY WEARING** tight bands or braids or buns may cause permanent patches of baldness

Research into signaling pathways that interact with the Wnt pathway will surely offer some clues to the answers. Scientists who study many different tissues and organisms have identified a host of proteins in such pathways, including sonic hedgehog, transforming growth factor-beta, bone morphogenic protein, noggin and fibroblast growth factor, to name just a few.

Sonic hedgehog could be particularly crucial for hair growth. Like Wnt proteins, it carries a signal from one cell to another and is known to participate in the proper development of embryos. Further, sonic-hedgehog and Wnt-signaling pathways often influence each other. Investigations reveal that although sonic hedgehog is not needed for formation of the hair germ, it is needed for subsequent conversion of the germ to a full-fledged follicle. And last year Ronald G. Crystal of Weill Medical College of Cornell University found that when hair follicles in adult mice are induced to make the protein during the resting, telogen stage, the follicles shift prematurely into the hair-producing, anagen stage. Thus, sonic hedgehog can stimulate dormant follicles to begin producing hair.

Although treatment with sonic hedgehog might seem an attractive idea for inducing hair growth, too much signaling by this molecule results in basal-cell skin cancers in humans. To develop therapies that involved sonic hedgehog, Wnts or other proteins able to induce cell division, pharmaceutical manufacturers would first have to make sure that those molecules were properly controlled.

The effects of bone morphogenic proteins and different forms of transforming growth factor-beta on Wnt signaling are proving difficult to sort out. But some scientists suspect that when that task is done, those proteins, too, could prove useful for stopping or starting hair growth.

## Styling Therapy

IDENTIFYING THE MULTITUDE of molecules that coordinate the development and cycling of hair follicles is clearly a daunting job. Yet thanks to the rapid pace of technological advancement, researchers should soon be able to discern all the genes that are activated in purified populations of cells at different stages of follicle development and cycling. With this information at the ready, they could assess how these complex patterns of gene activity are altered in people who have hair disorders. The technology should also enable skin biologists to uncover new proteins important to hair production as well as to specify which ones contribute to different disorders.

As researchers become more sophisticated in their knowledge of the molecular interactions underlying hair growth, they can begin animal testing of compounds that might restore order to deranged regulatory pathways and revive dormant follicles. If those tests go well, human scalp skin can be transplanted onto mice incapable of rejecting it to determine whether human and mouse follicles respond comparably to the agents. And if those results are good, investigators may attempt human trials of the most promising drug candidates.

No one can predict how soon dermatologists and pharmaceutical companies will be able to produce new therapies built on the discoveries emerging from basic research into hair follicle development and cycling. But that research is progressing remarkably fast. If the pace continues, Fuchs predicts, much of the information that is needed to understand the complex controls on hair manufacture will probably be in hand within the next five years. SA

*Ricki L. Rusting is a staff editor and writer.*

### MORE TO EXPLORE

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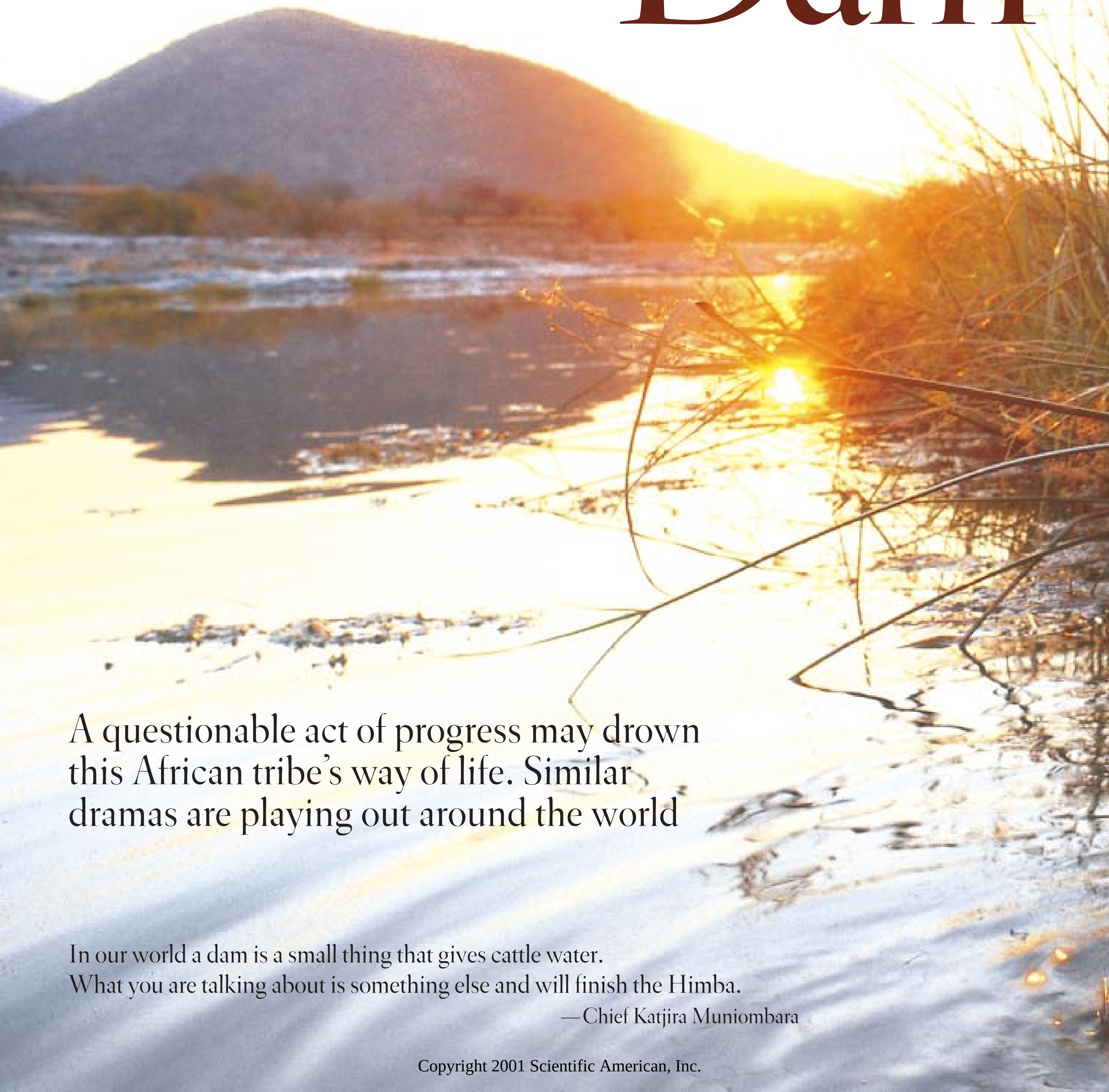
General information about hair can be found at **www.keratin.com**

# THE Himba AND THE Dam

By Carol Ezzell
Photography by Karin Retief



A questionable act of progress may drown this African tribe's way of life. Similar dramas are playing out around the world

In our world a dam is a small thing that gives cattle water.
What you are talking about is something else and will finish the Himba.

—Chief Katjira Muniombara

Jakatunga Tjiuma, counselor to a Himba headman in Namibia, washes his hands in the Kunene River, the site of a proposed hydroelectric dam.

**Not until** we stand on a ridge overlooking the Kunene River—which forms part of the border between the southern African nations of Angola and Namibia—does tribal leader Jakatunga Tjiuma comprehend the immensity of the proposed dam. "Look there," I tell him with the help of an interpreter, pointing to a distant notch in the river gorge that a feasibility study says would be the most likely site of the wall of concrete. "That's where the dam would be."

Turning, I point to hills in the east. "And the water would back up behind the dam to make a lake that would stretch to there." I can see the shock and incredulity in his eyes as he begins to understand how high the water would rise up the faraway hillsides, flooding more than 140 square miles of Himba settlements, grazing land and grave sites. He clutches a blanket around his shoulders and crouches on a rock, speechless.

Tjiuma is a counselor to one of the headmen for the Himba tribe, an essentially self-sufficient band of 16,000 people who eke out an existence from the barren, rocky terrain of northwest Namibia, living off the milk and meat of their cattle and goats, along with the occasional pumpkin or melon. The Himba are sometimes called the Red People because they traditionally cover their bodies, hair and the animal skins they wear with a mixture of butterfat and a powder ground from the iron ore ocher. They say they use the ocher-butter mixture because they like the way it looks, although it undoubtedly also protects their skin against the arid climate.

For decades, the Himba have lived in relative isolation. No other tribes wanted their hardscrabble land, and the Germans who colonized the area in the late 19th century rarely interacted with them. More recently, the Himba's main contact with outsiders has been with soldiers during the fight for Namibia's independence from South Africa (which was won in 1990), with marauding combatants spilling over from Angola's ongoing civil war, and with the occasional caravan of hippie Americans or Europeans. But if the Namibian government has its way, by 2008 more than 1,000 foreign workers will have settled in a temporary village just downstream from Epupa Falls, the site the government favors for the dam. With them will come a cash economy, alcohol, prostitution and AIDS—as well as improved roads, better access to medical care, schools and perhaps even electricity.

The situation surrounding the proposed dam on the Kunene River can be viewed as a microcosm of dam projects around the world that are affecting indigenous peoples. A survey by the World Commission on Dams, which issued its controversial final report last November, found that 68 of the 123 dams worldwide they studied would displace people, many of them in tribes that had little prior contact with the technological world. The largest dam project, the massive Three Gorges Dam on the Yangtze River, will require the resettlement of up to two million Chinese. Nearly all the dams will change local peoples' livelihoods and cultures—for good or ill, or some combination of the two.

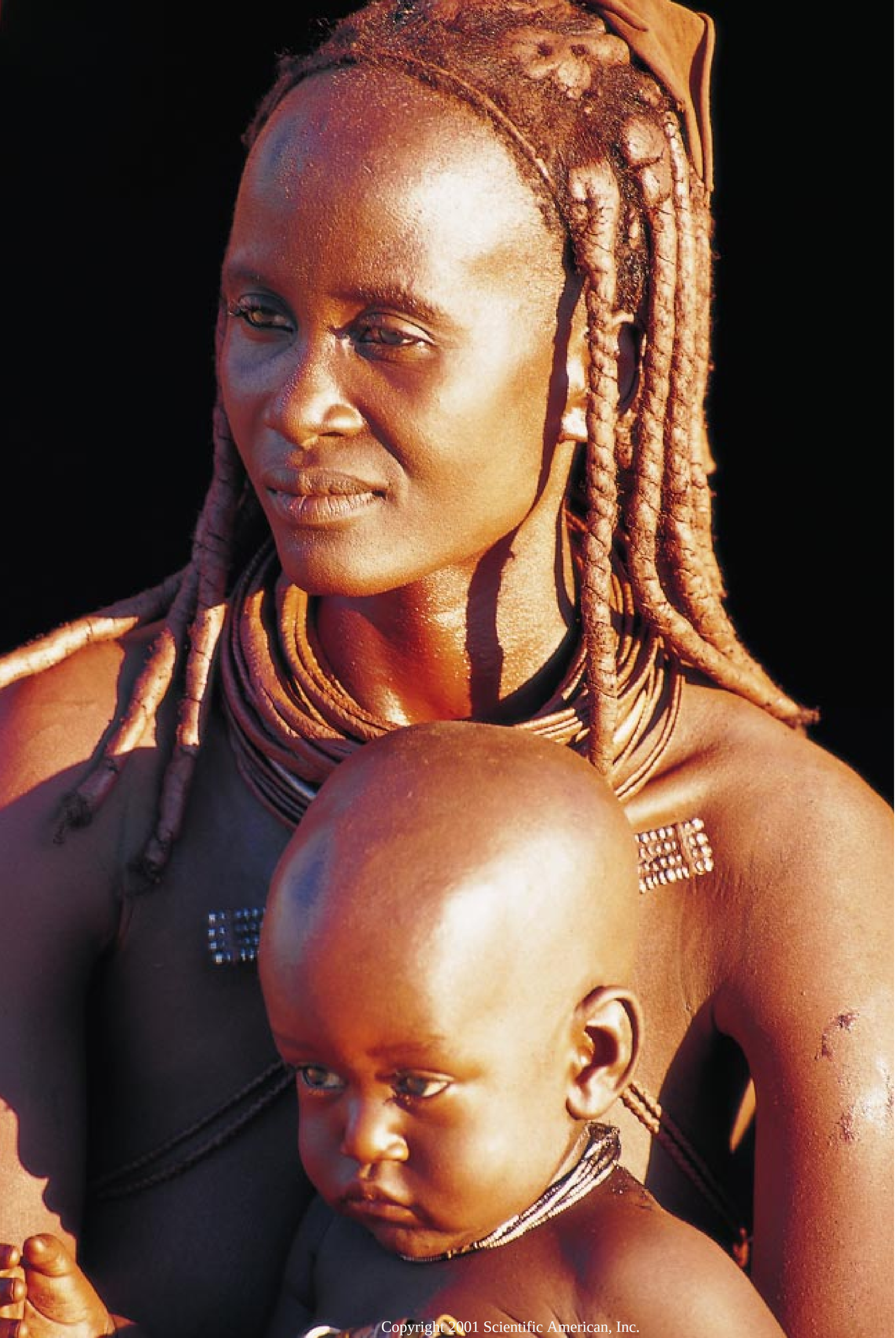
How should global society weigh the right of such peoples to be left alone against, in some cases, the very real necessity for developing countries to take advantage of their resources? Should such countries have the autonomy to decide what is in the best interests of all their citizens, even if some of them don't want to change? Perhaps most important, how can traditional peoples decide such issues for themselves when they have only a shaky idea of how more developed societies live and what they might be getting themselves into?

## Into the Desert

KAOKOLAND, THE CORNER OF NAMIBIA where the Himba live, is truly the back of beyond. We arrive at Epupa Falls, the modest waterfall on the Kunene River that would be inundated by the dam's reservoir, two days after leaving the last tarred road. Our 4×4 truck is packed with everything from jerricans of gasoline (the closest gas pump is a day's drive away) to cas-

Himba mother and child glisten red from a coating of butterfat mixed with the iron ore ocher. Like other adult women, the mother shaves her forehead and twists her hair into multiple braids that she daubs with a mud mixture. The heads of infants are shaved until they are weaned.

The situation surrounding the proposed dam on the Kunene River can be viewed as a microcosm of dam projects around the world that are affecting indigenous peoples.

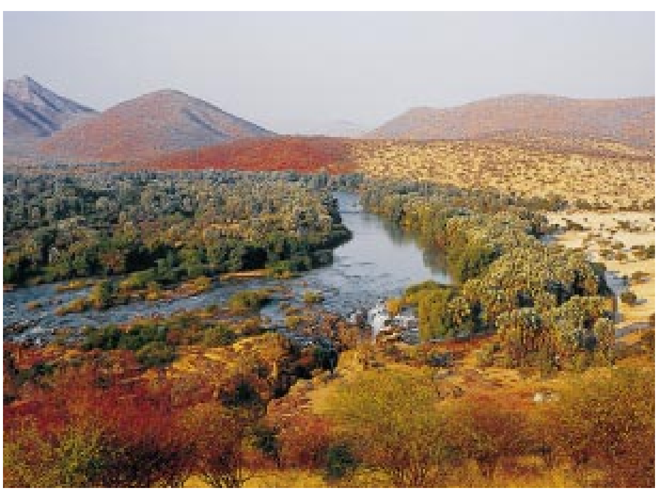


es of bottled water, spare tires, emergency medical supplies, camping gear, and small gifts of tobacco, sugar and blankets. Tied to the top of our vehicle is a brand-new bicycle—the payment requested by our Himba translator, Staygon Reiter, in exchange for his services, although how he will use it in this inhospitable landscape I don't know. He has asked specifically that the bicycle come equipped with a carrier basket large enough to hold a goat.

Much of our journey is bumpy, jerky and slow as we attempt to follow the rough track while swerving to avoid washouts and potentially tire-puncturing rocks. More than once we get stuck in sand while trying to cross a dry riverbed, our tires spinning and squealing until we jump out to deflate them a bit or to stuff branches behind them for traction. At one point we stop to look at a particularly large scorpion in our path; I comment that I've seen smaller lobsters.

The settlement at Epupa Falls, where we camp, is a kind of crossroads, a no-man's-land where Namibian Himba mix with their Himba relatives from across the river in Angola and with other tribes such as the Herero—to whom the Himba are closely related—as well as with the Zemba, Thwa and Ngambwe. There is a modest thatched church built by missionaries; a tiny but deluxe safari camp; a corrugated-metal store that sells mostly bags of cheap tobacco, maize meal, and tepid Coke, Sprite and Fanta; and a community-run campsite where visitors like us can pitch a tent under the palmlike *omerungu* trees for 50 Namibian dollars (about US$6) per night. Scarcely any people live at the settlement permanently: the Himba come for a few weeks or months at a time and build temporary huts while they attend funerals, divide inheritances, sell cattle, conduct other business, and visit with friends and relatives.

Our first stop is to meet Chief Hikuminwe Kapika at his compound near Epupa Falls, which is part of the territory he controls. It is immediately clear that Kapika—who is one of roughly a dozen Himba chiefs—is sick of talking about the proposed dam with outsiders but eager for us to appreciate the importance of his rank. From his shock of grayish hair and weathered face, I guess him to be in his 70s, although Himba don't have a calendar system, so they usually don't know the year in which they were born. He keeps us standing beside his white metal camp chair (the only one in his compound) swatting flies from our faces as I try to catch his attention long enough to answer my questions. Several times during our interview he spits

The Kunene River forms the northwest border between Angola and Namibia; the Himba live in the rocky, arid region known as Kaokoland (*top*). Tribal leader Tjiuma (*middle*) points to the spot (dam site 1 on map) the Namibian government favors as the most economical place for the proposed dam. The location is downstream of Epupa Falls (*bottom*), which would be inundated by the reservoir expected to back up behind the dam wall. The flooding would eliminate the *omerungu* palm trees that provide fruits the Himba depend on in times of drought. The Angolan government prefers a site farther downstream, in the Baynes Mountains (dam site 2), that would necessitate the renovation of another dam, which was damaged in the country's civil war.

MAP BY SUSAN CARLSON

through a gap in his front teeth created in his teens when, in keeping with Himba tradition, his lower two central incisors were knocked out and the top two filed to create a V-shaped opening. He makes a point of demonstrating what a busy man he is by continuing to sew a black fabric loincloth and interrupting our translator to correct a group of rowdy children.

Eventually Kapika tells us that he vehemently opposes the proposed dam. He is afraid that the people who will come to build it will steal the Himba's cattle—not an irrational fear, because the Himba were nearly wiped out at the end of the 19th century as a result of cattle raids by the Nama tribe, which lives to the south. And cattle theft continues today. He is also worried that the newcomers will take valuable grazing land, which the Himba are careful not to overuse. Family groups move their households several times a year so that extensively grazed regions can grow back. The area around Kapika's compound illustrates the need for such conservation: the cattle and goats have eaten everything green they can reach, leaving the bushes and trees top-heavy with scraggly growth overhanging trunks like lollipop sticks.

Himba leaders also object to the dam because it would flood hundreds of graves, which play a central role in the tribe's religious beliefs and social structure. In times of crisis, family patriarchs consult their forebears through special ceremonies at grave sites, and graves are often used to settle disputes over access to land. Acreage is owned communally, but each permanent settlement is guarded by an "owner of the land," usually the oldest man of the family who has lived at that place for the longest time. When deciding who should be able to graze their cattle in a particular area, Himba compare the number of ancestors they have buried there. They ask, "Whose ancestral graves are older, ours or theirs?"

Kapika says the Himba will resist and fight "with stones and spears" if the Namibian government tries to build a hydroelectric dam at Epupa Falls. "I'm a big man," he tells us. "I'm a man who can stand on his own."

## Dammed If They Do

HOW DO YOU DESCRIBE a megadam to someone who has never seen electricity? Or a building more than one story high? The dam planned for Epupa Falls would rise 535 feet—only 15 feet shorter than the massive Grand Coulee Dam in Washington State. It would generate 360 megawatts of electricity per day and cost more than US$500 million to build.

A dam was first proposed near Epupa Falls in 1969, when Namibia was South West Africa, a territory of South Africa. The idea went nowhere, but it was revived in 1991, a year after Namibia's independence, when Namibia and Angola commissioned a feasibility study to evaluate such a scheme. The study considered two sites for the dam: Epupa Falls and a spot in the Baynes Mountains farther downstream. It concluded that Epupa Falls made more economic sense, but Angola has favored the Baynes site in part because building a dam there would mean that the country would also get funds to renovate a dam on an Angolan tributary that was damaged during the civil war. That cost is one reason the Baynes site would be more expensive.

When the study's consultants first came to discuss the intended dam with the Himba, the tribal leaders initially had no objections, thinking it was going to be a small earthen dam like the ones they built to help water their cattle. The degree of miscommunication took a while to become apparent. Margaret Jacobsohn of Integrated Rural Development and Nature Conservation, a Namibian journalist turned anthropologist who worked on the social impact part of the feasibility study, recalls a telling incident a few months into the process. She went to visit a Himba family compound near Epupa Falls and began asking their views about the proposed dam. Oddly, they didn't seem to know anything about it, even though the Namibian government had told her that they had been informed. As she finished her questionnaire, a family member asked her to help them with a mysterious piece of paper they had received some time before. When the man brought an ocher-smeared envelope out of his hut, she recognized it as a letter about the dam in English that they had never even opened. After she translated it for them, an old man of the family shook his head and said, "You're talking about the great death of the Himba."

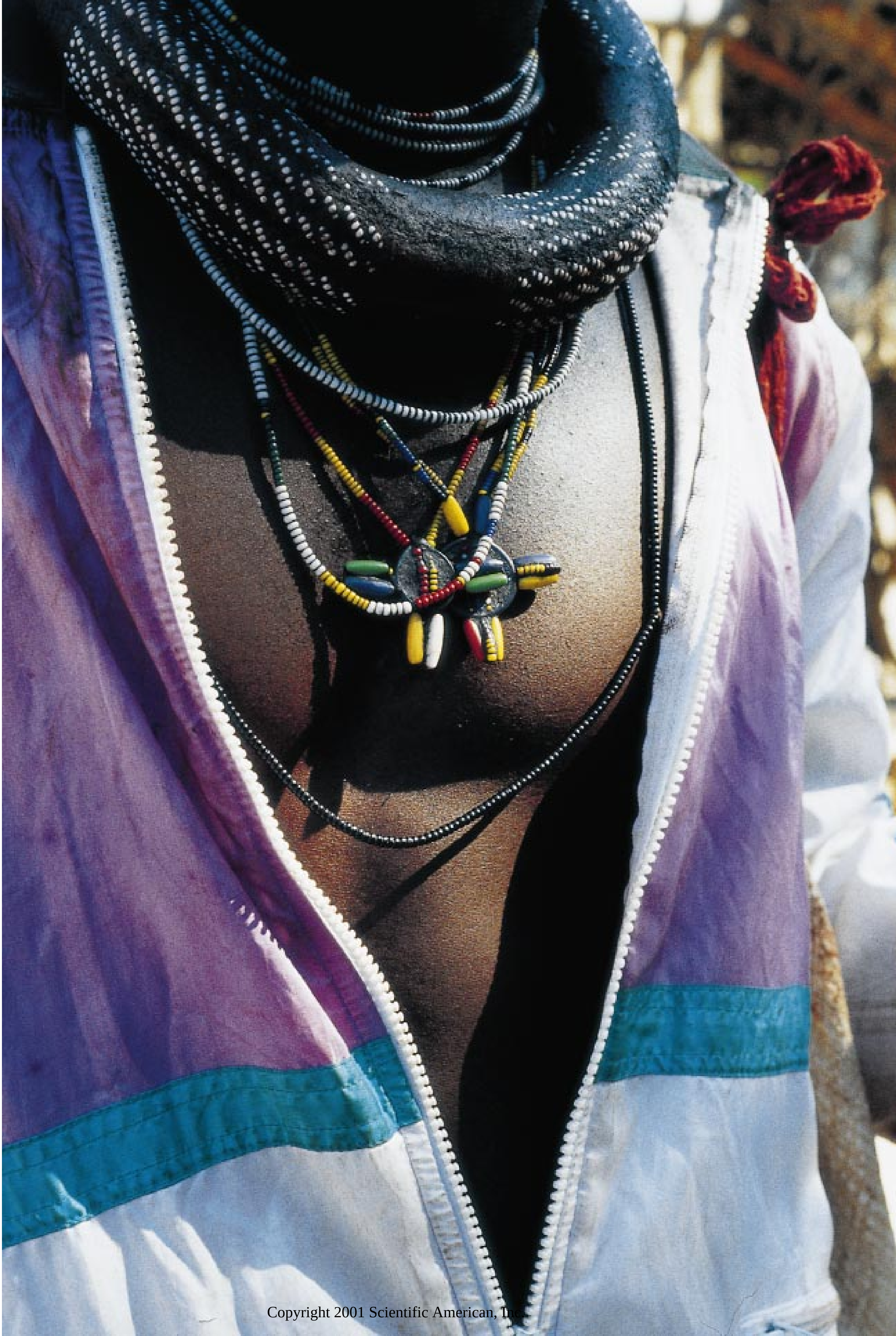
How do you describe a megadam to someone who has never seen electricity? Or a building more than one story high?

## Lifeways of the Himba

THE HIMBA ARE ONE of the last tribes of traditional people who are generally self-supporting and fully or partially isolated from global society. Anthropologists find them particularly interesting because they observe a system of bilateral descent. Every tribe member belongs to two clans, one through the father (a patriclan) and another through the mother (a matriclan). Tribes that practice bilateral descent are rare: besides the Himba, the custom occurs among only a few peoples in West Africa, India, Australia, Melanesia and Polynesia.

Each Himba patriclan is led by the oldest man in the family. Sons live with their fathers; following marriage, daughters leave to join their husband's family's household and become a member of that patriclan. But the inheritance of material wealth—in the Himba's case, primarily cattle—is determined by the matriclan. Accordingly, a son does not inherit his father's cattle but his maternal uncle's instead.

Bilateral descent is particularly advantageous for tribes that live in precarious environments, such as the drought-prone region of the Himba, because during a crisis it allows an individual to rely on two sets of relatives spread over different areas.



The system could also play a role in alleviating inbreeding among Himba livestock. Various patriclans have taboos prohibiting their members from owning cattle or goats of a certain color or coat pattern. When cattle are born that violate a patriclan's taboos, they must be swapped with nonoffending cattle from another patriclan.

The religion of the Himba is also organized according to bilateral descent and is practiced through an individual's patriclan. Himba believe in a god-creator, but that entity is very remote from human affairs and can be petitioned only by invoking dead paternal ancestors to act as intercessors. The tribe's religious observances center on holy fires that were initially kindled at the graves of ancestors and are maintained by the leader of each respective patriclan in his family compound.

The holy fire is small, often just a smoldering log surrounded by several rocks. It is always located between the opening of the headman's hut and the corral where the cattle are penned at night. That area of the compound is considered sacred: strangers cannot cross between the holy fire and the corral or between the holy fire and the headman's hut without first asking permission. Traditionally, the headman keeps the fire going during the day as he sits by it to commune with his ancestors about any problems facing the family. At night, the headman's wife takes an ember of the fire into the main hut; in the morning, the ember is taken outside to the hearth again.

The Himba are also intriguing to anthropologists as subjects of rapid social change. One way in which this change is manifesting itself is in patterns of dress. Many more Himba men than Himba women have adopted Western clothing and hairstyles. At Epupa Falls, where Himba occasionally have contact with outsiders, a Himba man can be seen one day barechested and wearing a Himba apron-skirt and jewelry, and the next day dressed in pants and a shirt. Few young men there wear the "bachelor ponytail" that is traditional for unmarried men, and even fewer married men follow the custom of not cutting their hair and of covering their heads with a cloth. And it is extremely rare to find a Himba man at Epupa Falls who wears ocher: indeed, many wash daily in the Kunene River using soap.

Himba women, however, are much more conservative in their dress. Even at Epupa Falls, most of the women go barebreasted and wear traditional apron-skirts made of calfskins or goatskins; they smear themselves liberally from head to toe every morning with the ocher-butter mixture and almost never use water to wash. Young girls wear their hair in two thick braids that drape over their foreheads and faces, whereas women have a cascade of long, thin braids, each of which they coat with a mud mixture that dries to a hard shell.

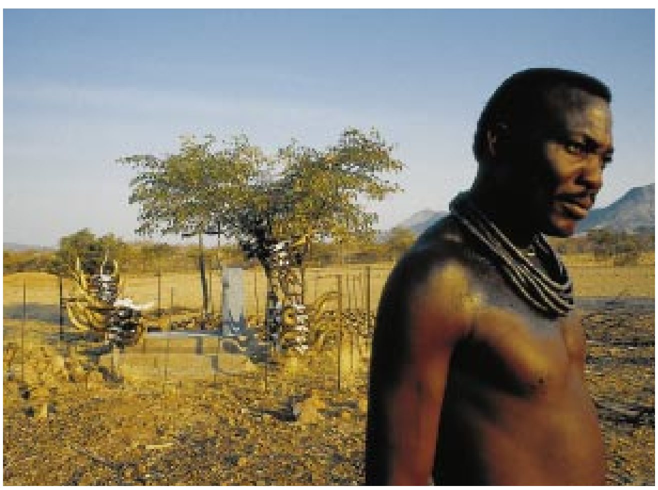
According to anthropologists, Himba women are not merely clinging passively to their traditional dress: they are actively rejecting change because it is the only way they can maintain their prestige and value. Himba men occasionally earn money doing menial jobs or selling livestock, but Himba women have not had such opportunities. By preserving their ocher-covered bodies, braids and calfskin skirts, Himba women are engaged in what modern anthropological theory calls "change through continuity" or "active conservatism." "Remaining apparently traditional can be a strategic—and rational—response to modern events," Margaret Jacobsohn says.

The recent report by the World Commission on Dams declares that tribal peoples such as the Himba, whether they are actively conservative or not, often get caught between a dam and a hard place. Such projects have "inadequately addressed the special needs and vulnerabilities of indigenous and tribal peoples," the report concludes, adding that the effects of a dam on local peoples are "often not acknowledged or considered in the planning process." It calls for improving existing water and energy facilities rather than constructing new megadams and stipulates that sponsoring countries and international lenders base their decisions to build new dams on agreements with affected communities.

But in February the World Bank said it would use the commission's guidelines only as "reference points" rather than as binding procedures for financing large dam projects. A group of 150 nongovernmental organizations from 39 countries—including Namibia—countered in March with a letter to World Bank president James Wolfensohn to reconsider that stance and to place a moratorium on funding new dams until the bank implements the commission's guidelines. The organizations are requesting that the bank conduct independent reviews of planned and ongoing projects and set up procedures for providing reparations to people harmed by earlier dams. In the letter, they insinuate that the World Bank helped create the World Commission on Dams in 1998 with the World Conservation Union–IUCN only "to deflect opposition or to buy time." Unless the bank amends its position, they write, they "may be less inclined to engage in future...dialogues with the World Bank." According to the commission, the bank has provided

The recent report by the World Commission on Dams declares that tribal peoples such as the Himba often get caught between a dam and a hard place.

Young Himba man living at a settlement near Epupa Falls shows the result of contact with other cultures. Besides the thick necklace traditional to the Himba, he also wears colorful necklaces from the Zemba tribe and a Western tracksuit jacket. Himba women have been more reluctant to change their traditional attire, perhaps because they seek to preserve their identity.



an estimated $75 billion for 538 large dams in 92 countries.

So what is the case for a dam at Epupa Falls? Jesaya Nyamu, Namibia's minister of mines and energy, emphasizes that his country currently imports 60 percent of its power from South Africa and needs to pull the plug as a matter of national sovereignty. "No one seems to see our need for independent power," he laments.

Ensconced in the deep upholstery of a sofa in his cabinet minister's office in Windhoek, Namibia's capital, he labels the foreign environmental groups that oppose the dam as meddlers with a double standard: one for their own industrial countries and another for countries they consider untouched and exotic. "The whole of Europe and America is dammed," Nyamu says. "These people live in their own countries on hydropower."

Indeed, according to a trade group of dam builders, the International Commission on Large Dams, the U.S. has the second-largest number of large dams (higher than 90 meters) in the world, after China. And the American experience with dams and indigenous peoples is less than laudatory: the Grand Coulee Dam inundated the lands of Native Americans from the Colville and Spokane tribes and ruined their salmon fishery. The tribes sued for reparations in 1951, but the government took 43 years to settle the lawsuit. In 1994 the tribes accepted a $54-million lump sum and $15 million per year as long as the dam produces electricity.

But Katuutire Kaura, president of Namibia's main opposition party, the Democratic Turnhalle Alliance/United Democratic Front Coalition, contends that another dam on the Kunene River is "absolutely not necessary." An existing dam that was built in the 1970s upstream at Ruacana is running at less than 20 percent capacity, he points out. And the recently discovered Kudu gas field off Namibia's southern coast is estimated to contain 20 trillion cubic feet of natural gas—more than enough for Namibia's needs. "The Kudu gas field can last us 25 to 30 years," Kaura asserts. Shell Oil and the Namibian government are currently working to tap those gas fields.

Kaura adds that the Himba will reap few of the dam's ben-

Himba women and children in a traditional family compound sit by their fires during the early morning (*top*) to warm themselves after the chilly desert night. The women wear *erembes,* pleated rabbit-skin hats that signify that they are married. Teenage boys (*middle*) tend the family's cattle as the animals graze during the day. Cattle are a sign of wealth among the Himba: when a rich man dies, his family often slaughters dozens of his cattle, whose skulls are used to decorate the man's grave (*bottom*) as a sign of status. Such graves—roughly 160 of which will be underwater once the dam is built—are the sites of important tribal rituals.

Namibia's minister of mines and energy says that his country currently imports 60 percent of its power from South Africa. "No one seems to see our need for independent power."

Social change is already coming to the settlements near Epupa Falls. A U.S.-based Christian church operates a mission near the river, where church members routinely baptize new Himba converts (*top*). A small shop (*middle*) sells staples such as maize meal but also does a brisk business in cheap liquor and beer. Himba sometimes loiter outside the shop to beg money from the occasional tourist to buy alcohol; the area around the shop is littered with empty bottles. Some of the bottles end up being used by other Himba to carry water (*bottom*). The young girl filling her bottle in the Kunene River wears the two forward-hanging braids traditional for preadolescent females.

efits while paying high costs. They are not qualified to work on the dam, so it will not bring them jobs. They are also unlikely to get electricity from the project. Electricity did not come to the residents of Opuwo, the town closest to the Ruacana Dam, until 1994, more than 20 years after it was built. In the meantime, a dam at Epupa Falls would destroy the Himba's livelihood. It "will dislocate the Himba to the margins of society where they cannot survive," predicts Phil Ya Nangoloh, executive director of Namibia's National Society for Human Rights.

In a way, the dam will take the river away from the Himba and confer its benefits to people outside Kaokoland. According to the World Commission on Dams report, "Dams take a set of resources ... generating food and livelihood for local people and transform them into another set of resources ... providing benefits to people living elsewhere. There is a sense, therefore, in which large dams export rivers and lands."

## Toward a Struggle?

ONE MORNING when Tjiuma comes to our camp to share a cup of coffee, I ask him what he really thinks will happen if the government goes ahead with its plans for the proposed dam. I know he is no stranger to combat, having been drafted as a tracker to fight on South Africa's side during the war for independence. As we gaze over the Kunene River in the still of the early morning, he admits that the Himba have a plan for resistance. More than 50 of the Himba headmen were in the military during the war, he says, and they still have their old .303 rifles in their compounds.

A week later, when I visit the minister of mines and energy in Windhoek, I tentatively ask him what the Namibian government would do if the Himba resist with violence. His response is chilling: "We know them; they cannot do anything. If they try anything, we will neutralize them, of course. But I don't think it will come to that." SA

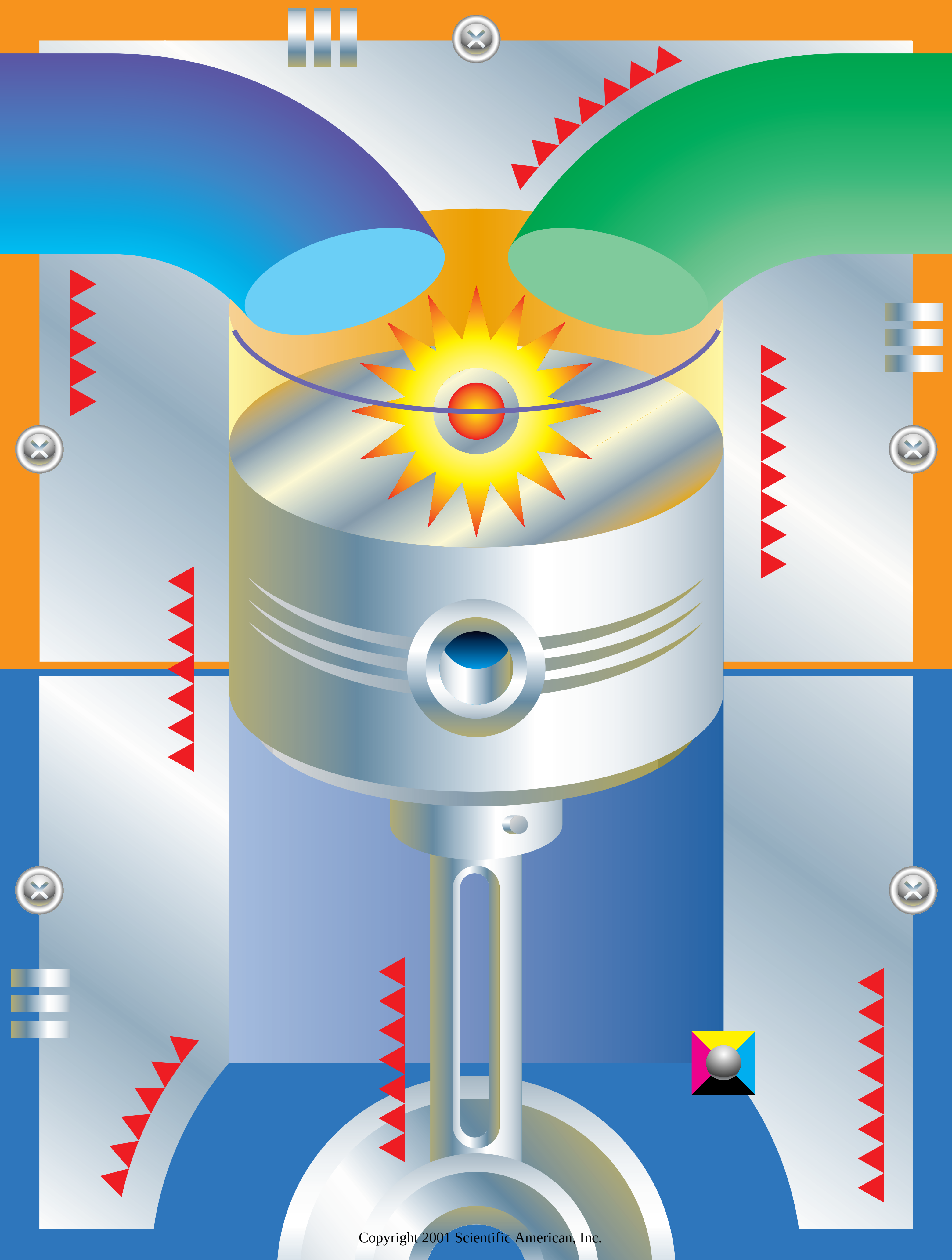
*Carol Ezzell is a staff editor and writer.*

### MORE TO EXPLORE

**Himba: Nomads of Namibia.** Margaret Jacobsohn, Peter Pickford and Beverly Pickford. Struik Publishers, Cape Town, 1990. Published in the U.S. by Appleton Communications, 1992.

**Dams and Development: A New Framework for Decision-Making.** World Commission on Dams, 2000. Available at **www.dams.org/report/**

For information on dam projects around the world, including the proposed Kunene River dam, visit the International Rivers Network site at **www.irn.org**



# A Low-Pollution Engine Solution

## CLEAN-BURNING, SPARKLESS-IGNITION AUTO ENGINES MAY OFFER THE BEST CHANCE OF MEETING NEW EXHAUST EMISSIONS STANDARDS

by Steven Ashley

Anyone who has driven a car, truck or motorcycle that is at least 20 years old is probably familiar with what engineers call after-run, an annoying and now rare condition in which an engine keeps turning over for a few seconds after the ignition is off. But today the fundamental fuel-burning process that causes after-run is firing the interest of the automotive industry. Known as homogeneous-charge compression-ignition combustion, or HCCI, the process could provide the basis for a new class of low-emission, high-mileage power plants. Many combustion engineers believe that HCCI-based piston engines will be able to deliver the good fuel economy of diesel engines without the diesel's high emissions of nitrogen oxides and soot.

Faced with increasingly stringent governmental pollution standards as well as the realization that practical and affordable fuel cell technology (in large production volumes) is still many years away, researchers at the world's major automakers and diesel-engine manufacturers are working to determine whether HCCI technology will be technically and economically feasible. If so, power plants based on this new combustion mode might serve as a potential bridge technology between today's high-emission diesel- and gasoline-fueled piston engines and tomorrow's ultraclean fuel cell power trains.

Standing-room-only attendance at the technical sessions on HCCI combustion at the recent Society of Automotive Engineers (SAE) 2001 World Congress in Detroit is one strong indication that the homogeneous-charge compression-ignition engine could be the next big thing in the car industry. Another is the marked rise in the numbers of technical papers written on the topic, says Dennis Assanis, professor of mechanical engi-

JOSÉ CRUZ

neering at the University of Michigan at Ann Arbor and director of the university's Automotive Research Center. "Since 1995, when only a few HCCI papers were published, we've seen what seems to be an exponential increase," he reports.

Yet another sign of HCCI's newfound status is growing research support from the U.S. Department of Energy, which began funding its study in 1997. The Partnership for a New Generation of Vehicles, an R&D consortium involving government, industry and university scientists and engineers devoted to advanced automotive technology, has established a $3-million, four-year academic research program on the novel combustion process. At the same time, industry and academic researchers in the field have prepared a report to the U.S. Congress about the technology. Interest is also great in Japan, where engineers who pioneered the exploitation of HCCI call it active thermo-atmosphere combustion, and in Europe, where it is known as controlled auto-ignition.

## Burning Lean and Clean

HCCI CAN BE THOUGHT OF as a crossbreed technology combining attractive aspects of both conventional gasoline and diesel engines to achieve good fuel economy and near-zero exhaust emissions. Roughly speaking, internal-combustion engines fall into four categories, defined by the degree of mixing in the charge of fuel and air in the cylinder and by how this charge is ignited. The familiar gasoline engine, in which a premixed, thoroughly commingled fuel-air charge is set aflame by a spark plug, falls into the spark-ignited, homogeneous-mixture classification. The diesel engine is an example of the compression-ignition, heterogeneous-mixture type: fuel is sprayed into the cylinder during the piston's compression stroke, and turbulent flow partially mixes it with air until the rising temperature induces burning. The gasoline direct-injection engine, in which injected fuel partially mixes with air until set alight by a spark, is considered a spark-ignited, heterogeneous engine. As its name indicates, the homogeneous-charge compression-ignition engine is a fourth type: it uses a thoroughly premixed charge of fuel and air that is compressed by a piston until it self-ignites.

Because the amount of burning fuel is low in comparison to the volume of air inside an HCCI engine, the combustion temperatures stay relatively low. That means the engine produces only small quantities of nitrogen oxide and dioxide (collectively, $NO_x$). Also, because the charge is well mixed and does not contain excess fuel, the combustion generates only small amounts of sooty particulates. Engine efficiencies are high because the HCCI combustion process allows the use of high, diesel-like compression ratios (generating more power per unit of fuel burned) and because, like diesels, HCCI engines can meet load demands without the use of intake throttling, thus eliminating so-called breathing losses. In addition, if properly engineered, these power plants could burn nearly any available hydrocarbon fuel or even hydrogen.

Automotive engineers and combustion researchers are pursuing this alternative form of the internal-combustion engine because current propulsion configurations are not likely to meet upcoming environmental regulations that will place severe limits on exhaust containing greenhouse gases—mostly carbon dioxide—and other pollutants, including $NO_x$, particulates, carbon monoxide and unburned hydrocarbons. The gasoline engine runs too hot and is too fuel-inefficient to make the grade. Poor fuel economy translates into excessive production of carbon dioxide, whereas high-temperature combustion yields too much $NO_x$. In contrast, the fuel-efficient diesel engine generates too much $NO_x$ and particulate emissions to satisfy soon-to-be-imposed pollution standards. Although catalytic after-treatment systems offer hope that exhaust emissions from these conventional power

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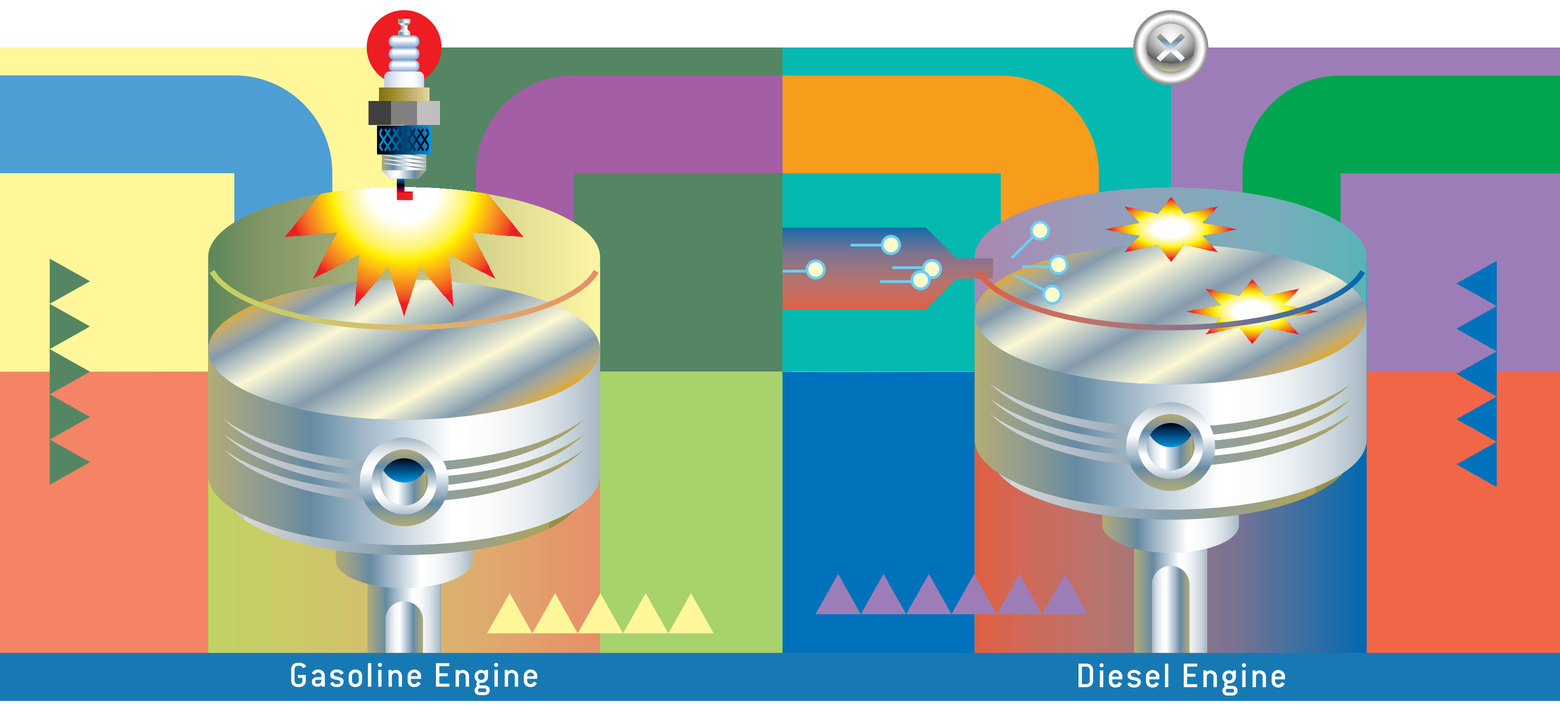


## The homogeneous-charge compression-ignition engine could be the next big thing.

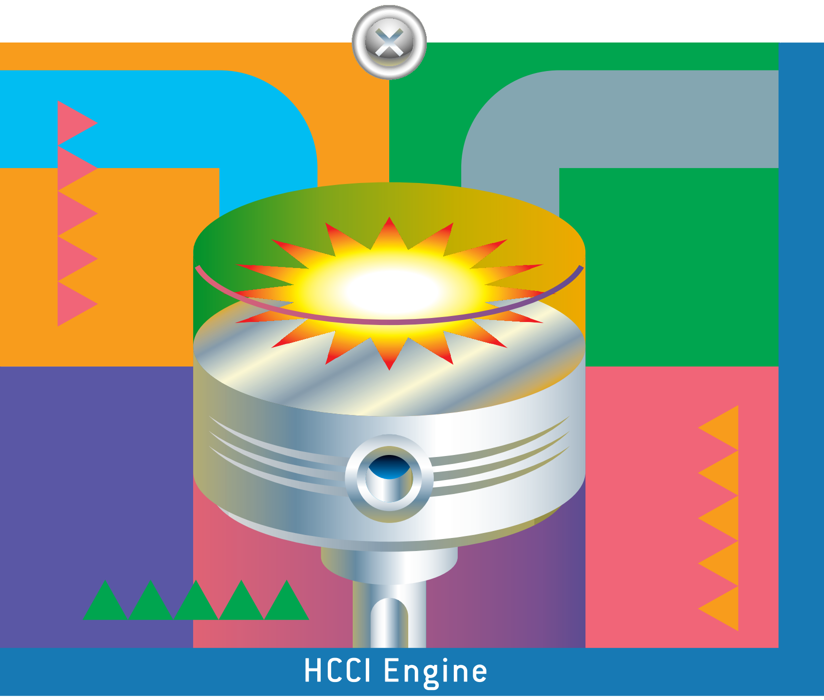
plants can be cleaned up after the fact, there is no surety that this can be accomplished affordably. Direct-injection gasoline engines offer better fuel economy, but their $NO_x$ and hydrocarbon emission levels are not much lower than their conventional gasoline counterparts. As such, they would still require the use of sophisticated exhaust after-treatment systems, which, in turn, need new grades of low-sulfur gasoline to avoid poisoning their catalysts.

Existing alternative propulsion technologies seem to provide little or no respite in the search for an environmentally and economically sound personal transportation technology for the near-term future. Because of the energy storage limitations of electrochemical batteries, electric cars now offer insufficient driving range, at best about 160 miles. The electric car's overall environmental fitness is, moreover, dependent on the cleanliness of the method employed to generate electric power. Widespread use of coal-burning power plants, for example, reduces the electric car's total system cleanliness substantially. Today's hybrid electric vehicles, which combine downsized internal-combustion engines with batteries and electric motors, produce less pollution than current cars and trucks, but auto companies must subsidize their price tags by as much as $10,000 apiece to make them cost-competitive with conventional vehicles. As a result, automotive engineers are searching for ways to improve the internal-combustion engine so that it can carry the industry through the forthcoming transition to ultraclean, next-generation propulsion systems.

### Taking the Load

HCCI COMBUSTION has been studied by many inventors and engineers under many different guises during the past century. But according to Paul Najt, spark-ignition-engine group manager at the General Motors Research and Development Center in Warren, Mich., the modern investigation of this unique combustion mode actually began in the late 1970s. At that time, a research team led by Shigeru Onishi of Nippon Clean Engine Company in Japan reported that it had been studying what members called active thermo-atmosphere combustion in two-stroke engines. "Rather than avoid this natural mode of combustion, Onishi said: 'Let's try to exploit it,'" says Najt, who was an engineering school graduate student in the early 1980s. He and his fellow students took up the challenge but soon found that the engine controls of the day could not manage the difficult task of controlling the auto-ignition process as engine speeds and loads were varied. Unfortunately, that problem remains unsolved.

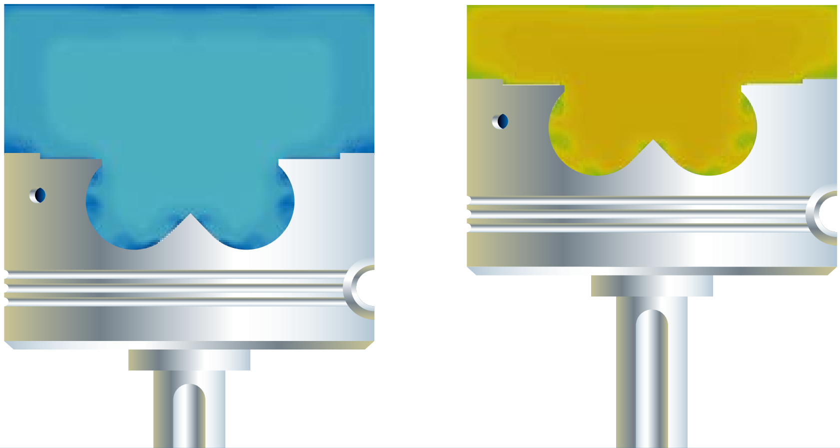
"The HCCI process really works well in the laboratory on a dynamometer when all the engine components are in thermal equilibrium," explains Thomas Asmus, senior research executive at DaimlerChrysler Liberty and Technical Affairs in Rochester Hills, Mich. "But when you add a load and try to make the engine do work, as it would in a vehicle, it just tends to slow down and stop completely. If you add more fuel so it can handle the increased load, it tends to start knocking very seriously." Nearly all HCCI experts mention how an engine




CROSSBREED CONCEPT—The homogeneous-charge compression-ignition (HCCI) engine can be considered a hybrid of the spark-ignition or gasoline engine and the compression-ignition or diesel engine. Gasoline engines use a premixed or homogeneous fuel-air charge that is placed in the cylinder and then ignited by a spark plug, causing a hot flame front to sweep through the charge. In diesel engines, fuel is injected into the cylinder during the piston's compression stroke, where it partially mixes with the air (producing a heterogeneous mixture) until the rising temperature induces self-ignition.

An HCCI power plant would combine aspects of both—the premixed fuel-air charge of the gasoline engine and the pressure-heated auto-ignition of the diesel—to produce a low-temperature, even-burning combustion process that yields good fuel efficiency as well as low emissions of nitrogen oxides and soot in the exhaust.

## Steps to Compression-Ignition



HOT-ZONE COMBUSTION—Computer simulations produced at Lawrence Livermore National Laboratory model the climbing temperatures inside the cylinder of a Volkswagen TDI diesel engine as the piston rises and compresses the air. The temperature distribution inside an HCCI engine is crucial because chemical kinetics, rather than turbulence, tend to control the combustion process, and chemical kinetics are sensitive to temperature. The hottest zones burn first. Colder zones may not fully react, producing hydrocarbon and carbon monoxide emissions. The coolest areas are where fuel contacts the walls.

running in HCCI mode can easily "run away on you," producing a tremendous pounding noise that will eventually destroy the engine hardware.

The problem is twofold, Asmus says. First, HCCI combustion occurs extremely quickly. Once the temperature in the engine cylinder is sufficiently high, the premixed fuel-air mixture ignites all at once. "For use in a practical engine, we need the combustion to have a smoother, more extended heat-release profile," he explains. For maximum efficiency, designers prefer for the ignition process to begin at 10 to 15 degrees of crank angle before the piston reaches top dead center and then the remainder to continue afterward. If the burn starts too early, the hot gas is exposed to the cylinder walls for too long and heat is lost, cutting efficiency. If it starts too late, the hot combustion gases do not undergo full expansion and therefore do not impart maximum work to the piston.


OPTICAL ENGINE—Special laboratory apparatus at Lotus Engineering in England allows researchers to see inside a test-engine cylinder as HCCI combustion, or what they call controlled auto-ignition, proceeds.

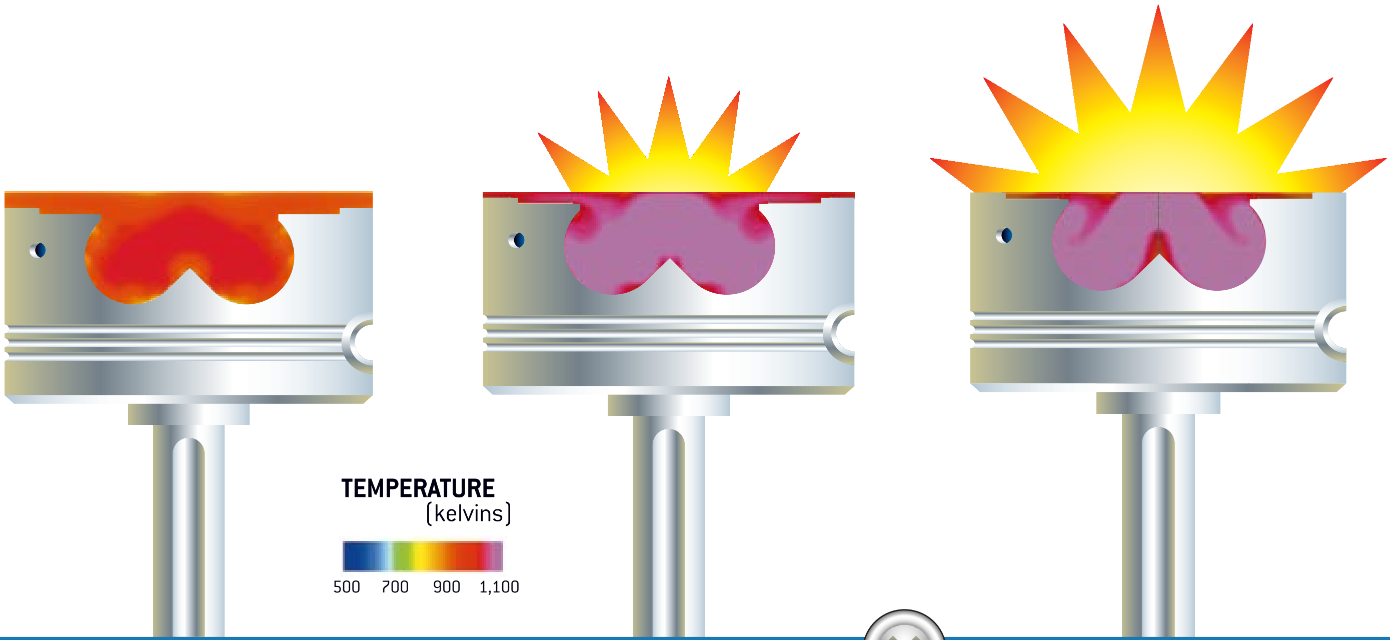
DON LAW AND JEFF ALLEN (photograph)

The second problem with HCCI, Asmus says, revolves around the fact that "there's no triggering event, like a spark or fuel injection, which are the handles we use for controlling the timing of the burn event" in conventional engines. To keep the process under control as speed and load changes occur (operating conditions that engineers call transients), the engine has to make very rapid adjustments from one cycle to the next. Currently no one knows exactly how to accomplish that reliably and affordably. "With HCCI," he points out, "it's not clear what will serve as a strong, robust lever for phasing the burn."

Najt concurs: "The benefits of HCCI are clear; the difficulty is in controlling HCCI combustion. Right now it's a question of technology execution. All kinds of control concepts that 20 years ago seemed a bit over the edge are being considered. It may be that, relative to fuel cell technology, these kinds of technologies and the extra cost to implement them don't seem as much of a stretch."

These still unproved engine-control technologies are manifold. They include variable-valve actuation, in which hot residuals—embers from the previous burn—are inducted into the cylinder to control the phasing of the next burn cycle. Variable-valve-timing systems are based on "camless valve trains" operated by electromagnetic, electrohydraulic or piezoelectric actuators rather than mechanical cams. To get the needed cycle-to-cycle response-rate resolution, however, the valves have to move extremely rapidly, and that kind of operation is difficult to keep up over the lifetime of an engine.

Another possibility, Dennis Assanis says, is to use variable-compression-ratio systems, which involve changing the volume of the combustion chamber, and so the compression ratio, on the fly. This effect can be accomplished by opening and closing engine valves at the appropriate time or by installing pistons that alter their height in accordion fashion in reaction to pressure changes, a radical concept that is under investigation




JOSÉ CRUZ (*illustration*); SALVADOR M. ACEVES, DANIEL L. FLOWERS AND JOEL MARTINEZ (*simulation*)

at the University of Michigan in cooperation with Ford Motor Company and Federal Mogul Corporation.

Yet another approach being looked at by many researchers is to add some inhomogeneity (variation in local density and temperature) into the fuel-air mixture to extend the duration of the burn. Of course, "that's like playing with the devil," Assanis notes. "You're giving up some homogeneity [thus boosting pollutant output] to get a smoother heat release."

"The problem with these advanced concepts," Najt says, "is that they introduce a whole series of mechanical-complexity and cost issues. The use of two unproved technologies often squares the difficulty of the original problem. And the cost of integrating them into a viable package may be too great."

## Handling High Loads and Hybrids

EVEN IF THESE OBSTACLES are surmounted, another overall concern must be addressed. Because the fuel-air mixture has to be lean (a low fuel fraction in relation to the volume of air) to obtain the emissions benefits, HCCI is suitable only for light and medium loads and speeds. To handle higher loads and speeds, more fuel needs to be added to the mixture, but doing so would raise combustion temperatures and eliminate much of the environmental benefit. Therefore, HCCI combustion would probably be used in what engineers call dual-mode engines. At high engine loads, the system would switch from auto-igniting HCCI mode to spark ignition (in gasoline-fueled engines) or to standard fuel injection (in diesel engines).

Najt notes that the most straightforward application of HCCI would probably be in a fuel-efficient hybrid-electric vehicle, which combines an internal-combustion engine, an electric motor and a battery. When used in a hybrid configuration, the internal-combustion engine, whether it is of the HCCI type or not, operates in a smaller speed and load range. As this suits clean-burning HCCI technology, this may turn out to be a perfect match for the hybrid-electric configuration. "Yet it's not clear that HCCI will end up as the optimal engine for hybrids, because even hybrids run through a fairly extensive speed and load range, so the engine must follow any increased load demands," he comments. This is the case because the energy storage capacity of today's batteries is not large enough to provide all the extra power for acceleration and hill climbing when it is needed.

The technical hurdles that must still be overcome have obviously done nothing to suppress enthusiasm for HCCI within much of the engineering community. Some observers wonder, however, whether it will really prove to be the long-sought-after solution to the environmental/economic quandary. Every few years the auto industry focuses eagerly on a particular engine technology as the next big thing that might do the trick, Najt says. Less optimistic experts attending the recent SAE sessions called HCCI the latest boutique engine.

"In the mid-1980s it was the two-stroke engine, which didn't pan out," Najt explains. "A couple of years ago it was the gasoline direct-injection engine, which, although it has been relatively successful, doesn't seem to be a panacea."

Many engine researchers expect that HCCI-based power plants will be the first automotive engines designed "from the inside out." In other words, using advanced computational modeling techniques, engineers will be able to explore the chemical kinetics of fuel-oxidation and fluid-mechanics phenomena associated with mixing and burning that control HCCI before they settle on an engine design. Nevertheless, a lot of good old experimental work with test engines will be needed before a practical, affordable engine can be developed.

"Clearly, it's too early to tell whether HCCI will prove to be successful," Najt concludes. "It's a high-risk technology." Still, most engineers agree that it is worth exploring while we're waiting for something cleaner to come along. SA

*Steven Ashley is a staff editor and writer.*

### MORE TO EXPLORE

Society of Automotive Engineers: **www.sae.org/servlets/index/**
University of California, Berkeley: **www.me.berkeley.edu/~mctai/hcci.html/**
Sandia National Laboratories:
**www.ca.sandia.gov/CRF/03_facilities/03_FacHCCI-SCCI.html/**
Lund Institute of Technology:
**www.vok.lth.se/CE/research/HCCI/i_HCCI_uk.html/**

GOLF BALLS

# Flight Control

**The quest to engineer** a golf ball that flies long and true dates back to 15th-century Scotland. Artisans there tediously stuffed a wet leather pouch with a hatfull of boiled goose feathers, then stitched it shut. The drying feathers expanded while the leather shrank, to form a ball as hard as a rock. A skilled ball maker could produce only four featheries a day, relegating the game of links to the rich.

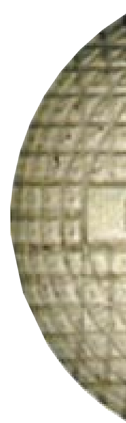
Four hundred years later, in the 1840s, the guttie arrived. Craftsmen heated and molded gutta-percha gum (which was, and is, used in dentistry) from the Malaysian *Palaquium* tree into a solid sphere. Durable and inexpensive, the guttie brought golf to the masses. Golfers noticed, however, that new, smooth gutties did not fly as straight or as far as old, nicked ones. Ball makers began cutting, hammering or impressing various patterns of indentations into each ball's surface, a practice that helped balls fly straighter and longer. Because the science of aerodynamics was still young, no one really knew why.

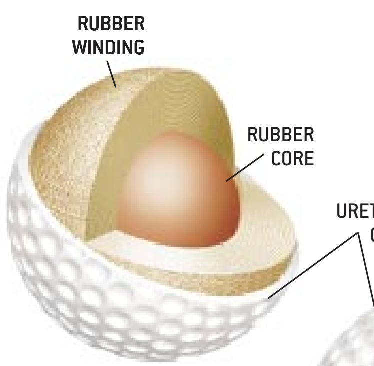
In 1898 Ohio golfer Coburn Haskell and B. F. Goodrich employee Bertram Work unveiled a rubber golf ball. They wound rubber thread around a solid rubber core. Soon the balls were coated with balata, a strong, water-resistant latex from the tropical bully tree. In 1908 English engineer William Taylor received a patent for an inverted bramble pattern of evenly distributed circular depressions imposed on the ball's surface; these dimples reduced aerodynamic drag and enhanced lift.

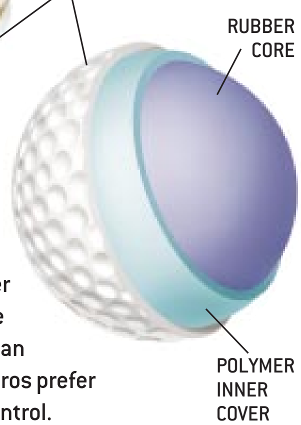
By 1930 British and American golf associations had standardized the diameter and weight of balls for tournament play. Manufacturers have tried all manner of dimple patterns since then. Today most balls sport around 400 dimples. Lately makers have been experimenting with two-tiered dimples in hopes of further reducing drag.

Some golfers complain that better technology gives players too much aid. It does help duffers, but it hasn't diminished the skill pros require. Wally Uihlein, CEO of Acushnet, maker of the Titleist brand, notes that "in spite of space-age balls and clubs, the average score on the PGA Tour has improved but one stroke over the past 17 years." —*Mark Fischetti*

Rubber/resin (2001)





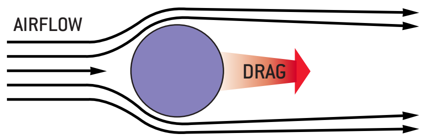

**MOST MODERN BALLS** are variations of two basic designs. Wound balls have a small, solid or liquid-filled rubber core wound with rubber thread. Solid balls have a large, solid rubber core and thin, polymer inner cover. Outer covers for either type may be composed of one or more layers of urethane or an ionomer resin such as Du Pont's Surlyn. Some pros prefer a soft, synthetic-balata cover for better spin control.

## DID YOU KNOW . . .

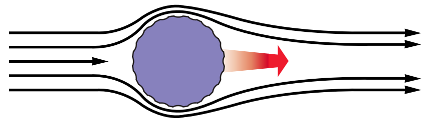
➤ DIMPLE WARS In 1983 Titleist introduced the 384 Tour ball with 60 extra dimples. Golfers said it went farther. Competitors responded by advertising balls with "more dimples for more distance." But if this argument were taken to its extreme, thousands of tiny dimples would re-create a smooth ball, which tests show travels only half as far as a dimpled one. A ball with 300 to 500 dimples works best, according to Steve Aoyama, principal scientist at Titleist.

➤ GOT YOUR NUMBER Manufacturers paint different digits on balls purely to help golfers in a party tell whose ball is whose. The numbers have nothing to do with ball quality or characteristics. Nevertheless, golfers will swear that they hit a Top-Flite 2 longer than a 5 or that a Maxfli 1 hooks less than a 6. Superstition? In golf? Never.

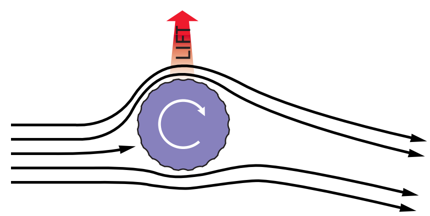
➤ SMASH TEST Hye Precision Products in Perry, Ga., tests the durability of newly minted golf balls' cores, paint, even logos in a closed, squat, 2,500-pound machine. The beast's air cannon fires 12 balls a minute at up to 300 feet a second across a five-foot chamber into a hardened steel plate. The same set of balls is continually and automatically collected, reloaded, refired, and inspected for deformation and surface condition.




DRAG on a smooth, soaring golf ball is created by the difference between high air pressure against the front of the ball and low pressure behind it, the latter caused by the laminar separation of airflow.



DIMPLES cause turbulence in the thin layer of air against the ball, which reduces airflow separation, creating more back pressure and thereby reducing drag.

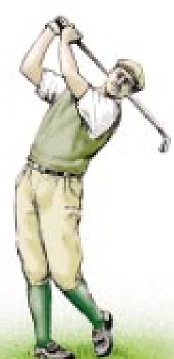



BACKSPIN, imparted by the angle of a golf club's head, deflects airflow downward just as an angled airplane wing does. The resulting upward reacting force gives the ball lift.


Rubber (1898)

Brambled guttie (1890s)

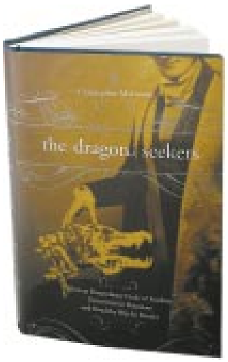
Featherie (late 1400s)



ILLUSTRATIONS BY GEORGE RETSECK; MICHAEL NEVEUX *Corbis* (rubber/resin); LEO M. KELLY, JR. *The Old Chicago Golf Shop* (rubber, guttie, featherie); AERODYNAMICS SOURCE: STEVE AOYAMA *Titleist*

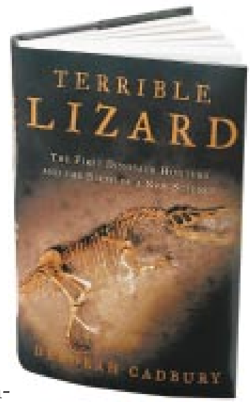
# Dinos and Darwin

JUST HOW IMPORTANT WERE THE DISCOVERIES OF DINOSAUR FOSSILS? **BY CARL ZIMMER**




**THE DRAGON SEEKERS: HOW AN EXTRAORDINARY CIRCLE OF FOSSILISTS DISCOVERED THE DINOSAURS AND PAVED THE WAY FOR DARWIN**
by Christopher McGowan
Perseus Publishing, Cambridge, Mass., 2001 ($26)

**TERRIBLE LIZARD: THE FIRST DINOSAUR HUNTERS AND THE BIRTH OF A NEW SCIENCE**
by Deborah Cadbury
Henry Holt, New York, 2001 ($27.50)




**Not long ago** my friend George, who recently celebrated his second birthday, put some of his vocabulary on display for me. "Tee-wex," he said, and roared. "Tie-say-watops," he said, and roared again. "Apatosaw-us." Roar number three. It is a remarkable thing that children today can speak Latin, but more remarkable still that the only Latin words they speak are the names of dinosaurs. I have yet to hear George or any other child say "*Hallucigenia,*" or "*Ambulocetus,*" or "*Acanthostega*"—although they were as remarkable as any velociraptor.

Dinosaurs have such a powerful grip on the public consciousness that it is easy to forget just how recently humans became aware of them. A two-year-old boy today may be able to rattle off three dinosaur names, but in 1824 there was only one dinosaur to be named, period. The word "dinosaur" didn't even exist until 1842. Those confused early years, when the world was baffled by the discovery of absurdly enormous reptiles, represent one of the most fascinating stories in the history of science.

One reason is that its cast is so extraordinary. On the south coast of England, Mary Anning, a poor and uneducated beachcomber, spent 30 years digging up giant marine reptiles and pterosaurs. Gideon Mantell, a shoemaker's son turned doctor, discovered the first dinosaur; he thought dinosaurs would make him rich, but they ultimately destroyed his life. William Buckland, an Oxford geologist who tried to reconcile giant extinct reptiles with Genesis, had a raft of eccentricities, including a penchant for keeping live hyenas and jackals in his college rooms. The time is ripe for a book for the general public about these early paleontologists, and now we have not one but two.

*The Dragon Seekers* is the work of a practicing paleontologist (Christopher McGowan is a senior curator at the Royal Ontario Museum and teaches at the University of Toronto). The book is therefore filled with historical details that matter to a fossil hunter: the methods the early fossilists used to extract bones from cliffs, the squabbles over naming new species, the staffing of museums. It is brief and pleasant, but for sheer narrative pleasure, I'd have to recommend Deborah Cadbury's *Terrible Lizard* instead. Cadbury, a BBC television producer, turns what could have been just a string of anecdotes into high drama. Much of her success comes from her depth of research: she has scoured diaries, letters and newspaper archives and can tell her story in the words of the people who lived it.

For Cadbury, Gideon Mantell is the tragic hero of the early days of dinosaur hunting. Scrounging one quarry after another, he built up one of the finest private fossil collections in the world at the time. Even when he had just a few scraps of dinosaur bones, Mantell knew that he had found the remains of giant reptiles. He didn't back down when the leading scientists of his day told him he had found nothing but fish teeth and rhino horns.

But Mantell's obsession with his fossils eventually left him bankrupt and alienated from his wife and children. And just when he began to earn scientific respect, he crossed paths with the ruthless Sir Richard Owen. Owen didn't know how to dig up fossils, but he did know how to pluck the strings of academic power. He managed to make himself England's authority on all life, both living and dead.

It was Owen, not Mantell, who in 1838 was appointed by the British Association for the Advancement of Science to survey the giant extinct reptiles of England. In his report, he gave them the

BETH PHILLIPS

name “dinosaurs” but mentioned Mantell only in scorn. The dinosaurs lifted Owen on their colossal backs to heights of fame and wealth. Mantell meanwhile faded into obscurity, his fossils dispersed and forgotten.

Owen used dinosaurs as an argument against evolution: if life progressed through time, it made no sense that the extinct dinosaurs were so much more impressive that today’s reptiles. He thought that life unfolded over geologic time according to certain laws, but no one—not even himself, it seems—really understood his ideas. Then Darwin blindsided Owen with an elegant, powerful theory that encompassed all of life, dinosaurs included. Owen ultimately became irrelevant. The dinosaur sculptures that he had built for the Crystal Palace exhibition are now chipped, broken and beset with weeds.

My chief complaint with both books is that they unintentionally raise an important question that neither answers: The discovery of dinosaurs was unquestionably fascinating, but was it ultimately very important? I’m not so sure. One of the great triumphs of 19th-century paleontologists was their use of fossils as Rosetta stones to decipher the global geologic record. But dinosaurs were only one group of animals among many that they used. Darwin was certainly inspired by fossils but not by dinosaurs. Instead it was the giant ground sloths and other extinct mammals he dug up in South America that made him think about the connections between present and past life. The word “dinosaur” appears nowhere in *The Origin of Species*.

In the 1940s George Gaylord Simpson reinvigorated paleontology when he showed that mutations and natural selection could account for changes in the fossil record. But he used horses and other mammals as proof, not dinosaurs. Since then, paleontology has surged from the backwaters of evolutionary research to the crest of the wave. Punctuated equilibrium, the causes and effects of mass extinctions, plate tectonics’ role in the origin of species, the coevolutionary arms races between predators and prey—in all these cases, it was fossils that showed how evolution works. Rarely did these fossils belong to dinosaurs; they were instead snails, plankton, pond scum and other unglamorous creatures. The fossils of dinosaurs are beautiful and spectacular, but compared with other animals, they’re also very hard to find. A thousand fossil crabs can say much more about how evolution works than a single *T. rex*.

Only in the past couple of generations have paleontologists really started to use dinosaurs in cutting-edge research in evolution. Dinosaur paleontologists were among the first scientists to use the newest methods of classification (known as cladistics), and as a result, they've been able to explore the incremental evolution of birds from dinosaurs. Dinosaurs are becoming important sources of information about how the breakup of continents influences evolution, how changing the rules by which embryos develop shapes new anatomy and how asteroids can trigger mass extinctions. The subtitle of *The Dragon Seekers* claims that the study of dinosaurs paved the way for Darwin, yet the reverse may be closer to the truth. SA

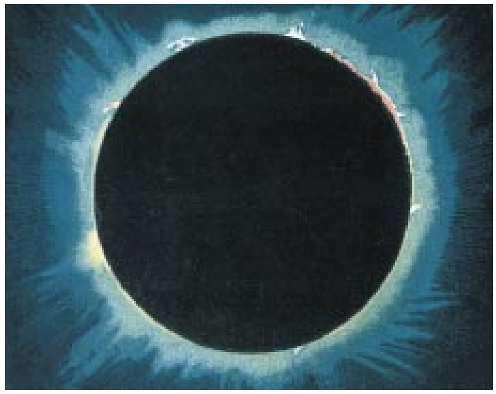
*Carl Zimmer is the author of* Parasite Rex *and* At the Water's Edge.

## THE EDITORS **RECOMMEND**

**GLORIOUS ECLIPSES: THEIR PAST, PRESENT AND FUTURE**

***by Serge Brunier and Jean-Pierre Luminet. Cambridge University Press, New York, 2000 ($39.95)***

An extraordinarily beautiful book, *Glorious Eclipses* guides us elegantly through the history of obscurations of the sun and moon—from the ancient Chinese belief that a dragon was devouring the daytime star through current theories and on to celestial events forthcoming in the next six decades. Some of the most startling images come from the days when photography was in its infancy and astronomers still made drawings of eclipses—the one at the right, by Warren de la Rue, is the solar eclipse of July 1860, observed from Spain.



Published in time for June's eclipse across southern Africa, the book, by Brunier, former editor of the magazine *Ciel et Espace,* and Luminet, a research director at CNRS, is translated from the French.

*Books reviewed can be purchased at www.sciam.com*

# Kibbles and Bytes

HOW MUCH IS THAT ROBOTIC DOGGY IN THE WINDOW? **BY MARK ALPERT**

**A wonderful childlike excitement** filled the halls of *Scientific American* on the day that the Aibo ERS-210 arrived in the mail. Clutching the box tightly, I rushed to the office of my colleague George Musser and shouted, "It's here! It's here!" George beamed like a kid on Christmas morning and immediately tore the box open. Inside was a foot-long, three-pound machine that looked like a Jack Russell terrier wearing gray plastic armor. Sony Electronics had bred the robotic dog in its research laboratories in Japan; the name "Aibo" (pronounced EYE-bo) means "pal" or "companion" in Japanese and is also a rough acronym for Artificial Intelligence Robot. For weeks I'd been begging Sony officials to let me evaluate the computerized canine.

In the past few years, toy companies have introduced an entire litter of electronic pets: Poo-Chi the Interactive Puppy (from Tiger Electronics), Tekno the Robotic Puppy (Manley Toy Quest) and Rocket the Wonder Dog (Fisher-Price), to name just a few. But Aibo is the most advanced pooch of the new breed. Sony unveiled the first-generation Aibo ERS-110 in 1999, producing a limited run of 5,000 robotic hounds priced at a howling $2,500 each. They sold out almost instantly, prompting Sony to rush 10,000 similar units to market. The improved second-generation ERS-210, a relative bargain at $1,500, has also won the hearts of well-heeled customers since it went on sale last November.

What can explain such intense devotion? Certainly part of Aibo's appeal is its sophisticated technology. Each mechanical mutt possesses nearly as much computing power as a typical desktop PC. Tucked into the rear of the dog's torso is a 200-megahertz microprocessor with 32 megabytes of main memory. (Like some people, Aibo has its brains in its posterior.) Sensors scattered throughout the dog's anatomy relay signals to the microprocessor, thus mimicking a flesh-and-blood nervous system. To simulate a sense of vision, for example, a transceiver in Aibo's head shines an infrared beam at nearby objects to gauge their distance; this information helps the robot avoid walking into walls. Aibo can perceive colors as well: in its muzzle is a complementary metal oxide semiconductor (CMOS) imager that gives the dog a 40,000-pixel view of the world.

MOVE OVER, ROVER, and let Aibo take over. The robotic dog from Sony Electronics walks, whines and wags its tail just like a real pooch. But be warned: this computerized canine will take a bite out of your wallet.

Aibo's software is equally impressive. Sony designed the robot so that a variety of programs, each encoded on a memory stick, can be inserted in the dog's belly. If you choose the Aibo Life program, for instance, the robot initially acts like a newborn pup and gradually learns how to walk and do tricks. But if you want a fully trained pooch right away, simply pop

PHOTOGRAPHS BY KEN KARP

in the memory stick containing the Hello Aibo program. The catch is that the memory sticks are not included in the $1,500 price; each costs about $90. If you throw in a spare battery charger and assorted extras, the total price can easily run over $2,000.

Perhaps the most intriguing aspect of Aibo's software is that the robot is imbued with canine instincts. We got our first look at Aibo's mercurial character just seconds after George took the dog out of the box and turned it on. (For the purposes of our review, Sony had equipped the machine with a fully charged battery pack and the Hello Aibo memory stick.) In response to George's enthusiastic petting, the mechanized mongrel nipped one of his fingers. The bite didn't hurt—Aibo has no teeth, just a motorized plastic jaw—but just the same, George gave the junkyard robot a firm rap on the top of the head. Aibo has a touch sensor there, and giving it a sharp tap admonishes the creature: the dog is programmed to avoid the behavior that led to the reprimand. Aibo's tail drooped as a sign of contrition, and red LEDs gleamed forlornly behind the visor of the dog's helmetlike head.

By this time several other members of the magazine's staff were peeking into George's office to see what all the fuss was about. Mark Clemens, one of our assistant art directors, cheered up Aibo by gently stroking the touch sensor on its head. Green LEDs behind the visor flashed a happier expression, and a miniature speaker in the dog's mouth warbled a jaunty sequence of high-pitched notes. Then Aibo began walking across the room, stopping every now and then to survey its surroundings.

It was fascinating to watch the robot scramble across the carpet. Each of its legs has three motors, one in the knee and two in the hip socket, allowing the machine to maneuver around obstacles skillfully. As the robot steps forward, it shifts its weight from side to side to keep its balance. Although Aibo's herky-jerky movements have the restless, playful quality of a dogtrot, they also seem vaguely menacing. On seeing Aibo for the first time, many of my colleagues remarked, "It's so cute!" But on reflection several added, "It's also kind of creepy."

Aibo's neatest trick is chasing the pink ball that comes with the dog. Sony has programmed the robot to become terrifically excited when its CMOS imager detects the colors pink or red. As soon as Aibo spots the ball, the LEDs in its tail and visor light up and the miniature speaker trumpets the familiar "Charge!" tune. The robot rushes toward the ball, whirring like mad, until it senses that it's in the right position. Then it lifts one of its front legs and gives the ball a kick. Aibo scans the room to see where the ball went and runs after it again, sometimes butting the thing with its head instead of kicking it.

Some of Aibo's other feats, however, failed to awe me, perhaps because the robot's lifelike behavior had unduly raised my expectations. The machine has two microphones in its head and voice-recognition software that can respond to simple commands. If you tell Aibo to say hello, it will either bow or wave its paw. If you say, "Let's dance," the robot will play a snatch of music and do a four-legged jig. But very often I had to shout the commands a few times before the digital dog would pay attention. Because Aibo is designed to be moody, it won't perform tricks unless it's in the proper frame of mind. Sony says the occasional disobedience makes the machine more lifelike, but I just found it annoying. If you shell out $1,500 for the cur, it should at least show a little respect.

Clearly, my Aibo needed to go to obedience school. I opened the dog's stomach cover and replaced the Hello Aibo memory stick with the Aibo Life program. An old robot can't learn new tricks, I thought, so I needed to work with a puppy. But when I turned on the machine, it just lay on the floor with its legs splayed, making pathetic mewling noises. As it turns out, the newborn Aibo needs at least 40 hours of training to develop into a fully functional adult.

AIBO'S BEST TRICK is chasing and kicking a pink ball across the room. Unfortunately, the mechanical mutt isn't programmed to fetch slippers.

I might have undertaken the task if I didn't have a wife, a kid or a job. But instead I turned back to my computer screen while the baby Aibo sprawled under my desk, crying its little LEDs out. In the end, I had to put the poor creature to sleep. Although the robot is a technological marvel, it didn't hold my attention for very long. Mind you, this is definitely a minority opinion—tens of thousands of customers have each plunked down a small fortune to adopt Aibo. I suspect that it appeals to people who have a lot of time on their hands. SA

# Alternating Liars

BY DENNIS E. SHASHA

**Five people are in a room.** One is a consistent truth teller, who will answer every question truthfully, and four are alternating liars, who will alternate between telling the truth and lying: true, false, true, false, true, false,... Unfortunately, you do not know whether the alternating liars will start by telling the truth or not. In fact, an alternating liar may not decide whether to answer your first question truthfully or falsely until he hears the question. But after his first answer, he must alternate truth with lies. You also know that everyone in the room knows who the consistent truth teller is.

All the suspects look equally untrustworthy. You, however, are to determine which one is the consistent truth teller. You are allowed only two questions, although they need not be yes/no questions. You have five people to choose among. You must address each question to one person (although both questions can be addressed to the same person), and you will be answered by that person only. Can you do it? (To figure out how to approach the problem, see the warm-up puzzle for three people, using yes/no questions, illustrated at right.)

For extra credit, here's an even trickier problem: How many questions would you need if there were seven people in the room? SA

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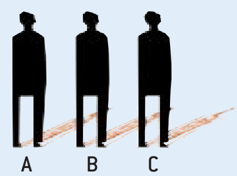
*Dennis E. Shasha, professor of computer science at the Courant Institute of New York University, creates and solves puzzles for a living.*

**WARM-UP PUZZLE:** Who is the consistent truth teller?




THREE PEOPLE

THREE **YES/NO** QUESTIONS

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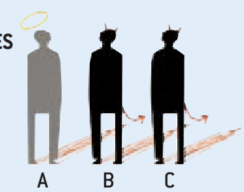
1) "**A**, are you a consistent truth teller?" **YES**

2) "**A**, are you a consistent truth teller?" **YES**

***A** is the consistent truth teller.*

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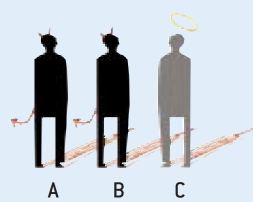
1) "**A**, are you a consistent truth teller?" **YES**

2) "**A**, are you a consistent truth teller?" **NO**

***A** is an alternating liar, and his next response will be a lie, so you ask:*

3) "**A**, is **B** a consistent truth teller?" **YES**

***C** is the consistent truth teller.*

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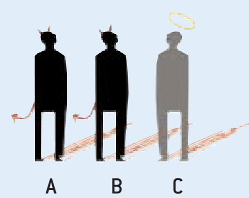
1) "**A**, are you a consistent truth teller?" **NO**

***A** is an alternating liar, but he is telling the truth this time. His next response will be a lie, so you ask:*

2) "**A**, is **B** a consistent truth teller?" **YES**

***C** is the consistent truth teller.*




JOHN McFAUL

**Answer to Last Month's Puzzle:**
The fish vandal must be in bungalow G. Because the vandal walked each pathway exactly once, he couldn't have ended up in any of the bungalows with an even number of pathways: each time he visited one of these bungalows, he had to use one pathway to enter and another to leave. Only D and G are touched by an odd number of pathways. The vandal entered the resort from the lagoon side, so he must have first visited bungalow D and then made his way to G.

**Web Solution:**
For a peek at the answer to this month's problem, visit www.sciam.com

# Nostrildamus

IN SPACE, NO ONE CAN HEAR YOU GAG. WHICH IS WHY YOU NEED PREDICTIONS ABOUT WHETHER SPACE STUFF STINKS **BY STEVE MIRSKY**

**Musky, floral, "etheral,"** camphoraceous, minty, pungent and putrid. No, these are not the names of the Seven Dwarfs before they went Hollywood. Rather they are the seven scents by which NASA calibrates and certifies the nose of George Aldrich every three months. If everything is up to snuff, George Aldrich smells.

At the White Sands Test Facility in Las Cruces, N.M., Aldrich and other volunteers put their noses to the grindstone and smell materials destined for spaceflight. First, rigorous instrumental analysis determines whether any gases coming off these objects are toxic or carcinogenic. (Coincidentally, Aldrich does these tests as well, in his role as a chemistry laboratory technician.) Once the gases are deemed safe, Aldrich and a four-colleague "odor panel" sniff the stuff. They decide whether the object would make an astronaut die for an open window, which is exactly what would happen 200 miles up.

Aldrich is the dean of about 25 smelling employees at White Sands, ranging from secretaries to engineers, who rotate in groups of five to lend NASA their noses. He started smelling back in 1974 and had lived through a record 743 "smell missions"—over 100 more than anyone else as of early April, when we spoke.

When a sample comes up for review, Aldrich and his co-panelists smell it and then rank the rankness from 0 to 4. "0 is a nondetect," he explains, "1 is barely detectable, 2 is easily detectable, 3 is objectionable, and 4 is get-me-out-of-here." Officially, 4 is "offensive." One may wonder why NASA has not switched to some high-tech electronic nose or to the supersensitive snouts of dogs. "We're a screening test for astronauts, and they're human," Aldrich points out, "so they want to use human subjects." Not to mention the fact that some dogs might rate a dead squirrel on a sizzling Albuquerque highway as a 2, with the additional comment, "Needs one more day." Electronic noses are getting better [see "Plenty to Sniff At," by Mia Schmiedeskamp, SCIENTIFIC AMERICAN, March], Aldrich notes, "but they can't tell you if an odor will leave an aftertaste in the back of your throat."

An aftertaste was just one bad thing about some Velcro straps that got hurried up to the space station in February without the all-important olfactory evaluation. The smell, reminiscent of your fingers after slicing onions, almost made the astronauts launch their lunch. "One of the astronauts opened the bag that these straps were in," Aldrich says. "It stunk. He zipped the bag right back up and put it back on the shuttle. They brought it to us, and we basically agreed. It stunk." (The nefarious funk most likely emanated from the compound used to bond the backing to the straps.)

Aldrich recently nosed his way into being a judge at the annual Odor-Eaters Rotten Sneaker contest, held in Vermont in March. The winner this year was unquestionably 11-year-old Rebekah Fahey, also of Las Cruces. To anyone smelling a New Mexican fix, Aldrich explains that Fahey was truly committed to victory: "She'd worn the same socks for three months. It just completely knocked me back. I asked for oxygen."

**They decide if the object would make an astronaut die for an open window, which is exactly what would happen 200 miles up.**


ILLUSTRATION BY MATT COLLINS; PHOTOGRAPH BY FRANK VERONSKY

Some men are born great, some become great, and some have greatness thrust up their noses. "Everybody thinks that I have this big schnozz," Aldrich remarks. "People say, 'Thank goodness I took a bath today.' But I tell everyone I may be average to slightly above average." Well above average is his willingness to endure, ad nauseam, people in effect asking, "Does this smell funny to you?" Thanks to him and his fellow smellers, astronauts in space can breathe a little easier. SA

# ENDPOINTS

## Q How is tempered glass made?

—Fred Mueller, Torrington, Conn.

**Mark Ford, fabrication development manager at AFG Industries, Inc., explains:**

Tempered glass is about four times stronger than ordinary, or annealed, glass. And unlike annealed glass, which can shatter into jagged shards, tempered glass fractures into small, relatively harmless pieces. It is therefore used in environments where human safety is an issue. Applications include side and rear windows in vehicles, entrance doors, shower and tub enclosures, racquetball courts, patio furniture, microwave ovens and skylights.

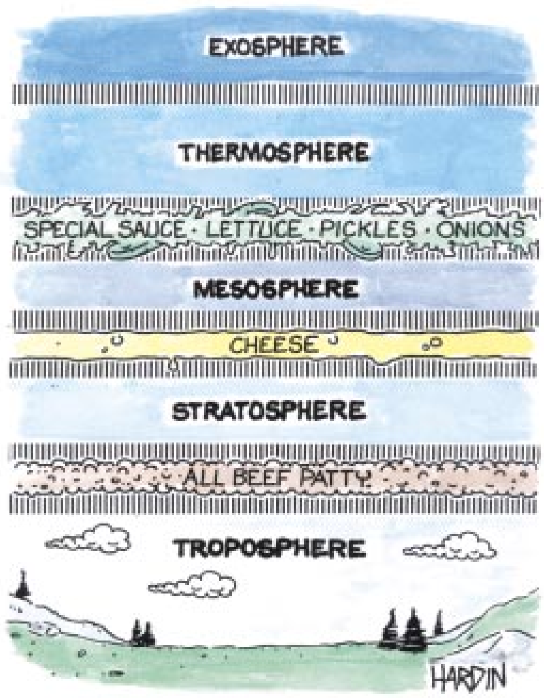
To prepare glass for the tempering process, it must first be cut to the desired size. (Any fabricating operations, such as etching or edging, that take place after the heat treatment run the risk of reducing the strength of the glass or causing product failure.) The glass is then examined for imperfections that could cause breakage at any step during tempering. An abrasive—such as sandpaper—takes sharp edges off the glass, which is subsequently washed.

Next, the glass undergoes a heat treatment in which it travels through a tempering oven. The oven heats the glass to more than 600 degrees Celsius. (The industry standard is 620 degrees C.) The glass then undergoes a high-pressure cooling procedure called quenching. During this process, which lasts just seconds, high-pressure air blasts the surface of the glass from an array of nozzles in varying positions. Quenching cools the outer surfaces of the glass much more quickly than it does the center. As the center cools, it tries to pull back from the outer surfaces. As a result, the center remains in tension, and the outer surfaces go into compression.

This compression is what gives tempered glass its strength. Glass in tension breaks about five times more easily than it does in compression. Annealed glass will break at 6,000 pounds per square inch (psi). Tempered glass generally breaks at approximately 24,000 psi.

Another approach to making tempered glass is chemical tempering, in which chemicals exchange ions on the surface to create compression. But because this method costs far more, it is not widely used. SA

*For answers to many other questions, visit Ask the Experts (www.sciam.com/askexpert).*




PATRICK HARDIN

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