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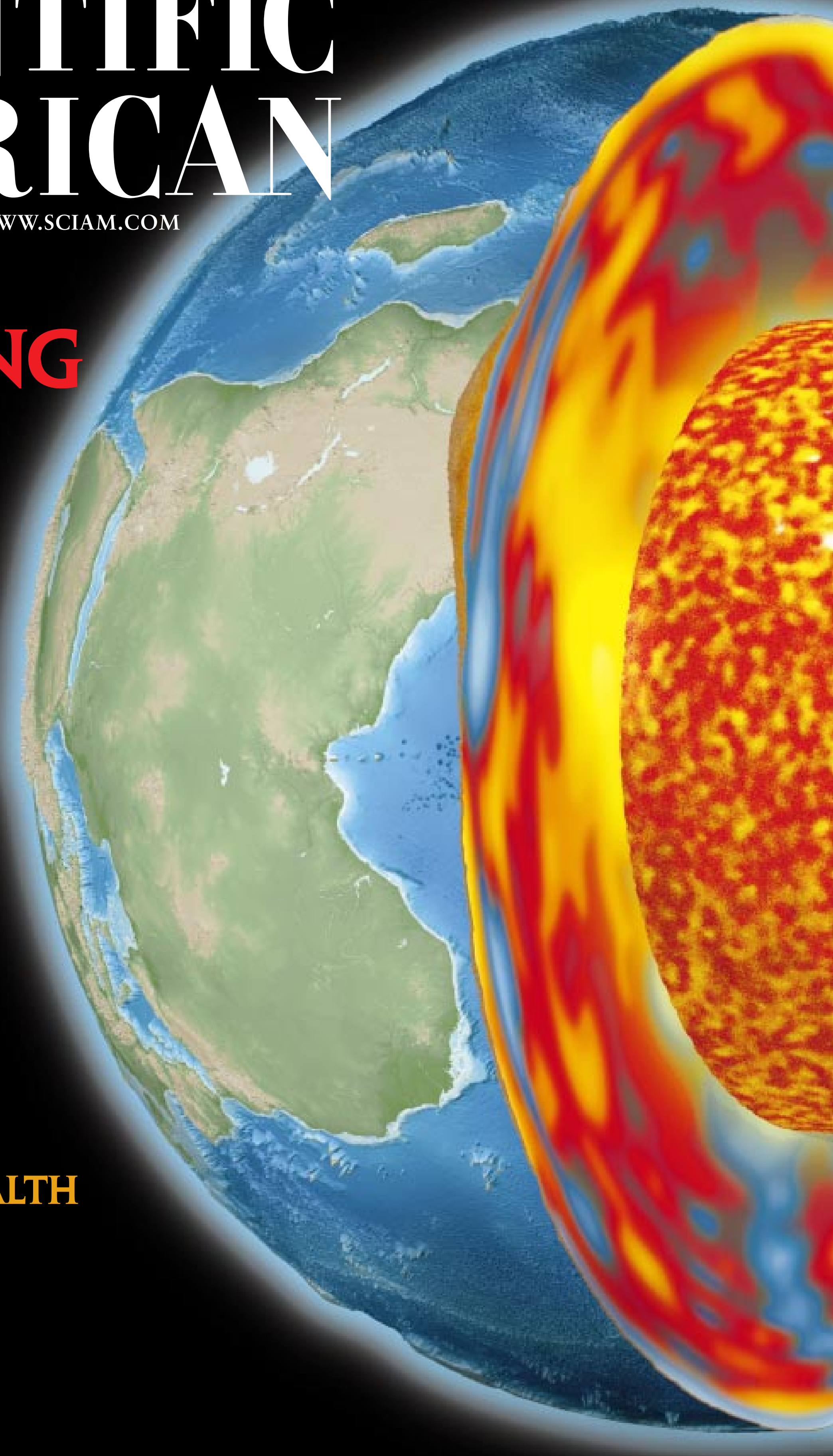

SCULPTING THE EARTH FROM INSIDE OUT

IF HUMANS WERE BUILT TO LAST

MAKING SENSE OF TASTE

GEOGRAPHY OF POVERTY AND WEALTH

SCIENTIFIC AMERICAN
March 2001 Volume 284 www.sciam.com Number 3

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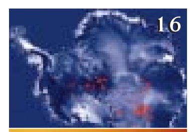

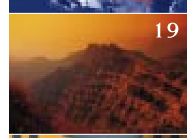

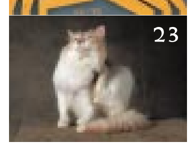

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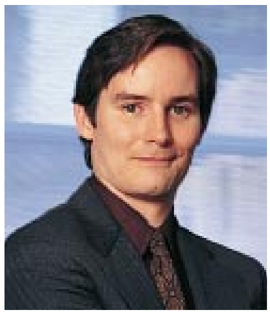
From the Editors

EDITOR_JOHN RENNIE

The Future of Human Evolution

Do you remember what people of the future used to look like? When science-fiction movies, television and comic books strained to portray humans of the technologically advanced future, they almost always pictured us with giant bald heads that could house our massive brains. (In a particularly memorable episode of *The Outer Limits,* the highly evolved David McCallum also had six fingers on each hand, the better for pushing buttons, I guess.) We would become a race of supergeniuses who somehow never invented Rogaine. Of course, there were other possibilities, too. The traveler in H. G. Wells's *Time Machine* went far into the future and found two divergent species: the brutish Morlocks, who lived in machine-clogged tunnels, and the beautiful, bucolic, tasty Eloi. Apparently, Wells envisioned that only New Yorkers and Swedes would survive atomic war.



ERICA LANSNER

These days speculation about how humans might evolve seems fallow. The characters on *Star Trek,* for example, look as though they could just be actors in Hollywood. Maybe this shift to a closer-to-home future represents a subtle change in the public's unconscious grasp of how evolution works (yes, yes, I know: dream on).

We would become a race of supergeniuses who somehow never invented Rogaine.

After all, the idea that we would grow bigger brains seems to arise from a view that evolutionary progress flows like a river: we are less hairy and generally have larger brains than our ancient ancestors did, so our descendants should carry these trends to even more of an extreme. But Darwinian evolution calls for circumstances either to favor strongly the big-brained chrome-domes or to weed out drastically us more limited fuzz-heads.

Thanks to modern technology and medicine, people have taken much more control over their differential survival. Bad eyes, weak bones and countless other ills are not the barriers that they once were, happily, a fact that somewhat lessens the reproductive premium on healthful genes. Moreover, in this mobile world, genes from all populations are constantly churning together, which works against distinct subgroups' emerging with new traits. We will certainly continue to evolve naturally in small ways, but our technology may exert the greatest influence. Which means that if we all have big bald heads someday, it's not destiny—it's a fashion statement.

The article "If Humans Were Built to Last," beginning on page 50, has fun with these kinds of arguments by asking how humans might look if they had been optimized to lead long, healthy lives. Evolution doesn't have the luxury of selecting for just one such factor, but the authors' analysis of our body's shortcomings in this regard is both entertaining and instructive.

John Rennie

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Cloning and Its Discontents

The problem posed by Robert P. Lanza, Betsy L. Dresser and Philip Damiani ["Cloning Noah's Ark"]—"how to get cells from two different species to yield the clone of one"—is not completely solved in the manner they suggest. The gaur they anticipate, Noah, is a hybrid; he contains DNA not only from different individuals but from different species, because the cow egg used to generate Noah contained mitochondrial DNA. Noah will contribute to the management of gaurs only if he is subsequently mated with a gaur female or if his nuclear DNA is incorporated into an enucleated gaur ovum. Resulting offspring would then contain only gaur DNA. This complication limits the potential contribution of somatic-cell nuclear transfer, at least as practiced in this case, to the management of species that are in danger of extinction.

MICHAEL R. MURPHY
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Damiani replies:

Nature will help us out with this problem. The sperm mitochondrial DNA is inactivated when it reacts with the egg cytoplasm; thus Noah's bovine mitochrondrial DNA (which is sperm-derived) will not be transmitted to his offspring. The female gaur's mitochondrial DNA will be transmitted, and the resulting offspring will be 100 percent gaur—in both mitochrondrial and nuclear DNA. [Editors' note: Noah was born on January 8 but died of a common bacterial infection within 48 hours. The scientists do not think the cloning process was a factor in his death.]

If habitat is continually being destroyed, where will these new genetic creations live? For example, in the case of the bucardo—"wiped out by poaching, habitat destruction and landslides"—what would prevent the same cycle from reoccurring? Cloning should be seen not as a replacement for wildlife preservation or a solution for ecosystem depletion but as a tool to aid in wildlife conservation. If funds are siphoned away from preservation to cloning, the practice ought to be reconsidered—an ecosystem is not merely fauna.

JONATHAN SUTER
Kanata, Ontario

PETER ARNOLD, INC.

GAUR, an oxlike native of India, Indochina and Southeast Asia, is one of the endangered animals scientists hope to clone.

In Praise of Classic Filmmaking, the 56K Modem

There is no doubt that the size and speed of the microprocessor has greatly increased the efficiency of many aspects of film production, particularly in editing and visual effects. But the article "Moviemaking in Transition," by Peter Broderick, left me unsettled. Filmmaking is a deceptively difficult form of art because it is a collaboration of so many mediums: theater, painting (lighting), literature, fashion and photography, to name just a few. It is essential that the director hire each of these artists and focus their unique talents toward a common vision.

Broderick would have you believe that for a nominal equipment investment and a more relaxed distribution policy, anyone could be the next Martin Scorsese or Spike Lee. Unfortunately, nothing could be further from the truth, and many a bank account is emptied in this pursuit every year. Filmmaking without adherence to its process is like scientific research without the scientific method, rendering films that are more or less unwatchable. It is this very process that Broderick shrugs off as nothing more than an "institutional investment."

The marriage of digital technology and moviemaking is exciting because, for the first time in history, young auteurs have a chance to hone their directing skills inexpensively and to communicate with and critique other filmmakers from around the world. But before we toss away 100 years of filmmaking process to digital technology, let us remember that it is the hours of intense labor and the tedious brush strokes, not the paint, that make a masterpiece.

ROBERT ALLEN SNYDER
Writer/Director
Member of International Alliance of
Theatrical and Stage Employees

I am disappointed that you downplay the power of the lowly 56K modem as insufficient for supporting online video. We should bear in mind that video-compres-

THE_MAIL

"How much technological invasion can our lives stand?" asks Steven Ginzburg of Santa Barbara, Calif. (See "As We May Live," by W. Wayt Gibbs; Technology and Business, November 2000.) "Technology is most tolerable when it provides a useful service without our noticing. Using this litmus test, Web-enhanced appliances (such as NCR's e-banking microwave oven) seem rather absurd. A house that unobtrusively monitors the health of elderly inhabitants is more promising, despite the inherent invasion of privacy, as is a Subaru car device that improves handling by monitoring motion and applying momentary brake pressure. I predict that future life will be much like life today, except that everyday gadgets will be safer and more efficient and will interoperate more readily, thanks to computerization. A houseful of hidden cameras and Web-browsing appliances is an improbable and unfortunate stereotype of the home of the future."

For additional comments and opinions about articles from the November 2000 issue—including an intriguing twist in the story of the race to build the A-bomb—please read on.

sion technology is still young. As it develops, we will find that our need for bandwidth will shrink instead of grow. Today's modems will operate far above 56K, but the limiting factor is how much bandwidth the phone companies will give us. A doubling or quadrupling of this limit could surely be achieved at minimal expense and would offer an extremely elegant solution to our needs. Requiring no additional investment from the end user, modems offer an inexpensive path to the entertainment world the report envisions. In contrast, expensive solutions will probably fail to generate enough market momentum to succeed. Which would you choose?

TOM KING
via e-mail

But for a Bit of Boron ...

William Lanouette ["The Odd Couple and the Bomb"] writes that both German and American scientists recognized that graphite could serve as a moderator for uranium fission but that the Germans gave up on it because graphite absorbed too many neutrons. It did so because, unbeknownst to them, their graphite contained a trace amount of boron that had gone undetected by the spectrochemical method they used to analyze it. This fact underlines how crucial Szilard's insistence that Fermi not publish his results on boron-free graphite as a moderator was to the outcome of World War II. Had the Germans learned of it at that point, their project would not have fizzled as it did.

ARNO ARRAK
Dix Hills, N.Y.

Voting Your Pocket

Rodger Doyle's comparison of voter turnouts for U.S. (47.2 percent) and European (71 percent) elections [By the Numbers] failed to mention one obvious reason why more Europeans go to the polls: voting is compulsory in a number of European countries, and nonvoters are liable to be fined. That's quite an incentive to vote!

STEVE MARCHANT
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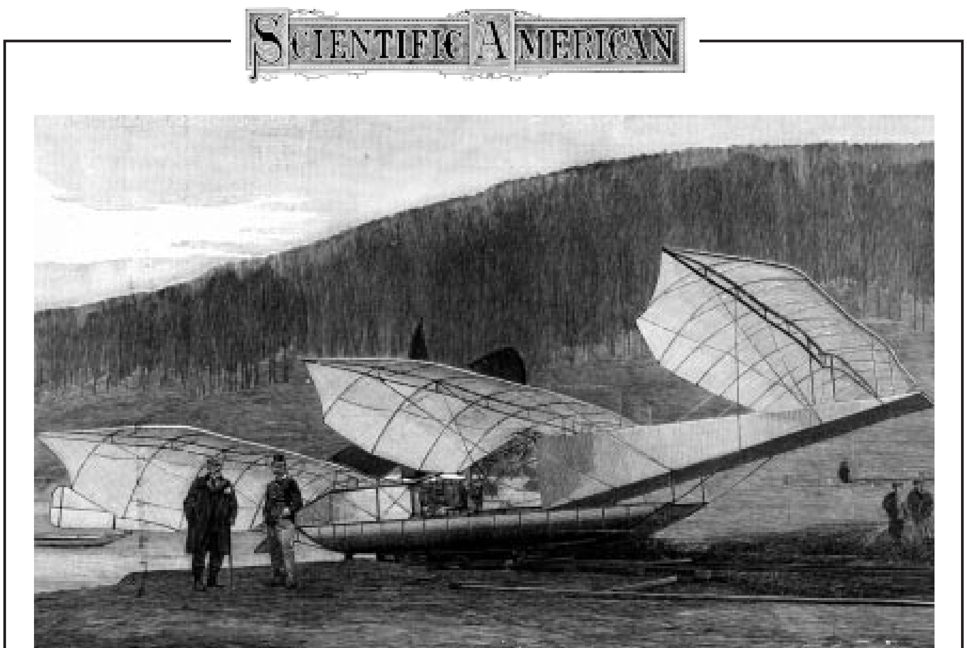
Martian Canals, 1901, The Crystal Palace, 1851

MARCH 1951

BEFORE TECHNICAL OUTERWEAR— "What fabrics best insulate the body against the loss of heat? Tests demonstrate, as expected, that an open-weave cotton fabric has the smallest insulation value. A dense cotton cloth gives somewhat more protection, and wool still more. But insulation value declines greatly when fabrics are damp; for wet cotton flannelette, the heat loss is greater than when the test surface has no cover at all. The study suggests these avenues of research in winter clothing: underclothing that will not readily absorb water, garments that will hold quantities of air in extremely small bubbles, and quilted clothes made of a batting of chicken feathers and cotton."

CELL CHEMISTRY—"It is of great importance in protein chemistry to find out precisely the quantities of each of the 20-odd amino acids yielded by the breakdown of a protein. In 1945 the authors undertook quantitative amino acid analysis with the aid of chromatography. It has been possible with this apparatus to separate and to determine quantitatively each of the 20 or more amino acids found among the cleavage products of a protein. It has been said by many that progress in science frequently depends upon the development of good methods. Chromatography furnishes a vivid example of the truth of this statement.—William H. Stein and Stanford Moore, Rockefeller Institute for Medical Research" [*Editors' note: With improved analytical methods, the authors ascertained the structure of pancreatic ribonuclease and earned the 1972 Nobel Prize for Chemistry.*]



THE DREAM OF FLIGHT—**before the crash, 1901**

MARCH 1901

CANALS ON MARS—"Discussion on this subject still rages with unabated vigor. While Mr. Lowell sees in the Martian 'canals' a vast system of artificial irrigation, M. du Ligondès sees geological fissures. But the enigmatical lines have appeared to so many that the ranks of the unbelievers grow thin. However, Signor Vincenzo Cerulli, from his private observatory of Collurania (near the city of Teramo), has showed how the regular lines and spots we find in the faint markings of Mars might be due to our limited optical means and our inability to see the irregular details. In addition, the artificial origin of the Martian 'canals' can hardly be maintained now that they have been seen to traverse the polar caps, and to appear in Venus, Mercury, and two of the Jovian satellites. —Mary Acworth Orr"

AEROPLANE—"The most recent attempt to solve the problem of artificial flight has been made by Wilhelm Kress, an engineer, who for twenty years has patiently labored on an aeroplane in which he has embodied his ideas. Two resilient sail-propellers, rotated by a benzene motor in opposite directions, drive the apparatus, which is an ice boat provided with arched sails [*see illustration*]. Preliminary water trials have been successful." [*Editors' note: The plane crashed on takeoff.*]

CHEATS NEVER PROSPER—"A correspondent from the city of Boone, Iowa, sends $5 and some sketches of a table he is building, evidently intended for some gambling establishment. There is a plate of soft iron in the middle of the table under the cloth, which by an electric current may become magnetized. Loaded dice can thereby be manipulated at the will of the operator. He desires us to assist him in overcoming some defects in his design. We have returned the amount of the bribe offered, and take the opportunity of informing him that we do not care to become an accessory in his crime."

MARCH 1851

OPEN SORE—"The population of the United States amounts to 20,067,720 free persons, and 2,077,034 slaves."

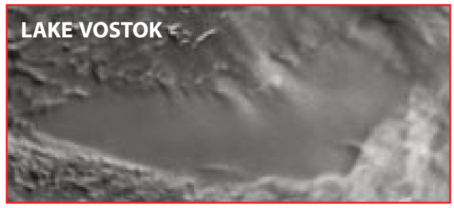
CRYSTAL PALACE—"The great Crystal Palace, as the building for the World's Industrial Exhibition has been termed, is now nearly finished. Some scientific men have objected to the building as erected, on the ground of a want of strength: To look upon it, in all its vast extent and fairy-like fragility, a feeling of insecurity respecting its strength is natural, but we have been so accustomed to witness large structures, having giant pillars of stone for supports, that we are ready to forget the superior strength of iron, of which this building is mainly composed."

FROM *SCIENTIFIC AMERICAN*

GLACIOLOGY_EXTREME LIFE

Out in the Cold

Ambitious plans to penetrate icebound Lake Vostok have slowed to a crawl

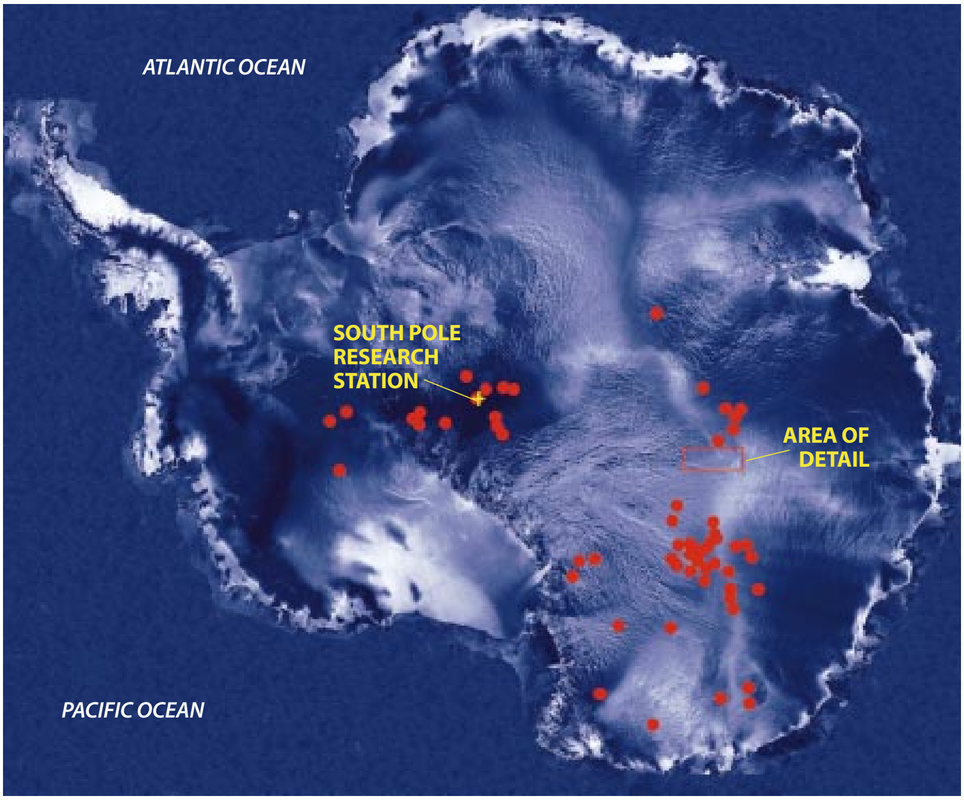


SAN FRANCISCO—Of all the great lakes of the world, just one remains untouched by humanity. The very existence of Lake Vostok, buried as it is beneath some four kilometers (13,000 feet) of ice in one of the most remote parts of Antarctica, was unknown when Soviet explorers serendipitously built a base directly above it in 1957. Not until 1994—by which time Russian glaciologists had drilled three quarters of the way down to the lake in order to read 400,000 years of climate history recorded in the ice—did satellite and seismographic measurements reveal Vostok's impressive size, almost equal in area to Lake Ontario but up to four times as deep. Cut off from direct contact with the sun, wind and life of the surface world for as long as 14 million years, Lake Vostok seems to scientists to be a unique time capsule that, once opened, could help solve old and difficult puzzles. Some technologists consider it the best place on Earth to test probes that are designed to bore through the icy shell of Europa, a moon of Jupiter suspected of harboring a watery ocean and possibly life.

But many environmental activists disagree, and recently scientists and technologists have been stepping back from proposals they started making in 1996 to send robotic probes into the lake to analyze the water, look for microorganisms and return sediment samples. At a workshop sponsored by the National Science Foundation in late 1998, several dozen researchers drew up a timeline calling for penetration of the lake in 2002 and sample returns in 2003. In late 1999 a follow-up meeting pushed the mission back to 2004 at the earliest. Now previously bullish researchers concede it may well be a decade before instruments are lowered into the lake.

Growing uncertainties of three kinds have forced this retreat. One question is whether and how a probe could be lowered into a subglacial lake without contaminating it with microbes from the surface or the ice pack. "The general idea is to drill down 3.5 kilometers or so with hot water and then deploy a cryobot," explains Frank D. Carsey, lead scientist on the ice-probe project at the Jet Propulsion Laboratory in Pasadena, Calif. After waiting for the hole above it to freeze shut, the cylindrical probe would sterilize itself, heat up and melt its way down to the lake, spooling electrical cable from its body as it goes. In September, Carsey's team showed that a simple prototype device could move through a few meters of ice. But almost no testing has been done on sterilization techniques, he says. "No body, national or international, has said how clean is clean enough," Carsey observes. "We need a target to work toward."

The cost—and who will pay it—is also uncertain. A project based at the Vostok research station has been estimated to run $20 million. But the station sits above the southern tip of the lake, where freshwater is refreezing onto the icy ceiling. "There is a really good chance that we'll decide the best place to send a probe is the northern end, where the bottom of the ice is actually melting and nutrients in it"—salts, dust and microbes deposited with the snow eons ago—"are being added to the water," says Robin E. Bell, a geophysicist at Columbia University's Lamont-Doherty Earth Observatory. If so, then the project would require construction of new buildings, runways, fuel depots and other infrastructure, dramatically raising the cost.



ANTARCTICA'S LAKE VOSTOK is so large that its outline is visible from space as a flat spot in the 4,000-meter-thick ice sheet that covers it (*detail above*). But radar soundings have revealed about 70 smaller subglacial lakes (*red*), some of them near the South Pole research station.

So far neither the NSF nor the National Aeronautics and Space Administration has offered to pay for the development of a fully instrumented probe or for the drilling. Carsey's grant from NASA to build a more sophisticated cryobot prototype was not renewed this year. "We'll have a completed gadget by this summer," he says, "but we may not ever be able to test it." He complains that "NASA is seriously dragging its feet" in sponsoring research on noncontaminating instruments for Vostok and Europa.

Until tests in less pristine settings, such as ice-covered volcanic lakes in Iceland, prove that a cryobot can enter the water without dragging along foreign life-forms, it is likely that conservationists will continue to oppose plans to penetrate Lake Vostok. "We firmly believe that a comprehensive environmental evaluation [required by the Antarctic Treaty] would not permit this to go forward with current technology," says Beth Clark, director of the Antarctica Project, speaking for a coalition of more than 200 environmental groups. In October the World Conservation Union adopted a resolution urging treaty members to "defer for the foreseeable future" drilling into the lake and to designate Vostok a "specially protected" area.

Perhaps the greatest uncertainty is whether Vostok is the only lake that can answer the important questions scientists are asking of it. Analyses of ice-penetrating radar soundings by Martin Siegert of the University of Bristol and others have turned up at least 70 lakes beneath the Antarctic ice sheet. Bell and other proponents of a Vostok mission have argued that Vostok is probably unique in a number of ways: in its sediments, in its depth, in its age, in its sloped ceiling (which may cause its waters to circulate) and in its possible geological origin as a rift in Earth's crust.

But preliminary results from new radar, magnetic and seismic data taken in January reveal just how little scientists truly know about Vostok. "The lake is not the big homogeneous feature we thought before," says Columbia geophysicist Michael Studinger. It contains "islands" where land meets ice and pockets where water rises to different levels. "Another surprising observation is a big magnetic anomaly" near one shoreline, he adds. And Bell, who with Studinger co-directs the radar study, reports that in places the water is 1,000 meters deep—almost twice what was previously thought.

Yes, Vostok is larger by far than any of the other subglacial lakes, Siegert allows. But whether it is unique in more important ways is anyone's guess, he suggests: "It is the only lake where seismic data have been acquired. There may very well be sediments at the base of other lakes. As for the water depth, the same thing is true." The average age of the water in Vostok, one million years according to some estimates, depends crucially on whether it is connected with other lakes by streams beneath the ice. "All the other lakes have a sloping ice roof," Siegert adds, and he argues that "labeling Vostok as a rift valley lake is premature."

In July the Scientific Committee on Antarctic Research issued a statement that urged the investigation of smaller lakes first but maintained that Lake Vostok "must be the ultimate target of a subglacial lake exploration program." Siegert disagrees. "The goal should be to solve scientific problems," he says, "not just to explore."

—W. Wayt Gibbs

ENVIRONMENT_CONTAMINATION

Scotchgard Scotched

Following the fabric protector's slippery trail to a new class of pollutant

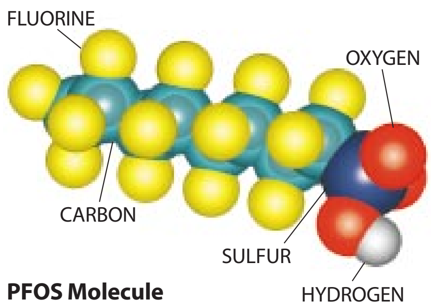
In a surprise announcement last May, 3M Corporation declared that it would stop making the chemical used in its popular Scotchgard fabric protector by the end of 2000 and discontinue other, similar compounds completely by 2002. The chemicals belong to a class of fluorinated compounds that are also incorporated into hundreds of products, ranging from microwave popcorn bags and fast-food wrappers to semiconductor coatings and airplane hydraulic fluid. To its credit, 3M decided to phase out its flourishing $300-million-a-year fluorochemical business after it discovered a particular fluorochemical in the blood of humans and animals from pristine areas far from any apparent source.

That compound is perfluoro-octanyl sulfonate, or PFOS, a breakdown product of other 3M fluorochemicals. "It is new and unexpected to find fluorochemicals in the environment," remarks zoologist John P. Giesy of Michigan State University's National Food Safety and Toxicology Center, who with colleague Kurunthachalam Kannan has analyzed about 2,000 animal tissue samples for 3M. Despite the chemical's ubiquity, company officials are adamant that there is no evidence of any danger thus far.

PFOS caught everyone off guard because it is so different from the known environmental baddies, such as the organochlorine compounds PCB and DDT. Those chemicals are notorious for their longevity, but PFOS appears to outdo them. "PFOS redefines the meaning of persistence," says University of Toronto chemist Scott A. Mabury. "It doesn't just last a long time; it likely lasts forever." The persistence comes from PFOS's makeup as a chain of eight carbon atoms surrounded by fluorine atoms, he explains. The fluorine atoms act like a stiff armor around the carbon chains, making them practically impossible for microbes to degrade, according to Stanford University environmental engineer Craig S. Criddle.

And PFOS can travel. Despite a relatively low production volume, less than 10 million pounds a year (the top 50 U.S. chemicals each have annual production volumes of more than one billion pounds), it has spread around the world in the 40 years since 3M began production. This distribution is a puzzle because for a chemical, global travel usually means atmospheric transport—PCB and DDT both evaporate and can be carried by winds. But PFOS does not volatilize.

Don Mackay, Thomas A. Cahill and Ian Cousins of Trent University in Ontario, who study the fate of chemicals in the environment, believe that some other, more volatile chemicals involved in the production of fluorochemicals are getting into the air, traveling the world and breaking down into PFOS. These agents could be precursors used by 3M or part of the process by which other manufacturers incorporate fluorochemicals into their products. Volatile fluorochemicals may also come from materials discarded in landfills.



PFOS Molecule

SOMETHING IN THE AIR: Perfluoro-octanyl sulfonate, or PFOS (*model below*), is a key compound in Scotchgard that has turned up in remote areas.

Whatever the transport mechanism, once PFOS gets into an animal, it stays. But unlike PCB and DDT, which build up in fatty tissues, PFOS binds to protein in the blood and then accumulates in the liver or gallbladder, according to Kannan. He and Giesy have found levels of up to six parts per million in mink and eagles. Richard E. Purdy, an independent toxicologist who worked for 3M for 19 years, notes that these levels are only about one tenth the concentrations at which lab toxicity tests on rats and monkeys have showed adverse effects. That safety margin of 10-fold or less is too low, considering the variability in species sensitivities, Purdy insists: "The numbers are close enough to convince me that wildlife is being killed by this compound now."

But most researchers say this speculation is premature and that there is no evidence that PFOS in the environment is harming humans or animals. "We have to learn a lot more about its toxicity," states Kannan, who notes that most of the wildlife tested, including polar bears and seals, harbored much lower levels, about 1⁄50 the minimum toxicity thresholds determined in the lab. "We need to look at more sensitive indicators of adverse effects. But at this stage we don't know what those indicators are," Kannan says.

The PFOS discovery is bringing other fluorochemicals under scrutiny. Companies that make fluorinated compounds similar to those of 3M have embarked on research programs to see if those fluorochemicals could ultimately act like PFOS. The Organization for Economic Cooperation and Development, an advisory group consisting of 29 member countries, is working with U.S., U.K., Canadian and Japanese environmental agencies to assess the problem on a global scale.

Meanwhile 3M is developing nonfluorine-based alternatives for Scotchgard and other fabric protectors. According to 3M environmental director Michael A. Santoro, those coatings will be on the market later this year. —*Rebecca Renner*

REBECCA RENNER trained as a geologist but now digs for facts as a science writer in Williamsport, Pa.

PAUL D. JONES *Michigan State University (model)*; JOEL HOLLAND *(illustration)*

Volcanic Accomplice

Deadly impacts may have exacerbated massive eruptions

RENO, NEV.—The Chicxulub Crater, sprawled across the Gulf of Mexico and the Yucatán Peninsula, is an approximately 180-kilometer-wide remnant of the impact of a 10-kilometer-wide meteorite. It has been called the smoking gun in the extinction of the dinosaurs between the Cretaceous and Tertiary periods 65 million years ago. Some geologists, though, are starting to believe the meteorite didn't act alone. Volcanic phenomena known as superplumes may have been accomplices in that and other mass extinctions. "The general idea is that plumes are strengthened by impacts," says Dallas Abbott, a researcher at Columbia University's Lamont-Doherty Earth Observatory. At the Geological Society of America meeting in Reno last November, she showed a correlation between the timing of purported superplumes and large impact events—and their possible association with mass extinctions.

A plume can be visualized as a rising glob of liquid in a slowly warming lava lamp: material hotter than the surrounding rock of the earth's mantle pushes toward the surface in a concentrated stream. The funnel ends below the earth's outer crust, where the plume material spreads and ponds. If the molten rock erupts through the earth's surface, it releases gas and particulates into the air and produces lava flows. A superplume may be a gathering of small plumes, the size of those under the Hawaiian Island chain and Iceland, or one very large plume.

Abbott and her co-worker Ann Isley of the State University of New York at Oswego have catalogued remnants of possible superplumes, including the Deccan Traps in India, the Columbia River flood basalts in the Pacific Northwest and the Siberian Traps. These basalt flows and other associated rocks have large amounts of magnesium, indicating their origin in the depths of the mantle.

The researchers have also logged the probability of large impacts occurring at the same time as plume events. There are about 36 craters more than 10 kilometers wide that formed over the past 120 million years, Abbott says: "It's a small sample of the potential number." Using the record of earth and lunar impacts, she calculates that of the estimated 400 large impactors in the earth's history, 40 percent should have hit continental crust. The rest should have struck ocean crust, in which case their craters would have been subducted into the mantle. "Therefore, we've found only 19 percent of the big ones," Abbott concludes. Of those, "there's one definitely associated with the Permo-Triassic," she says of the mass extinction 250 million years ago. The timing of the other five main mass extinctions, impacts and plume events is close, but you could argue about them, Abbott admits.

One of those events is Chicxulub—and its relation to the Deccan Traps. Mark Boslough of Sandia National Laboratories modeled the so-called seismic focusing that would occur from an impact event on the earth's innards. A large energy release on one side of the earth would set off seismic waves, which would travel through the mantle and converge at the opposite side, or antipode, creating another energy peak. That energy would be converted to heat, raising temperatures in the mantle and increasing melting of the rocky material—thereby heightening the effects of any plume already there and further contributing to conditions that lead to extinctions.

Abbott is unsure of the exact mechanisms that would strengthen an existing plume, but one possibility is that increasing temperature differentials between the core and the mantle would cause fingerlings of hot core rock to enter the earth's crust. The subsequent increase in volcanism and release of climate-affecting gases would be more than expected for a superplume or impact event alone.

Thanks to plate tectonics, however, the Deccan Traps may not have been antipodal at the time of the Chicxulub impact. If they weren't, Boslough says, "you would have to propose a second impact," directly opposite the Traps, "in the eastern Pacific, on seafloor that's been subducted." Any geological evidence would be gone.

"You have to figure out what is in the geological record" to draw any firm conclusions, Boslough says. From his models, an impact might produce the same kinds of surface manifestations attributed to superplumes: flood basalts, large changes in sea level, radically increased mechanical erosion that alters ocean water chemistry, and sediment deposits that indicate a global change has occurred.

But Abbott and Isley think there is hard evidence for impact-enhanced superplumes: certain types of rocks associated only with superplumes, say, or some kind of universal, physical characteristic in the earth consistent only with major plume events. For now, though, not enough evidence exists to indict superplumes as an extinction accomplice. —*Naomi Lubick*

DECCAN TRAPS are a remnant of volcanism that may have helped kill the dinosaurs.

MILIND A. KETKAR *Dinodia Picture Agency*

NAOMI LUBICK is a freelance writer based in the San Francisco Bay Area.

OPTOELECTRONICS_SELF-ASSEMBLY

Pour Me Another

A novel way of embedding chips in polymers may let you have your computer and sit on it, too

John Stephen Smith inherited eight graduate students in the mid-1990s after one of his electrical engineering colleagues at the University of California at Berkeley died. Smith had little idea (and, truthfully, scant interest in) how to keep his colleague's research going and his new students occupied. Numerous efforts to marry silicon electronics with gallium arsenide optical devices—the focus of the group's research—had dragged on for years, with decidedly mixed results.

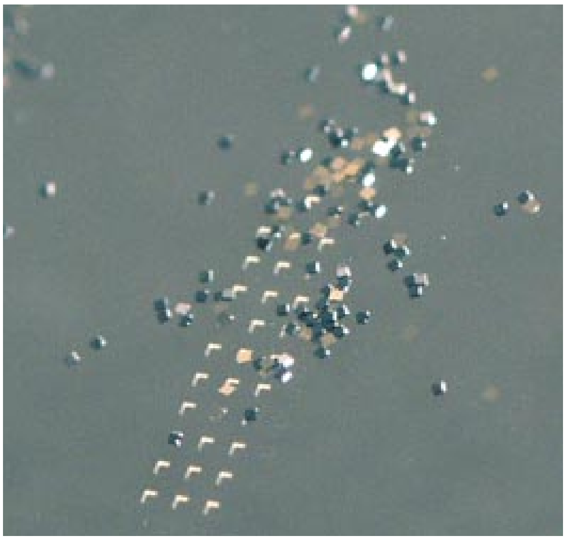
Inspiration struck while Smith waited for his wife at the chiropractor's office. He fiddled with a child's toy, a plastic box that he tilted back and forth to try to get tiny metal balls to enter perforations in a cardboard sheet. The eureka moment arrived when he had the odd thought that a similar method might be used for optoelectronic integration.

What if the microscopic lasers the group worked with could be shaken—or better yet, placed in a liquid and poured—into little holes on a silicon wafer? "My graduate students looked at me like I was nuts," Smith says. "But one guy decided a few weeks later to try it, and it worked." Under the microscope, the student, James Yeh, saw that the specks of gallium arsenide, each one just 30 microns across, had dispersed in the water and neatly plugged into a few hundred of the thousands of carefully machined, trapezoidal holes on the silicon surface.

Smith named the process fluidic self-assembly. The project succeeded in helping his graduate students get their degrees. But it also did much more. Pouring circuits has become a means of integrating electronics with polymers to build displays that can bend like taffy in your back-pocket wallet or be rolled up and stuffed in a mailing tube.

Most important, it may be a new way to simplify the complex and expensive process of designing electronic displays. Today display makers channel hundreds or thousands of wires to off-display chips, which dictate when the multitude of picture elements on a screen should turn off and on. Fluidic self-assembly locates dense circuitry on the display itself, dramatically reducing the off-display wiring required.

Alien Technology, a company that Smith founded, has used fluidic self-assembly to make inexpensive plastic displays. The company outsources the manufacture of the silicon wafers that contain the chips, which it calls nanoblocks. The wafer is cut into trapezoidal chips—picture an upside-down pyramid with its top cut off—that are then put in a solution containing water, a surfactant and a binding agent and poured onto a substrate of silicon, glass, polymer or other material. The tapered ends of the nanoblocks fit into the trapezoidal holes. Any excess electronic elements are then washed away, and the emplaced nanoblocks are wired together.



NANOBLOCKS fall through water toward rows of machined holes, where some of the chip elements become embedded—a means of assembling electronic devices.

Nanoblocks can be poured onto a section of a plastic sheet, and then the sheet can be unrolled further to pour more. For some forms of display manufacturing, an ink-jet printer might then be used to place bits of red, green and blue light-emitting polymers above each nanoblock to form a picture element. Arno Penzias, a former vice president of research at Bell Laboratories who is now a member of a venture-capital firm that has invested in Alien, commented on prospects for this form of inexpensive low-cost manufacturing: "Water gets a very low salary."

Alien has built a pilot plant for making small polymer displays that can show the cash balance left on "smart" cards. But the technology could go beyond displays and into a host of other applications: a plastic roll that could be unfurled to show a changing mix of color topographic maps, for example, or a sheet that could serve as chameleonlike camouflage, altering color as needed to hide a tank. In addition, affordable versions of the phased-array radar that graces battleships could steer beams electronically so that every cellular phone could get its own high-bandwidth signal. Smart tags could become cheap enough to track your lost keys or the whereabouts of a teddy bear. "All of a sudden, everything in the house has a two-way radio," Penzias comments.

Whether the technique becomes as cheap and simple as the company claims remains to be seen—nonstandard processing steps, like pouring nanoblocks into holes, mean that other competitive manufacturing methods may emerge. "If flexible displays turn out to be the thing that everybody needs," remarks electrical engineer Kaigham Gabriel of Carnegie Mellon University, "someone will come up with a faster and cheaper way of doing this." Indeed, Alien is still wrestling with some of the challenges of making polymer displays—spacing the holes at uniform distances, for instance. If in the end the technology proves itself, though, it will be a case of how seemingly idle child's play can produce great ideas. —*Gary Stix*

STEVE POMBO

DERMATOLOGY_CANCER

Skin So Fixed

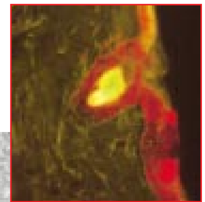
A topical lotion with DNA-repair enzymes cuts down skin carcinomas

Every year about 1.3 million Americans are diagnosed with basal or squamous cell carcinoma, the two most common forms of skin cancer. The sun's ultraviolet light is the chief culprit in causing genetic mutations in skin cells. Researchers now say they have a skin lotion that can enter cells and fix their damaged DNA before they have a chance to develop into full-blown cancer cells.

The principle is simple: the lotion contains liposomes, little oily vesicles, filled with a viral DNA-repair enzyme called T4 endonuclease V. The liposomes penetrate the epidermis and enter the cells. Once released inside, the enzymes are small enough to make their way into the nucleus, which contains the DNA. Here they bind very tightly to the most common DNA mutations caused by sunlight—so-called cyclobutane pyrimidine dimers, in which two DNA bases are fused. By partially cutting off the dimers and breaking the DNA strand next to them, the enzymes initiate a repair process that other cellular enzymes complete.

Daniel Yarosh is the founder and CEO of AGI Dermatics, the company that manufactures the "repairosome" lotion. In the February 9 *Lancet*, he and his colleagues report the results of a clinical trial of individuals suffering from xeroderma pigmentosum (XP), an inherited disorder rendering patients extremely sensitive to sunlight and prone to skin cancer. These people usually cannot produce one of the seven enzymes needed to repair UV-damaged DNA (called nucleotide excision repair). Thirty XP patients who applied the skin product daily to their face and arms for one year experienced a decrease in these skin areas of basal cell carcinoma by about one third and of actinic keratosis, a sun-induced skin lesion that can develop into squamous cell carcinoma, by as much as two thirds.

These remarkable results, which began to show up after only three months of therapy, probably do not stem from the repair activity alone: the enzyme's action may have also returned the skin's immune response—which is weakened by UV light—to normal. AGI Dermatics is currently seeking Food and Drug Administration approval to market the new drug to XP patients, although Yarosh wouldn't go so far as to say that the drug would enable these "children of the moon" to enjoy the sun.



CORA BUCANA

DNA-REPAIR ENZYMES (*black dots*) successfully enter a mouse cell and nucleus. Liposomes filled with the enzyme can reach into the epidermis and hair follicles (*inset, red areas*).

Other people may benefit from the drug as well, because XP is "just an accelerated version of what's happening to all of us," Yarosh says. At the moment he is preparing a clinical trial involving several hundred people with a history of skin cancer. And someday the treatment might become available to the general population to speed up the skin's natural ability to repair itself. "I could see it combined with sunscreen," says David Leffell, a dermatologist at Yale University. "It is always better to prevent the problem than to try to fix it."

The viral endonuclease is not the only repair protein that has been tested in a lotion. Jean Krutmann, a dermatologist at the University of Düsseldorf and coauthor of the XP report, published a study last year using photolyase, a fascinating DNA-repair enzyme, from cyanobacteria. It directly reverts UV-induced dimers back to normal, using the energy of visible light. Applied in liposomes, the enzyme decreased the number of cyclobutane pyrimidine dimers in human skin by about 40 percent.

Protein therapy is nothing new—insulin and human growth hormone have been used for years—but applying proteins externally to the skin is. Thus far the lotion seems to be safe: very little of the microbial enzymes tested by AGI Dermatics and others penetrates down into the dermis, and they did not cause allergic reactions.

Delivering biologically active proteins through the skin might also become a way to treat other inherited skin diseases caused by enzyme deficiencies. Yarosh thinks that a protein lotion could work for a form of epidermolysis bullosa, in which the skin blisters as a result of a lack of the protein laminin, or x-linked ichthyosis, in which the skin gets scaly because an enzyme called steroid sulfatase is missing.

Already AGI Dermatics, which holds 19 patents for the delivery of DNA-repair enzymes and other biologically active proteins in liposomes, supplies cosmetics companies with "photosomes" and "ultrasomes," liposomes that contain extracts from bacteria that harbor DNA-repair enzymes. *Micrococcus luteus* is one such bacterium; it contains a protein similar to T4 endonuclease V and can tolerate six times more UV light than *E. coli*. These liposomes do not require FDA approval, because they are regarded as "botanical extracts," and the companies do not make any therapeutic claims for them. But even if these beauty products help to reduce skin cancer, they may not prevent other symptoms of skin photoaging, such as lack of elasticity, wrinkles or color changes. The best advice for healthy skin remains unchanged: Stay out of the sun.

—Julia Karow

JULIA KAROW, who has a Ph.D. in biochemistry, is a science writer based in New York City.

Trapped over a Chip

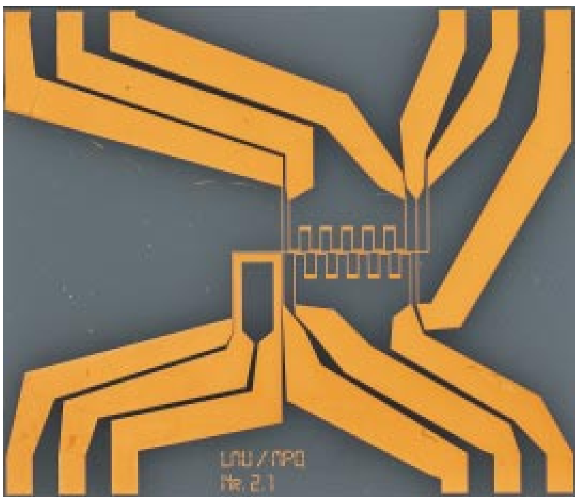
Microchips that control hovering atoms may lead to new quantum computers

Until recently, a typical atom trap has consisted of a temperamental labyrinth of electric coils, custom-built and then fine-tuned and maintained by dedicated graduate students. Now scientists are adapting microchip technology to build robust miniaturized devices to trap and control tiny clouds of chilled atoms. Research groups in the U.S., Austria and Germany have demonstrated atom versions of optical fibers and beam splitters, as well as a magnetic "conveyor belt" for moving atoms around precisely—all on devices that look like crude computer chips. According to Jakob Reichel of the Max Planck Institute for Quantum Optics in Garching, Germany, "these microtraps are a promising tool to get quantum coherent interactions on the atomic scale." And that, he adds, "is the most important ingredient for a quantum computer."

For more than a decade, physicists have trapped and manipulated atoms (such as those in so-called Bose-Einstein condensation experiments) using macroscopic tools. Electric coils produce magnetic fields that trap a cloud of atoms and cool them below a thousandth of a kelvin, just a hair above absolute zero. In 1995 Kenneth G. Libbrecht and a student of his at the California Institute of Technology proposed that microscopic atom traps could be built on chips. Six years on, the proposal is being realized, using lithographically manufactured wires on chip surfaces to produce magnetic fields that can trap and guide atoms tens to hundreds of microns above the chip surface.

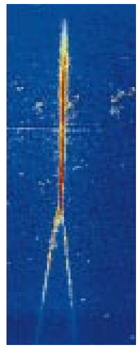
At present, the submillikelvin atoms are still produced in conventional traps and are then transferred to the chips, all within a vacuum chamber. The advantages of chip-based systems include tighter trapping, the precision of the designs that can be made and the ease with which complicated systems can be built. "If you can make one device on the chip, you can make a million," says Jörg Schmiedmayer of the University of Heidelberg.

One of the simplest tools is a wave guide, the equivalent of an optical fiber for atoms. Electric current passing through one or more wires generates a magnetic field that combines with external fields. The total field is weakest a small distance above the wire all along its path, producing a channel that confines chilled magnetic atoms. In 1999 Dana Z. Anderson, Eric A. Cornell and their colleagues at JILA and the University of Colorado at Boulder transported chilled atoms around several curves using such guides on a sapphire substrate. Mara Prentiss and her co-workers at Harvard University have also done experiments guiding atoms on chips.



CONVEYOR BELT on a chip (*square-tooth pattern*) can slide atoms along the central 50-micron-wide track.

In recent papers, Schmiedmayer and his associates report an atom beam splitter on a nanofabricated chip built while they were at the University of Innsbruck in Austria. Their device uses 10-micron-wide wires—the smallest that have been used in these experiments—made by etching a gold layer atop a gallium arsenide substrate. The wire, and thus its atom-guiding magnetic field, splits into a Y. Currents in the wire can be configured so that half of the atoms moving along the stem of the Y go into one arm and half go into the other, much like photons being either reflected or transmitted at an optical beam splitter. Earlier in 2000 the group in Colorado had demonstrated a larger beam splitter consisting of two atom guides crossing in a very narrow X shape.



ATOM BEAM IS SPLIT in two by a nanofabricated magnetic wave guide.

Atoms travel passively along such wave guides, propelled by their thermal motions. Reichel, Theodor W. Hänsch and their co-workers have demonstrated a conveyor belt that actively transports atoms. Instead of having a uniform low-field track above the guide wire, a square-tooth pattern of wires on each side breaks up that magnetic tube into a chain of 0.5-millimeter-long atom traps. Varying the electric currents moves the traps along the guide, carrying their atoms with them (see www.mpq.mpg.de/~jar/conveyer.html for a movie). The conveyor belt could be used to move atoms in a quantum computer from one logic gate to another. In addition, fundamental experiments can be performed by, for example, separating and recombining a cloud of atoms—or the wave function of a single atom—to study quantum interference.

Some basic questions remain, however. All the experiments have used atoms in a mixture of states—that is, the clouds were not in a pure quantum state, a crucial requirement for quantum computing, which relies on the preservation of quantum conditions such as superposition. The Colorado group and Reichel's group are working on running Bose-Einstein condensates through their microchip devices, a development that would allow true quantum studies to begin.

Reichel believes that microchip atom traps, though just getting out of the gate, are one of the most promising candidates for medium-scale quantum computers because "it's straightforward to scale up [atom microchips] to larger numbers of qubits." Schmiedmayer points out that problems could well arise that stymie the usefulness of atom chips for processing quantum information. "In five years we will know if it's an interesting physics problem or if it's really something that we can use," he says. —*Graham P. Collins*

JAKOB REICHEL *Max Planck Institute for Quantum Optics (conveyor belt)*; JÖRG SCHMIEDMAYER *University of Heidelberg (beam splitter)*

NEUROLOGY

Music of the 'Spheres

People with frontotemporal dementia, which affects the front part of the brain, often experience changes in their behavior—and perhaps even in their taste in music. In the December 26, 2000, *Neurology,* researchers describe a 68-year-old man who, two years after diagnosis of that dementia, changed his musical preference from classical to pop, a genre that he had previously disliked, and a woman, 73, who adopted her granddaughter's taste in pop music after a lifetime of musical indifference.

This shift may have resulted from changes in the cerebral component that deals with novelty or from lesions in the lobes that handle perception of pitch, rhythm and timbre. The authors emphasize that these results do not suggest that a liking of pop tunes results from mental dysfunction. *—Alison McCook*

SENSES

Scratching an Old Theory

Anyone who's been driven to distraction by a persistent itch knows that itching ranks right up there with the three main touch sensations—pain, pressure and temperature. Researchers, however, have been unsure about the neural basis for itch; some have thought it is a subthreshold feeling of pain, whereas others argued that it is a distinct sensory type—a view bolstered a few years ago by the discovery of peripheral nerves that respond solely to itchy stimuli. Now neuroscientists have shown that certain spinal cord neurons connected to the thalamus (the brain's sensory gateway) are responsible for feeling an itch. Examining anesthetized cats, they tracked the response of these neurons when itch-inducing histamine was applied to the skin. The discovery, reported in the January *Nature Neuroscience,* may lead to better understanding and treatment for pathological itching, or pruritus. *—Steven Ashley*

YANN ARTHUS-BERTRAND *Corbis*

Itchy pathway

News Briefs

HISTORY OF SCIENCE

Copernican Counterrevolution

It all started when our planet was rudely ejected from the center of the universe. Then our sun became just another star, our galaxy just one among many, and man a mere animal. Five centuries of science have simply continued the Copernican Revolution. Or so it is said. This tidy tale has been disputed by historians such as the late Thomas S. Kuhn but never so forcefully as by Dennis R. Danielson of the University of British Columbia. At the January joint meeting of the American Astronomical Society and the American Association of Physics Teachers, Danielson pointed out that for medieval and Renaissance Europeans, the center of the universe was not a position of importance. To the contrary, it was the lowest point—in Galileo's words, "the sump where the universe's filth and ephemera collect." The earth resides there simply because it is the heaviest of the five Aristotelian elements. If anything, Copernicus's sun-centered theory elevated the earth to the status of a star, the realm of angels—one reason it raised religious hackles. —*George Musser*


PAUL ALMASY *Corbis*

Copernicus, 1473–1543

DATA POINTS

Fulfilling Your Darwinian Destiny


MATT COLLINS

U.S. fertility rate for women ages 15 to 44:
- **In 1990:** 70.9 births per 1,000 women
- **In 1998:** 65.6 per 1,000

Number of women using infertility services, 1995: 9.3 million
Percent of in vitro fertilizations that result in a live birth: 27.7
Cost of one IVF procedure: $8,000 to $12,000

Percent of women who have ever been married ages 18 to 44 who have adopted a child:
- **In 1982:** 2.2
- **In 1995:** 1.3

Percent of women adopters who took a child related to them:
- **In 1982:** 20.3
- **In 1995:** 56.1

Adoption costs:
- **Public agency:** $0 to $2,500
- **Private agency:** $4,000 to $30,000+
- **Independent adoption:** $8,000 to $30,000+
- **Intercountry adoption:** $7,000 to $25,000

SOURCES: National Vital Statistics Reports; *National Center for Health Statistics; Centers for Disease Control and Prevention;* New York Times; *National Adoption Information Clearinghouse. 1995 data are the latest available; IVF success statistic from 1997.*

PUBLIC HEALTH

Sloppy Feeding

Not enough precautions are being taken in the U.S. to prevent bovine spongiform encephalopathy (BSE), or mad cow disease, according to a report released January 10 by the Food and Drug Administration. The use of rendered ruminant feed, containing parts from cattle and sheep, is most likely responsible for the spread of BSE in Europe. Although no one has reported BSE in U.S. cattle, in 1997 the FDA adopted regulations to prevent an outbreak. The new FDA report reveals that almost one quarter of companies that render ruminants, along with 20 percent of FDA-licensed feed mills and 40 percent of non-FDA-licensed mills, do not properly label their products, as required. In addition, not all companies had a system to prevent ruminant products from mixing with food made from chicken, pork or fish. —*A.M.*


Bad rendering
RICHARD HAMILTON SMITH *Corbis*

Briefs from www.sciam.com/news

In December, researchers announced that ANDi, a rhesus monkey genetically modified to have a **fluorescence gene** from a jellyfish, was born. ANDi doesn't glow, but the toenails and hair follicles of his stillborn siblings did. /011201/1.html

Researchers discovered the **oldest rock**, a zircon crystal 4.4 billion years old. It suggests oceans and continents formed early in the earth's history—and that perhaps life took longer to arise than previously thought. /011101/1.html

Mitochondrial DNA found in early Australians differs from that of today's modern humans as much as Neandertal DNA differs from moderns'—indicating that the genomic disparities between Neandertals and moderns do not necessarily indicate they are different species. /010901/2.html

Many **male salmon** in the Columbia River have become female, perhaps because of pesticides and other chemicals that mimic estrogen. /121900/3.html

Sprawling into the Third Millennium

At the dawn of the 20th century, suburbia was a dream inspired by revulsion to the poverty and crowding of the cities. In the visions of architects such as Frederick Law Olmsted, there would be neighborhood parks, tree-lined streets and low-density housing free from the pollution and social problems of the cities. As the top map of the New York City metropolitan area shows, commuter suburbs had sprung up near the railway lines on Long Island and Westchester County by 1930, but further expansion was fueled in large part by the automobile. Eventually it was apparent that much of suburbia—Levittown was the popular example—was not delivering on the early promise, although for many, even Levittown must have seemed like heaven compared with the tenements of their childhood.

The extraordinary growth of car ownership in 20th-century America was made possible by abundant domestic oil, the world's largest highway system, and low taxes on vehicles and gasoline. But suburban growth would not have been nearly as great were it not for government policies that penalized cities and rewarded suburbs. For instance, federal mortgage insurance programs tended to promote new housing on outlying land rather than repair of existing city housing and, furthermore, excluded racially mixed neighborhoods that were deemed unstable. American communities have far fewer impediments to expansion than European ones: London, for instance, restricted sprawl by establishing greenbelts on its periphery.

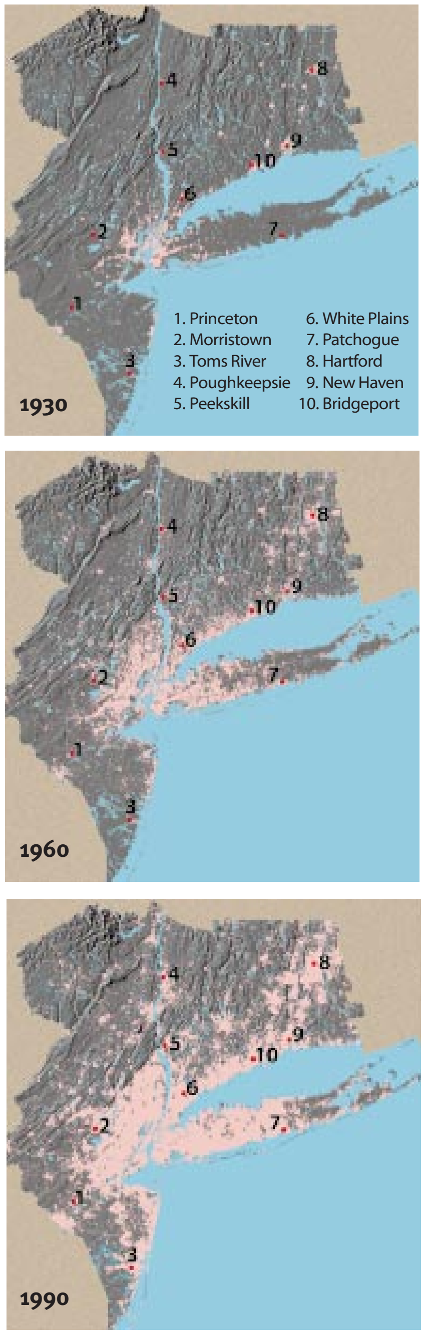
Tax deductions for mortgage interest in the U.S. have been larger than those of most other countries. Furthermore, suburban jurisdictions in the U.S. have far greater zoning powers than their foreign counterparts and use this power to reinforce low-density housing by requiring large lots, thus increasing the number of affluent taxpayers and reducing the need to supply services to needy families. Arguably, the most important stimulus to white flight out of the city was fear of crime, particularly crime by blacks—a fear reinforced by the social pathologies of public housing, where blacks and other minorities predominate. Such apprehension helps to explain why revitalization projects and improved mass-transit systems have failed to lure the middle class back to the city in large numbers.

Suburban expansion may conjure up images of aesthetic degradation and cultural sterility, but it has provided better housing for millions. In the process of suburbanization, low-income city families have also benefited because of the housing stock that became available as the middle class fled. By spreading out, U.S. cities avoided the sometimes oppressive densities of Japanese and European cities. Indeed, so great is the compaction in Tokyo that Japanese officials see deconcentration as a high priority.

Overall, however, the suburban push financially hurt cities, which saw their tax bases shrink. They were disproportionately affected by unfunded federal mandates and thus hindered in efforts to provide quality schools and reliable municipal services. Indeed, New York City's fiscal problems in the 1970s followed, and were exacerbated by, the previous decades' massive middle-class exodus into the suburbs. The exodus, rather than population growth, drove suburban proliferation: from 1970 to 1990 regional population grew by only 8 percent, but urban land increased by 65 percent. Unlike other cities, such as Detroit, New York has maintained a vibrant economy, partly because millions of immigrants, many well educated and interested in starting new businesses, have replaced the old middle class. Certain other cities as disparate as Los Angeles, Miami, San Francisco and Omaha have also benefited substantially from international migration.

Like New York, most metropolitan areas, regardless of whether the central city is dying or still vibrant, have spread outward, a significant exception being Portland, Ore., which has enforced drastic restrictions on sprawl. As a result, it accommodated a 50 percent growth in population from 1975 to the mid-1990s with only a 2 percent increase in land area. Because of the new restrictions, however, housing prices and the cost of doing business in Portland have been driven up.

—*Rodger Doyle (rdoyle2@aol.com)*



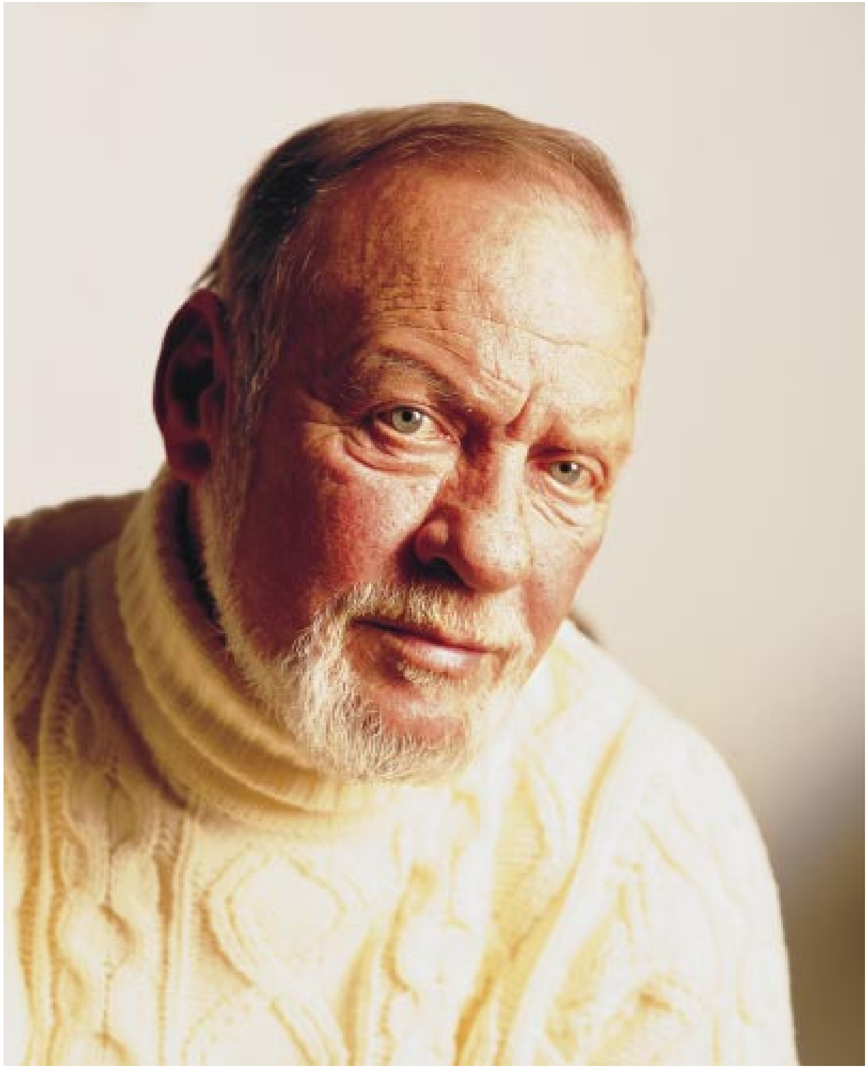
SOURCE: U.S. Geological Survey; Urban Dynamic Research Program. Maps are based on satellite images and historical records. Urban land is defined as that occupied by buildings, asphalt, concrete and suburban gardens, with a systematic street pattern and a minimum density of three houses per 2.5 acres.

DANIEL R. SECHRIST AND JANET S. C. TILLEY

ANTHROPOLOGIST_NAPOLEON CHAGNON

Fighting the Darkness in El Dorado

The embattled researcher answers a book's charges that he incited and exaggerated the violence of the Yanomamö



"I'M NOT ASHAMED OF WHAT I'VE DONE," states Napoleon Chagnon of his studies of the Yanomamö, one of the last people to be touched by modern civilization.

TRAVERSE CITY, MICH.—In 1964 a 26-year-old graduate student embarked on an expedition that would take him back in time, venturing deep into the Venezuelan jungle to study a primitive Indian tribe known as the Yanomamö. Over the years he would make more than 25 trips into remote regions of Amazonia to study these people, vividly chronicling their way of life in a record-selling book and prizewinning documentaries. Napoleon Chagnon's research catapulted the Yanomamö into the limelight as the fierce people of the rain forest, and as their ethnographer Chagnon became, as one scholar described him, the most famous anthropologist in the world, living or dead.

Today the 62-year-old Chagnon (Americanized to "SHAG-non"), clad in jeans and a khaki shirt, looks the part of the contented retiree. Indeed, the casual observer would hardly suspect that the man seated on the chenille sofa across from me, with his hands behind his head and his feet up on the coffee table, now stands accused of misrepresenting and harming—perhaps even killing—the very people he was studying. Yet in *Darkness in El Dorado,* published last fall, journalist Patrick Tierney claims that Chagnon cultivated violence among the Yanomamö and cooked his data to exaggerate their behavior. He also insinuates that Chagnon and a colleague sparked a deadly measles epidemic. "If you read more than two pages of the book, you think I'm Josef Mengele," Chagnon remarks bitterly.

With such sordid scandal swirling around him, I'm a bit surprised by his relaxed demeanor. But perhaps I shouldn't be. Napoleon Chagnon is no stranger to controversy, and he has a history of rising to the challenge.

The second of 12 children, he grew up in rural Port Austin, Mich., in a house that lacked indoor plumbing. His father, having been discharged from the military, took odd jobs as a painter, police officer, bartender and factory worker to support the family. "Most of my youth was spent with my father off working someplace," Chagnon recollects. "I didn't really get to know him." High school was "stimulus-free," he laments, and after graduating, his father handed him a small sum of money and told him he was on his own.

Chagnon secured a modest scholarship that enabled him to take an intensive eight-week course on surveying. This led to a job with the Michigan State Highway Department, where he worked for a year, saving his money to go to college. As a physics major at the University of Michigan, he had to meet certain distribution requirements, including a two-semester sequence in a social science. All he could fit into his schedule was anthropology, which he had never heard of. But it didn't take long before Chagnon was hooked: "The second week into the second course, I decided that that's what I wanted to be." He stayed on at Michigan for his Ph.D.

Once he decided to study "really primitive people," Chagnon says, he had two parts of the world to choose from: New

PETER MURPHY

Guinea or the Amazon Basin. He opted for the latter, as it was the lesser studied of the two, and initially selected a central Brazilian tribe called the Suyà. Just before leaving, however, a revolution broke out in Brazil, making fieldwork impossible. Around the same time, James Neel, a geneticist at the university, was looking into doing research in Venezuela. The two decided to conduct a multidisciplinary study of the Yanomamö—a tribe of about 27,000 Indians who live in some 300 villages spread across an area roughly the size of Texas—about whom there were only a few published accounts. "They were quite unknown at the time, but I did know they lived in both Venezuela and Brazil," Chagnon recalls. "So if Brazil was in a revolution, I would study them in Venezuela, and vice versa." Soon thereafter, the young Chagnon set off with his wife and two small children. His family stayed in Caracas for the 15-month period while he plunged deep into the rain forest in search of "primitive man."

What little Chagnon knew about the Yanomamö beforehand did not prepare him for that initial encounter, which he described memorably in his first book, *Yanomamö: The Fierce People:*

> I looked up and gasped when I saw a dozen burly, naked, sweaty, hideous men staring at us down the shafts of their drawn arrows! Immense wads of green tobacco were stuck between their lower teeth and lips making them look even more hideous, and strands of dark-green slime dripped or hung from their nostrils—strands so long that they clung to their pectoral muscles or drizzled down their chins.

He later learned that the men had taken a hallucinogenic snuff, which causes a runny nose, and that he and his missionary companion had arrived just after a serious fight between this village and a neighboring group—a fight that apparently had erupted over women. It was a pattern of violence that Chagnon would observe and report on again and again and one that would ultimately pit many of his colleagues against him.

Chagnon did not expect to see violence among the Yanomamö, nor did he anticipate that he would discover biological underpinnings to their behavior, he says. But in asserting that these conflicts arose over women and not material resources such as food, he broke with the view held by many cultural anthropologists—including those who had trained him. In that view, influenced in part by Marxist economics, material forces drive human behavior.

"Even though it was an unwanted discovery in anthropology—it was too biological—I nevertheless had to confront the fact that they were fighting over women, not scarce material resources," Chagnon recounts. In doing so, he adds, "I basically had to create and invent my own theory of society." Chagnon's Darwinian perspective on culture jibed with Harvard University scientist E. O. Wilson's 1975 treatise on animal behavior, *Sociobiology.* Chagnon—who tends to refer to his detractors as Marxists and left-wingers—thus became identified with that school of thought, which also made him unpopular among social scientists who believe that culture alone shapes human behavior.

In the years that followed, Chagnon took various academic posts and continued to return to Yanomamö territory, conducting censuses and collecting detailed genealogical data. (Appropriately enough, the Yanomamö, unable to pronounce Chagnon's name, dubbed him "Shaki"—their word for a pesky bee.) Then, in 1988, he published a paper in *Science* in which he reported that 40 percent of adult males in the 12 villages he sampled had participated in the killing of another Yanomamö; 25 percent of adult male deaths resulted from violence; and around two thirds of all people age 40 or older had lost at least one parent, sibling or child through violence.

Perhaps most stunning of all, he found that men who had killed were more successful in obtaining wives and had more children than men who had not killed. "The general principle is not so much that violence causes reproductive success. It's that things that are culturally admired and strived for are often correlated with reproductive success," Chagnon explains. "It may be wealth in one society, or political power. You don't have to be violent to have political power. But in the primitive world, where the state doesn't exist, one of the most admired skills is to be a successful warrior."

The *Science* paper came out as the Brazilian gold rush was reaching full throttle in Yanomamö territory, prompting impassioned responses from Brazilian anthropologists and human-rights activists. Portraying the Yanomamö as killers, they warned, furnished miners with a powerful means of turning the public against the Indians. Neither was Chagnon making friends in Venezuela, where his relationship with the Salesian Catholic missionaries who control the region had soured. Indeed, on a 1991 trip to a Yanomamö village he had visited on friendly terms several times before, the headman threatened Chagnon with his ax, claiming that Chagnon had killed their babies and poisoned their water. The headman later revealed that Salesian missionaries had spread these lies.

"The Salesians don't want anybody in with the Yanomamö whom they don't have control over," observes University of New Mexico anthropologist Kim Hill, an Amazon specialist. He further notes that there aren't many researchers in that area who are not openly allied with the missionaries. "Nap was the wild card. He wouldn't play by their rules, and he openly opposed them on some of their policies. I think they just decided they were going to make damn sure that he never came back again." (Raised Catholic, Chagnon recalls with irony that his mother had wanted him to enter the priesthood. "I reassured her that although I hadn't become a priest, I'm very well known in the highest circles of the Catholic Church.")

Chagnon retired in 1999 from the University of California at Santa Barbara after realizing that he probably would not be able to return to Yanomamö territory. On his last three attempts, officials in Boa Vista and Caracas had denied him the necessary permits. So he and his wife, Carlene, moved back to Michigan, into an airy, sun-filled house tucked away in the woods, on the outskirts of Traverse City, a resort town bordering Lake Michigan. There Chagnon figured he would work on a new book and maybe do some bird hunting with his dog, Cody.

That reverie was shattered, however, when a book brimming with explosive allegations leveled against Chagnon and other Yanomamö researchers came out last November. Specifically, Tierney's *Darkness in El Dorado* charges Chagnon with inciting warfare, staging films and falsifying data on the Yanomamö in order to create the myth of "the fierce people." In reality, Tierney suggests, the Yanomamö are generally fragile and fearful. The violence that did occur, he asserts, erupted over the windfall of machetes and axes Chagnon distributed in exchange for their cooperation. He further accuses Chagnon of tawdry activities such as demanding a Yanomamö wife and indulging in drugs. Tierney also strongly implies that Chagnon and the geneticist Neel, who died in February of last year, sparked a deadly measles epidemic among the Indians, claiming perhaps thousands of lives, by using an outmoded vaccine known to have potentially severe side effects.

The famed anthropologist denies it all. The idea that his gifts of steel goods (given to make their daily tasks easier) caused the warfare he observed is preposterous, he says, noting that the Yanomamö have a history of violence that predates his arrival. Gift exchange is par for the course if one wants to study the Yanomamö, he insists. Even so, he adds, his contributions hardly compare to the number of machetes doled out at the missions.

I read Chagnon the passage describing his purported request for a Yanomamö wife. "That's so goddamn crazy," he retorts, explaining that the story is a distortion of his referring to a girl as his cross-cousin—a kinship term also used for "wife" in the Yanomamö language. The claim that he staged his award-winning documentaries is likewise false, Chagnon maintains. And with regard to drugs, he says he took the ceremonial snuff only once—to reassure some Indians who had been threatened by a missionary with being thrown into a chasm of fire if they continued to worship their "demons."

As to mischaracterizing the Yanomamö as fierce, John Peters, a sociologist at Wilfred Laurier University in Ontario who spent 10 years among the Brazilian Yanomamö, notes that the Indians proudly describe themselves that way. "They are a very passionate people," he observes, who are willing to go to extremes in "their anger and fury and their sense of justice." Moreover, according to Hill, who has posted a scathing critique of *Darkness* on the Internet, the only other South American tribes in which Chagnon's hypothesis has been tested—the Waorani and the Ache—appear to link "killers" and reproductive success, too. (Hill, however, interprets the data to indicate that women are attracted not to killers but to men who are big, strong and healthy—traits that also make them more likely to be successful at killing during a raid.)

"Tierney is not a scientist," Chagnon bristles, referring to the journalist's suggestion that he adjusted his data to fit his theory. "No serious scientist has ever doubted my data."

Tierney's measles argument has also drawn criticism. Anthropologist Thomas N. Headland of the Summer Institute of Linguistics in Dallas obtained documents from Protestant missionaries indicating that the measles outbreak preceded the arrival of Chagnon and Neel. And various vaccine experts argue that although the side effects of the Edmonston B vaccine may have been severe, without it, many more Yanomamö would have died.

"YOU THINK I'M JOSEF MENGELE" **if you read *Darkness*, Chagnon complains.**

Yet even those who have defended him so vigorously acknowledge that Chagnon does not have a sterling record. Around 1991 he started collaborating with Charles Brewer-Carías, a controversial Venezuelan naturalist and gold miner, and Cecilia Matos, the ill-reputed mistress of Venezuela's then president, Carlos Andres Pérez. Chagnon was being prevented from doing research at the time, and going this route was his last resort, recalls University of Nebraska anthropologist Raymond Hames, who has worked with Chagnon. Still, "it was really unwise," he says. And Hill notes that some Yanomamö with whom he has spoken complain that, considering the fact that Chagnon made his career off working with them, they have received very little in return.

For his part, Chagnon is staunchly unapologetic about the way he conducted his life's work. "I'm not ashamed of what I've done. I think that I've produced one of the most significant and rare sets of archives and anthropological data that could have possibly been collected in this kind of a society," he declares. Although their lands are protected (thanks in large part, Chagnon says, to the influence he and Brewer-Carías had on Pérez), their culture is changing rapidly. "It may turn out that future anthropologists will have to rely entirely on archived materials—the sort I collected—to figure out some of the questions they want answers to about the primitive world. People like the Yanomamö aren't going to be around very long."

As of press time, the American Anthropological Association task force that had been appointed to determine whether the allegations made in *Darkness* warrant formal investigation was still deliberating. The organization is also reviewing its code of ethics and guidelines for research. In Venezuela, the government has issued a moratorium on all research in indigenous areas.

It is too soon to know if the controversy will be anthropology's Armageddon. But Chagnon himself seems destined to remain the lightning rod. He was one of the first people to explore the connection between biology and behavior, "at a time when it was politically very unpopular to do so," Hill reflects. "And he's still paying the price for that."

—Kate Wong

PETER MURPHY

Plenty to Sniff At

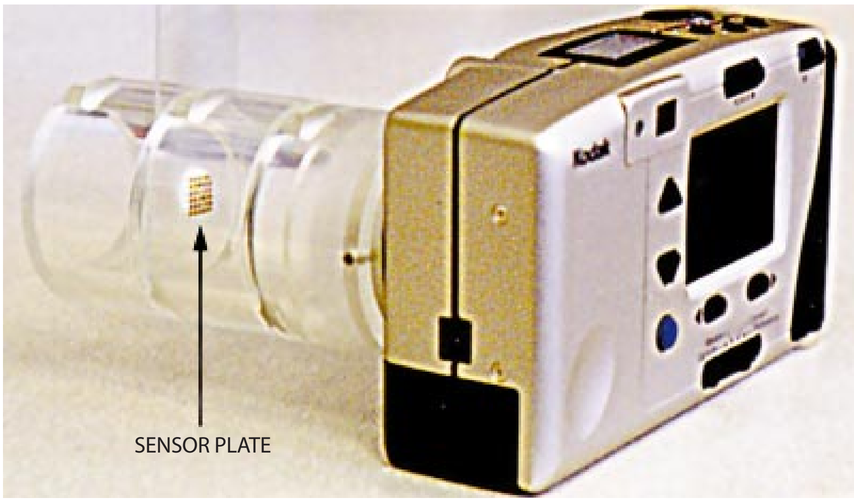
Smaller and more sensitive electronic noses open up new applications

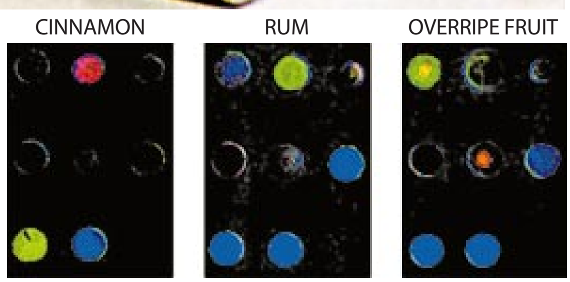
Your dog knows in a sniff if you have been cavorting with the despised feline next door or fingering his favorite treats. He knows because his nose is replete with more than 100,000 sensory cells that bind to chemicals wafting through the air. Humans have harnessed this fine canine sense for sniffing out bombs, drugs and fugitives, but there are many smelly jobs for which Fido won't do—including discerning if the food on the conveyor belt at the dog food plant smells exactly the same as it did yesterday. Or if a pigsty is too fetid, or treated sewage is odor-free. Human testers traditionally have pulled such pungent duties.

Electronic noses are now poised to fill these roles. The devices are collections of diverse detectors analogous to the sensing cells in a hound's nose. Each aroma pumped across the array induces a unique pattern of responses that is fed into a computer. The electronic nose "recognizes that pattern, draws it from its memory banks and says, 'Aha, that's root beer or a rose or some other vapor that I've smelled before,'" explains chemist David R. Walt of **Tufts University**.

Such electronic noses are already at work in industry, detecting bad batches of food and drink as well as substandard packaging and recycled goods, to name just a few applications. But new advances in miniaturization and sensitivity promise to broaden their scope; they may eventually identify chemical spills, diagnose strep throat, hunt for truffles and even keep toast from burning.

In England in the early 1980s George H. Dodd, then at the **University of Warwick**, and Krishna C. Persaud, currently at the **University of Manchester Institute of Science and Technology**, introduced the array concept of aroma detection. Their initial research relied on metal oxide sensors, which worked properly only at about 300 degrees Celsius; these are suited "to measure the mixture of gases in, say, the carburetor of a motorcar," Persaud explains, but are potentially inappropriate to evaluate more delicate fragrances, as in coffee or perfumes.





ODORS are recorded visually by a camera after wafting past metal-ion-based dyes arrayed on a sensor plate. Odor molecules bond to the ions and produce different color patterns (*right*).

K. S. SUSLICK AND N. A. RAKOW *University of Illinois at Urbana-Champaign*

Most electronic noses today function under gentler conditions. They exploit the fact that when vapor binds to a polymer, key attributes of the polymer, such as its conductance, change in detectable ways. One of the oldest companies on the electronic nose scene, founded in 1994, is **Osmetech** (formerly **AromaScan**), which adopted the conducting polymer technology that Persaud helped to develop. Osmetech's market is broad—its noses have been used to sniff out mold in grain and off-odor toothpaste ingredients. Now the Osmetech nose is being tested for diagnostic detection of bacteria that cause urinary tract infection and pneumonia.

Cyrano Sciences, which manufactures a handheld electronic nose, relies on a different polymer technology, one that is licensed from the **California Institute of Technology**. When these polymers swell on interaction with a vapor, conducting material in the polymer moves with the swelling, altering an electrical signal. Because the conducting material is added to the polymer, just about any plastic is fair game as a sensor—vastly increasing the number of suitable sensor materials for nose engineers. The Cyranose 320 retails for about $8,000 (compared with tens of thousands of dollars for typical benchtop noses performing comparable tasks) and is the size of an old walkie-talkie. The company is targeting markets in quality control for food, packaging, cosmetics and environmental monitoring.

All told, more than a dozen companies sell electronic noses—including **Alpha MOS**, **Hewlett-Packard** and **Applied Sensor**—and the current annual market is estimated to be in the low tens of millions of dollars. Some of the most intriguing uses so far aren't commercial, however; in 1995 a nose that Persaud helped to develop went on board the Mir Space Station. "I think this was the first electronic nose in space," he chuckles. It turned out that the nose could track subtle environmental changes in the capsule—as well as not so subtle ones, such as the occasional fire. This year the **Jet Propulsion Laboratory** in Pasadena, Calif., placed on a space shuttle a nose designed to detect harmful gases (happily, none were found).

Unlike a dog's nose, the electronic noses now on the market get by with a mere handful of sensors. Nathan S. Lewis of Caltech, who developed the technology licensed by Cyrano, puts it this way: "A dog has a big brain because it doesn't know what it's supposed to smell tomorrow. But if the only thing I care about is burned toast, then I'm not going to have to have a very big algorithm." The latter point is good news for the nose industry. For simple jobs, the existing technology will probably suffice. From there it's just a matter of getting it small enough and cheap enough for widespread use.

Lewis's research may offer a solution. His composite polymers are amenable to microchip fabrication. "We have chips that have several hundred different pixels on them, each one with a different polymer. They're tiny—they're a few millimeters by a few millimeters," Lewis says. When the detection electronics, processing power and a micromachine pump to deliver the vapor are all included, Lewis envisions a device that could eventually be as small as a thumbnail.

Unfortunately, polymer-based electronic noses often miss the smelliest smells: small amines and thiols responsible for fishy, skunky and rotten-egg odors, all of which interact poorly with most polymers. Lewis recently crafted composite polymers that will detect amines, but Kenneth S. Suslick of the **University of Illinois** has been working on a different kind of chip, based, he says, on his insight that "everything that binds to metal ions really stinks." He has developed inks based on organometallic compounds that change color when bound by vapor molecules—analogous to the iron heme in hemoglobin that gives oxygen-rich blood its scarlet hue—and can be printed on chips. "Our sensitivities are, at least for amines and most thiols, comparable to or better than the human nose," he says. This spring Suslick plans to launch a company to be called **ChemSensing, Inc.**, to advance his "smell-see" technology into the commercial realm.

HANDHELD E-NOSE called Cyranose relies on polymers that swell in the presence of vapor.

One of the biggest challenges for the future of electronic noses is detecting complex odors against an intricate backdrop. For example, Julian W. Gardner of the University of Warwick has designed a nose that can routinely distinguish among different types of bacteria in a lab culture. But getting the nose to diagnose staph versus strep infections by sniffing a patient's breath is another matter altogether. Sensitivity and resolution are crucial to pull a small signal from such a messy background.

One answer is redundancy: canines achieve sensitive and discriminating olfaction using many replicates of about 1,000 different receptor types. It's possible to squeeze many of the same sensors onto a chip. Tufts University's Walt prefers fiber optics. In a bundle less than half a millimeter thick, he makes tens of thousands of smell sensors by placing a polymer bead doped with fluorescent dye at each fiber end. The binding of vapor molecules to the polymers shifts the light emitted by the dyes, forming a color signature—a technology licensed by **Illumina** in San Diego. This method can detect the presence of explosives vapor in the low parts per billion—nearly doglike.

Others suggest that attempts at replicating the olfactory system may be futile. "The problem is, [an array] doesn't give you an instrument. You can't calibrate them, because the sensors are not specific," contends Edward J. Staples, managing director of **Electronic Sensor Technology** in Newbury Park, Calif. Staples argues that the workhorses of the analytical lab—gas chromatography and mass spectrometry—beat sensor arrays in specificity, sensitivity and quantitation. His zNose is a portable gas chromatograph/mass spectrometer instrument that uses sound waves to detect volatile molecules. It sells for less than $20,000 and can finish an analytical run in 10 seconds. It's being used for rapid quality control in breweries and wineries, including **Sutter Home**. "You can set it right on a table and quantitate the chemistry around you," Staples says.

In truth, there is probably room for both the zNoses and the e-noses. There are potential markets for cheap and small devices (think toasters)—a tough row to hoe for gas chromatographs and mass specs but well suited to electronic noses of the world. And there are potential markets for precise quantitation (think process control)—an area in which electronic noses may always lag. "A fast, cheap, front-end screen is where I see electronic noses," Gardner says. "We're at the early stages of the technology. It's hard to predict which [approach] will win, but if you can do it for under $100 and make it work, then you'll be a winner." *—Mia Schmiedeskamp*

MIA SCHMIEDESKAMP is a freelance science writer based in Seattle.

A Nose for Taste

Next up: an electronic tongue

Electronic noses are good at sniffing the air, but there are plenty of interesting substances to detect in solution, too, especially in medical diagnostics and environmental monitoring. The electronic "taste" field is even younger than the still green electronic nose field. But researchers are applying lessons learned from noses to tackle liquids.

There are already many tests to determine the components of a solution, of course, but most rely on parallel laboratory workups that can be expensive, time-consuming and sample-hungry. "We would like to be able to do a whole battery of tests with a small sample of a liquid—a drop of water or a drop of blood," explains Dean P. Neikirk of the University of Texas at Austin. "Wouldn't it be neat if a primary care physician or emergency medical technician could get a whole panel of results back in almost real time?"

Neikirk and his colleagues and a new company called Labnetics are busy working on a disposable tongue chip that consists of sensor beads in 150-micron-wide wells. The beads change color when exposed to different types of liquids, revealing the presence of acids, sugars and the like, corresponding to the limited sensing ability of the human tongue. Such technology has the potential for even more specificity if, say, antibodies to various organisms are linked to the beads. Others want to move the technology closer to the electronic nose model. Julian W. Gardner of the University of Warwick is developing a combination of tongue and nose; David R. Walt of Tufts University is working to apply broad electronic-nose-style pattern recognition to sensing in complex solutions. "It would be more like a nose that works in water than a tongue," he says. *—M.S.*

CYRANO SCIENCES, INC.

To Protect and Self-Serve

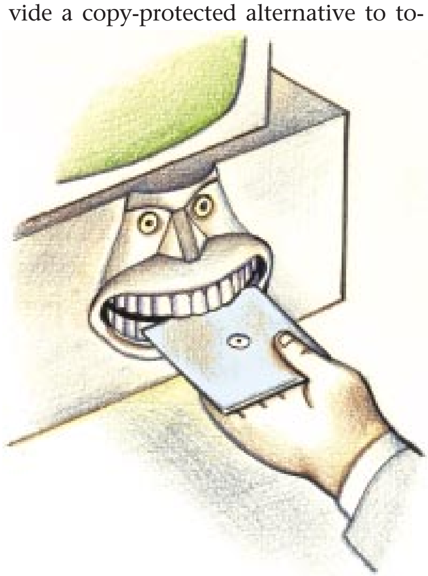
Will we see hard disks with copy-preventing codes?

LONDON—Coming down hard and fast on any organization that threatens technological liberty is an ancient geek pastime of unusual ferocity. Last December the U.K.-based online news service *The Register* broke the story that a consortium of companies—Intel, IBM, Toshiba and Matsushita—were plotting to include a scheme known as content protection for recordable media (CPRM) in the next-generation standard for computer hard disks. The companies responded almost immediately by saying that the scheme was intended to apply only to removable media, not to fixed hard disks. It seems clear, however, that the idea is indeed at least being considered by the technical committee that decides the hard-disk standard. Given that the firms behind the plan also invented the regional encoding that prevents a DVD made for one part of the world from playing in another, techies are worried. They fear that the result would be crippled, generic, mass-market hardware, its technology bent to accommodate financial interests.

The difference is that mass-market electronics devices are typically sealed boxes. CD recorders, MiniDisc players and DVD machines are not devices that end users generally can program. For probably most consumers, the same is (sadly) true of computers. But this most versatile of tools is always partly open.

CPRM could change that. The plan, which is still being worked out, would issue every hard disk its own identification number, to be authenticated before compliant files are run, moved or copied. In a widely distributed posting, John Gilmore, co-founder of the Electronic Frontier Foundation, described the idea as "the latest tragedy of copyright mania," saying you wouldn't be able to make backup copies of your own data or of commercial software without third-party permission. Free-software guru Richard Stallman predicted in another *Register* story that CPRM would kill off open-source software by fragmenting it into two camps, one supporting the copy-protection regime and one not. Andre Hedrick, who represents the Linux (or GNU-Linux, as Stallman insists, because Linux incorporates aspects of GNU, a free software clone of UNIX) community on the technical committee considering the idea, proposed changes to the implementation that would make turning on the copy-protection system optional for users.

Even if we grant that, for the moment, encryption is unlikely to take up residence in generic PC hardware, the reason for the furor is that the industry has taken a number of steps down this path already. Efforts by the music industry to put together the secure digital music initiative (SDMI), Hollywood-inspired DVD encoding, copy protection embedded in MiniDiscs—all are examples of technology that has been deliberately crippled. SDMI, for example, is intended to provide a copy-protected alternative to today's open MP3, despite the fact that the popularity of music online depends on its being easily shared. DVD encoding has become an ongoing technical battle between the studios, who want to assert regional control, and frustrated consumers, particularly in Europe, who want to see movies sooner and enjoy the many features on American disks that are missing on European ones. The result is that many Europeans obtain devices hacked to play all regions' disks.



DAVID SUTER

MiniDiscs have embedded copy protection so that you can't make more than one generation of digital copies. You can certainly go on churning out digital copies from the original. But you can't record your own material and hand out your MiniDiscs with a note that they can be freely copied, because the players themselves won't allow it. The same applies to today's mass-market audio CD recorders.

The presumption behind this copy protection is that ordinary consumers don't create their own material but use their machines only to create illegal copies. In my own case, that's not true: the recordings on the album I released in 1980 when I was working as a folksinger belong to me, and so generally applied copy-protection schemes in fact deprive me of the choice of how I want the music distributed. In a very real sense, corporate rights holders are attempting, more or less out of public oversight, to extend the lock they currently have on physical-world distribution to electronic media. The major record companies claim that they could not afford to invest in promoting and marketing bands if today's electronic media continue to be so hospitable to unauthorized copying. But conversely, small-time musicians often remain small-time not through lack of talent but through lack of access to radio play, record stores and audiences.

Certainly, creators of intellectual property must make enough of a living to be able to afford being creators. The public has a right to access ideas and their expression, too. Copyright laws have traditionally balanced these two needs. But a regime under which consumers would lose control even over generic computer hardware would upend the balance. Worse than that, CPRM uses the technology to embed the interests of powerful organizations without public discussion. Lawrence Lessig, a professor of law at Stanford University, points out in his book *Code and Other Laws of Cyberspace* that technology, far from being neutral, is designed with assumptions that wind up controlling what we do and how. In this case, what is being embedded—in removable media, if not permanent media—is the presumption that we are guilty until proven innocent. —*Wendy M. Grossman*

WENDY M. GROSSMAN is proud that she bought a hacked DVD player.

Making Sense of Taste

How do cells on the tongue register the sensations of sweet, salty, sour and bitter? Scientists are finding out—and discovering how the brain interprets these signals as various tastes

by David V. Smith and Robert F. Margolskee

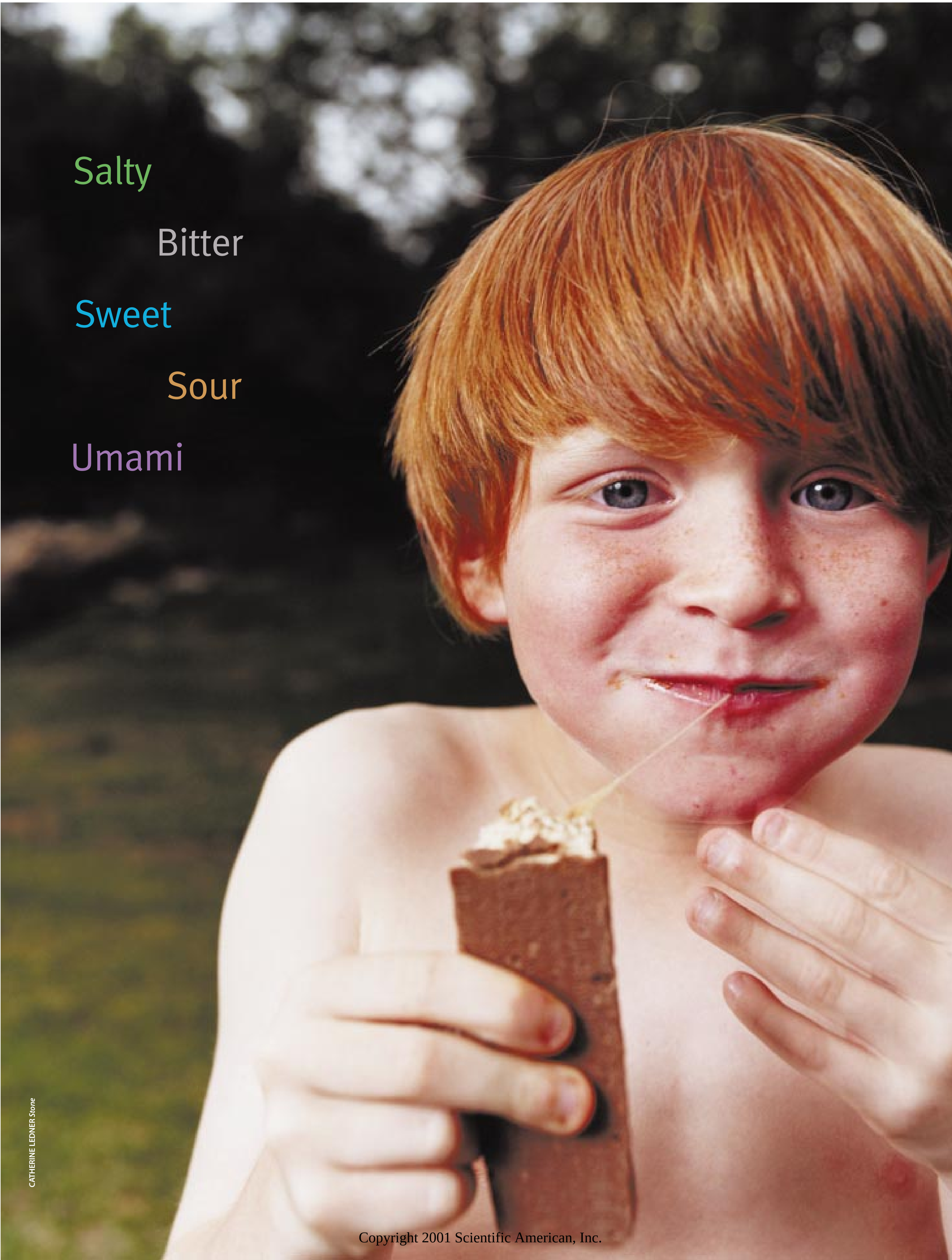
Bite into a gooey candy bar, and what mouth sensations do you experience? Mmmm ... chewy, sweet, creamy—with the signature, slightly bitter richness of chocolate as you close your mouth to swallow and the aroma wafts up into your nasal passages. Indeed, smell is an important component of flavor, as anyone with a severe head cold can testify.

Flavor is a complex mixture of sensory input composed of taste (gustation), smell (olfaction) and the tactile sensation of food as it is being munched, a characteristic that food scientists often term "mouthfeel." Although people may use the word "taste" to mean "flavor," in the strict sense it is applicable only to the sensations arising from specialized taste cells in the mouth. Scientists generally describe human taste perception in terms of four qualities: saltiness, sourness, sweetness and bitterness. Some have suggested, however, that other categories exist as well—most notably *umami,* the sensation elicited by glutamate, one of the 20 amino acids that make up the proteins in meat, fish and legumes. Glutamate also serves as a flavor enhancer in the form of the additive monosodium glutamate (MSG).

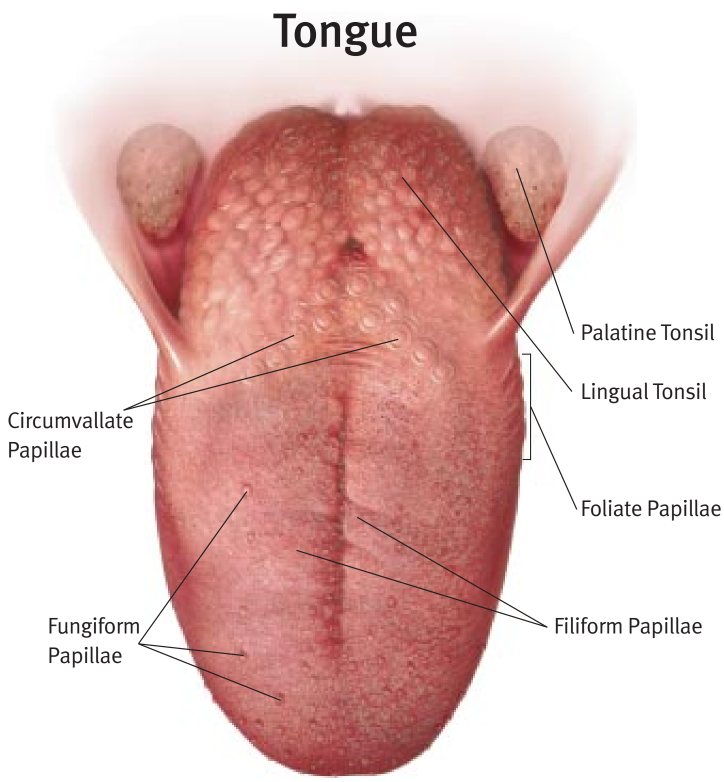
Within the past several years, researchers such as ourselves have made strides in elucidating exactly how taste works. Neurobiologists, including one of us (Margolskee), have identified proteins that are crucial for taste cells to detect sweet and bitter chemicals and have found that they are very similar to related proteins involved in vision. Other scientists, including the other one of us (Smith) and his co-workers, have obtained evidence that nerve cells, or neurons, in the brain can respond to more than one type of taste signal, just as those that process visual stimuli from the retinas can react to more than one color. The findings are illuminating what has historically been one of the least understood senses.

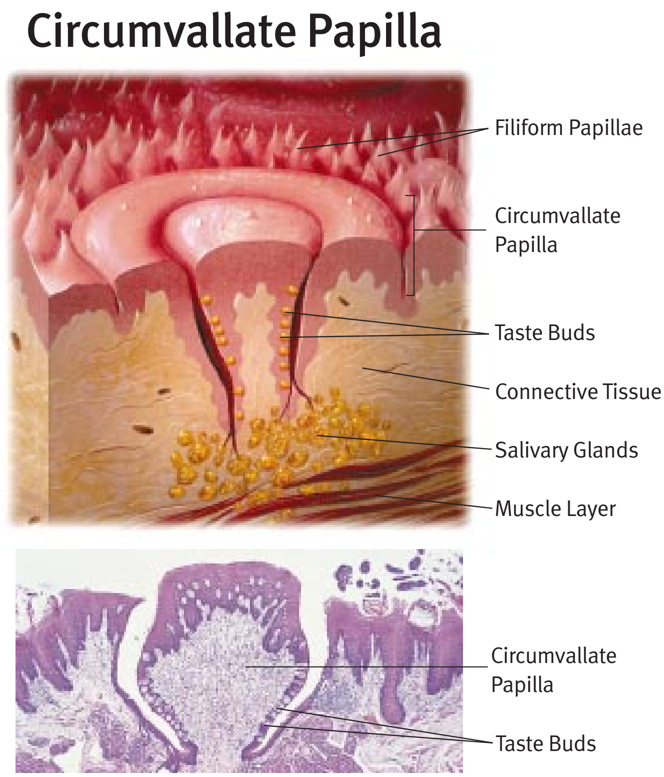
The Taste Detectors

Taste cells lie within specialized structures called taste buds, which are situated predominantly on the tongue and soft palate. The majority of taste buds on the tongue are located within papillae, the tiny projections that give the tongue its velvety appearance. (The most numerous papillae on the tongue—the filiform, or threadlike, ones—lack taste buds, however, and are involved in tactile sensation.) Of those with taste buds, the fungiform ("mushroomlike") papillae on the front part of the tongue are most noticeable; these contain one or more taste buds. The fungiform papillae appear as pinkish spots distributed around the edge of the tongue and are readily visible after taking a drink of milk or placing a drop of food coloring on the tip of the tongue. At the back of the tongue are roughly 12 larger taste bud–containing papillae called the circumvallate ("wall-like") papillae, which are distributed in the shape of an inverted V. Taste buds are also located in the foliate ("leaf-



CATHERINE LEDNER *Stone*





ANATOMY OF TASTE shows the four types of projections called papillae on the human tongue, the structure of one papilla—the circumvallate papilla—and details of human taste buds. (The circumvallate papilla and the taste bud are shown as both diagrams and micrographs.) Only the circumvallate, foliate and fungiform papillae bear taste buds. During chewing, chemicals

like") papillae, small trenches on the sides of the rear of the tongue.

Taste buds are onion-shaped structures of between 50 and 100 taste cells, each of which has fingerlike projections called microvilli that poke through an opening at the top of the taste bud called the taste pore. Chemicals from food termed tastants dissolve in saliva and contact the taste cells through the taste pore. There they interact either with proteins on the surfaces of the cells known as taste receptors or with porelike proteins called ion channels. These interactions cause electrical changes in the taste cells that trigger them to send chemical signals that ultimately result in impulses to the brain.

The electrical changes in the taste cells that prompt signals to the brain are based on the varying concentrations of charged atoms, or ions. Taste cells, like neurons, normally have a net negative charge internally and a net positive charge externally. Tastants alter this state of affairs by using various means to increase the concentration of positive ions inside taste cells, eliminating the charge difference [*see illustrations on pages 36 and 37*]. Such depolarization causes the taste cells to release tiny packets of chemical signals called neurotransmitters, which prompt neurons connected to the taste cells to relay electrical messages.

Studies of animals and people, however, show that there is not always a strict correlation between taste quality and chemical class, particularly for bitter and sweet tastants. Many carbohydrates are sweet, for instance, but some are not. Furthermore, very disparate types of chemicals can evoke the same sensation: people deem chloroform and the artificial sweeteners aspartame and saccharin sweet even though their chemical structures have nothing in common with sugar. The compounds that elicit salty or sour tastes are less diverse and are typically ions.

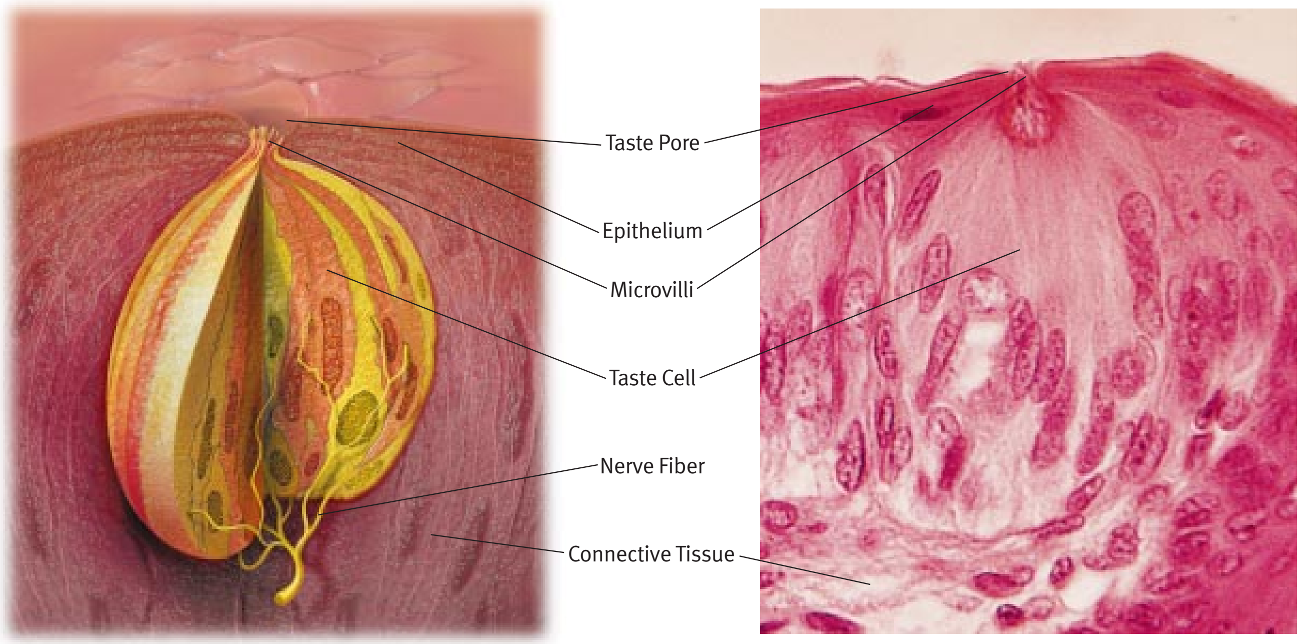
The chemicals that produce salty and sour tastes act directly through ion channels, whereas those responsible for sweet and bitter tastes bind to surface receptors that trigger a bucket brigade of signals to the cells' interiors that ultimately results in the opening and closing of ion channels. In 1992 Margolskee and his colleagues Susan K. McLaughlin and Peter J. McKinnon identified a key member of this bucket brigade. They named the molecule "gustducin" because of its similarity to transducin, a protein in retinal cells that helps to convert, or transduce, the signal of light hitting the retina into an electrical impulse that constitutes vision.

Gustducin and transducin are both so-called G-proteins, which are found stuck to the undersides of many different types of receptors. (The name "G-protein" derives from the fact that the activity of such proteins is regulated by a chemical called guanosine triphosphate, GTP.) When the right tastant molecule binds to a taste cell receptor, like a key in a lock, it prompts the subunits of gustducin to split apart and carry out biochemical reactions that ultimately open and close ion channels and make the cell interior more positively charged.

In 1996 Margolskee and colleagues Gwendolyn T. Wong and Kimberley S. Gannon used mice they genetically engineered to lack one of gustducin's three subunits to demonstrate that the G-protein is crucial for tasting bitter and sweet compounds. Unlike normal mice, the altered mice did not prefer sweet foods or avoid bitter substances: they did not avidly drink highly sweetened water and instead drank solutions of very bitter compounds as readily as they

KEITH KASNOT (*illustrations*); BIOPHOTO ASSOCIATES/PHOTO RESEARCHERS, INC. (*papilla*); PHOTO RESEARCHERS, INC. (*taste buds*)

Taste Bud



from food called tastants enter the taste pores of taste buds, where they interact with molecules on fingerlike processes called microvilli on the surfaces of specialized taste cells. The interactions trigger electrochemical changes in the taste cells that cause them to transmit signals that ultimately reach the brain. The impulses are interpreted, together with smell and other sensory input, as flavors.

did plain water. The researchers also showed that key nerves in the mice lacking gustducin had a reduced electrical response to sweet and bitter tastants but could still respond to salts and acidic compounds.

Last year two groups of scientists—one led jointly by Charles S. Zuker of the Howard Hughes Medical Institute (HHMI) at the University of California at San Diego and by Nicholas J. Ryba of the National Institute of Dental and Craniofacial Research, and the other led by HHMI investigator Linda B. Buck of Harvard Medical School—identified in mice and humans the actual receptors that bind to bitter tastants and activate gustducin. The teams found that the so-called T2R/TRB receptors are part of a family of related receptors that is estimated to have between 40 and 80 members.

Zuker and Ryba's group inserted the genes that encode two of these mouse taste receptors, mT2R5 and mT2R8, into cells grown in the laboratory and found that the engineered cells became activated when they were exposed to two bitter compounds. The researchers noted that in particular strains of mice a specific version of the gene for mT2R5 tended to be handed down along with the ability to sense the bitterness of the antibiotic cycloheximide, a further indication that the genes for the T2R receptors were responsible for detecting bitter substances. Scientists are now searching for the receptors that detect sweet compounds.

Researchers are also studying a receptor that might be responsible for a taste Japanese scientists call *umami*, which loosely translates into "meaty" or "savory." In 1998 Nirupa Chaudhari and Stephen D. Roper of the University of Miami isolated a receptor from rat tissue that binds to the amino acid glutamate and proposed that it underlies the *umami* taste.

Other researchers, however, are still skeptical that *umami* constitutes a fifth major taste as significant as sweet, sour, salty and bitter. Although the taste of glutamate might be a unique sensation, only the Japanese have a word for it.

But taste is much more than just receptors for the four (or five) primary tastants and the biochemical interactions they induce in taste cells. Although we tend to think of taste information in terms of the qualities of salty, sour, sweet and bitter, the taste system represents other attributes of chemical stimuli as well. We sense the intensity of a taste and whether it is pleasant, unpleasant or neutral. Neurons in the taste pathway record these attributes simultaneously, much as those in the visual system represent shape, brightness, color and movement. Taste neurons often respond to touch and temperature stimuli as well.

Taste in the Brain

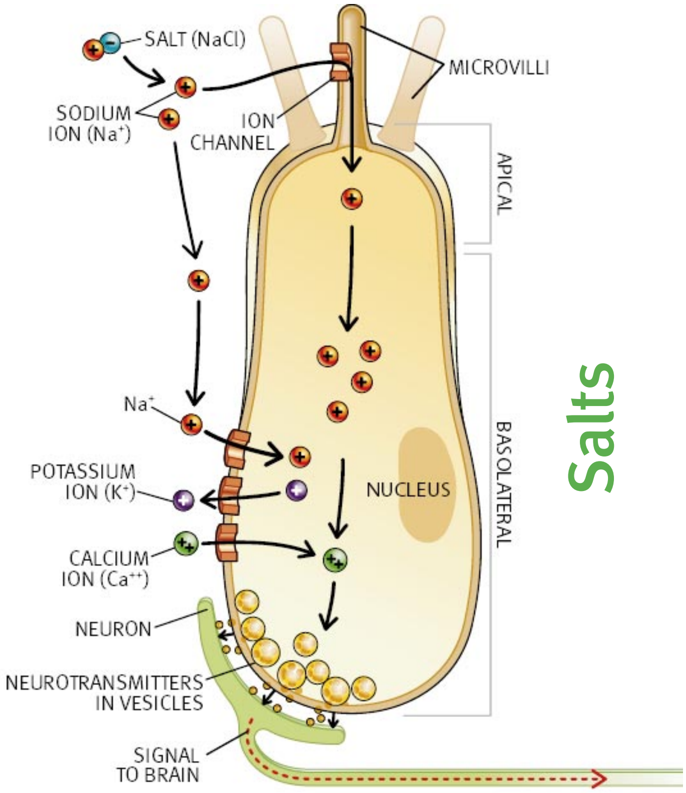
Scientists have gone back and forth on whether individual neurons are "tuned" to respond only to a single tastant such as salt or sugar—and therefore signal only one taste quality—or whether the activity in a given neuron contributes to the neural representation of more than one taste. Studies by one of us (Smith) and those of several other colleagues show that both peripheral and central gustatory neurons typically respond to more than one kind of stimulus. Although each neuron responds most strongly to one tastant, it usually also generates a response to one or more other stimuli with dissimilar taste qualities.

How then can the brain represent

Taste Fundamentals

The stimuli that the brain interprets as the basic tastes—salty, sour, sweet, bitter and, possibly, *umami*—are registered via a series of chemical reactions in the taste cells of the taste buds. The five biochemical pathways underlying each taste quality are depicted here in separate taste cells solely for clarity. In reality, individual taste cells are not programmed, or "tuned," to respond to only one kind of taste stimulus.

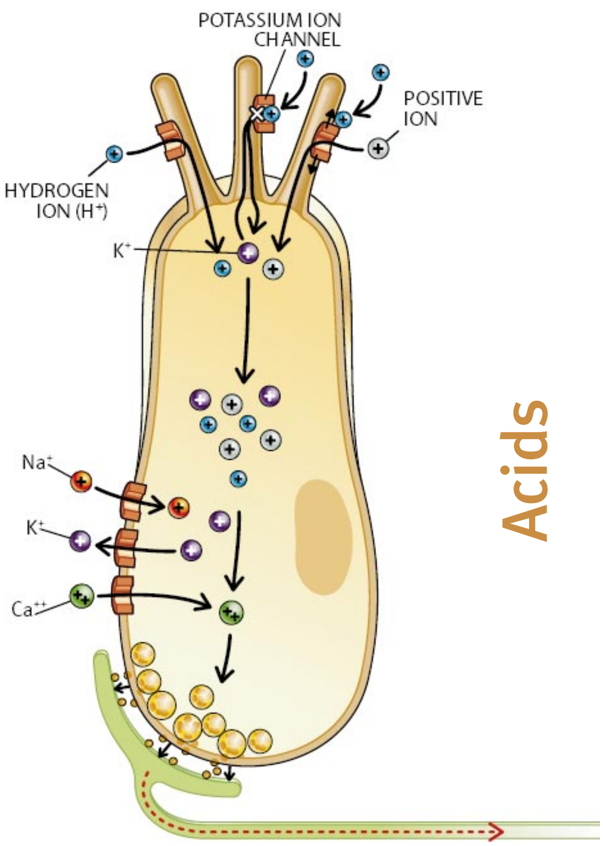
Taste Cell

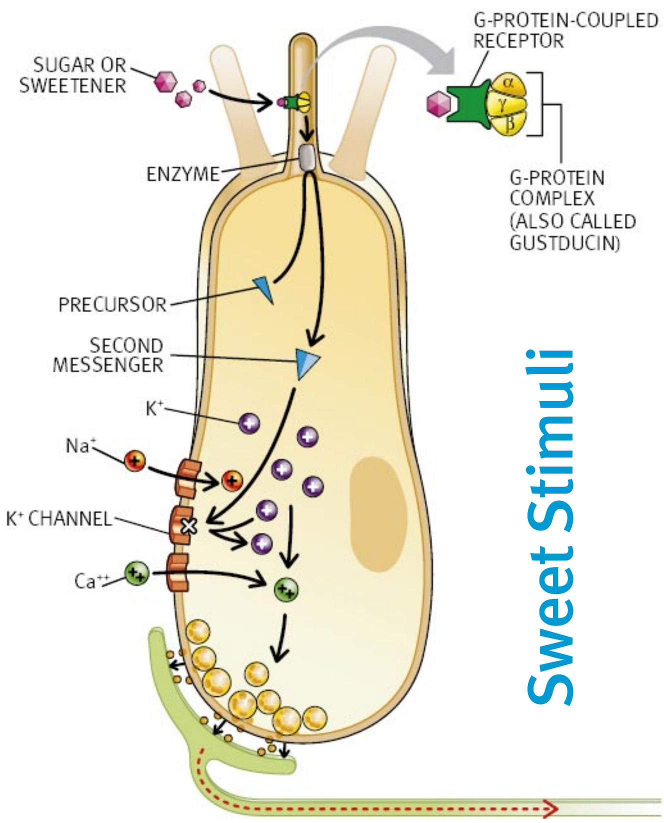


SALTS, such as sodium chloride (NaCl), trigger taste cells when sodium ions (Na^+) enter through ion channels on microvilli at the cell's apical, or top, surface. (Sodium ions can also enter via channels on the cell's basolateral, or side, surface.) The accumulation of sodium ions causes an electrochemical change called depolarization that results in calcium ions (Ca^{++}) entering the cell. The calcium, in turn, prompts the cell to release chemical signals called neurotransmitters from packets known as vesicles. Nerve cells, or neurons, receive the message and convey a signal to the brain. Taste cells repolarize, or "reset," themselves in part by opening potassium ion channels so that potassium ions (K^+) can exit.

ACIDS taste sour because they generate hydrogen ions (H^+) in solution. Those ions act on a taste cell in three ways: by directly entering the cell; by blocking potassium ion (K^+) channels on the microvilli; and by binding to and opening channels on the microvilli that allow other positive ions to enter the cell. The resulting accumulation of positive charges depolarizes the cell and leads to neurotransmitter release.

SWEET STIMULI, such as sugar or artificial sweeteners, do not enter taste cells but trigger changes within the cells. They bind to receptors on a taste cell's surface that are coupled to molecules named G-proteins. This prompts the subunits (α, β and γ) of the G-proteins to split into α and βγ, which activate a nearby enzyme. The enzyme then converts a precursor within the cell into so-called second messengers that close potassium channels indirectly.





JARED SCHNEIDMAN DESIGN

various taste qualities if each neuron responds to many different-tasting stimuli? Many researchers believe it can do so only by generating unique patterns of activity across a large set of neurons.

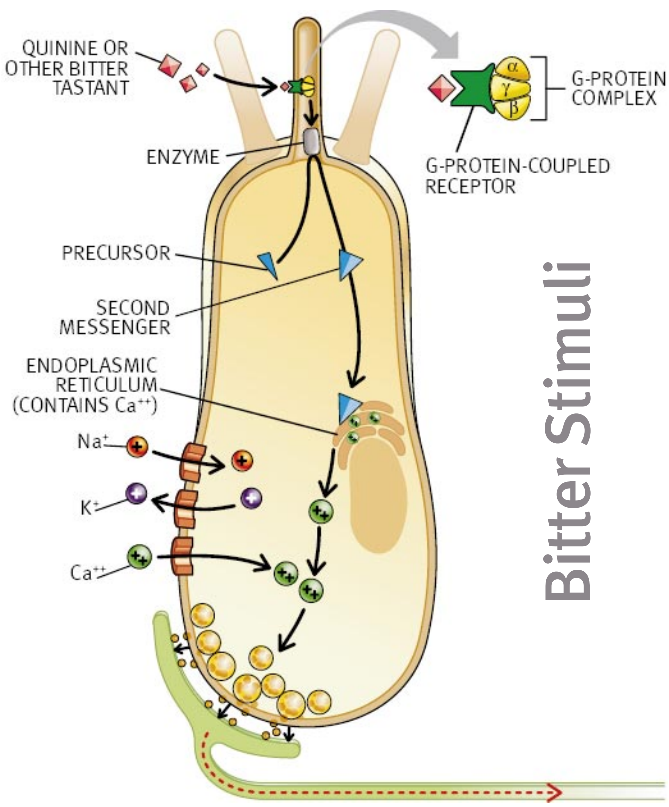
This thinking represents a "back to the future" movement among taste researchers. The very first electrophysiological studies of gustatory sensory neurons, done in the early 1940s by Carl Pfaffmann of Brown University, demonstrated that peripheral neurons are not specifically responsive to stimuli representing a single taste quality but instead record a spectrum of tastes. Pfaffmann suggested that taste quality might be represented by the pattern of activity across gustatory neurons because the activity of any one cell was ambiguous. But in the 1970s and 1980s several scientists began to accumulate data indicating that individual neurons are tuned maximally for one taste. They interpreted this as evidence that activity in a particular type of cell represented a given taste quality—an idea they called the labeled-line hypothesis. According to this idea, activity in neurons that respond best to sugar would signal "sweetness," activity in those that respond best to acids would signal "sourness" and so on [*see illustration on next page*].

As early as 1983 Smith and his colleagues Richard L. Van Buskirk, Joseph B. Travers and Stephen L. Bieber demonstrated that the same cells that others had interpreted as labeled lines actually defined the similarities and differences in the patterns of activity across taste neurons. This suggested that the same neurons were responsible for taste-quality representation, whether they were viewed as labeled lines or as critical parts of an across-neuron pattern. These investigators further demonstrated that the neural distinction among stimuli of different qualities depended on the simultaneous activation of different cell types, much as color vision depends on the comparison of activity across photoreceptor cells in the eye. These and other considerations have led us to favor the idea that the patterns of activity are key to coding taste information.

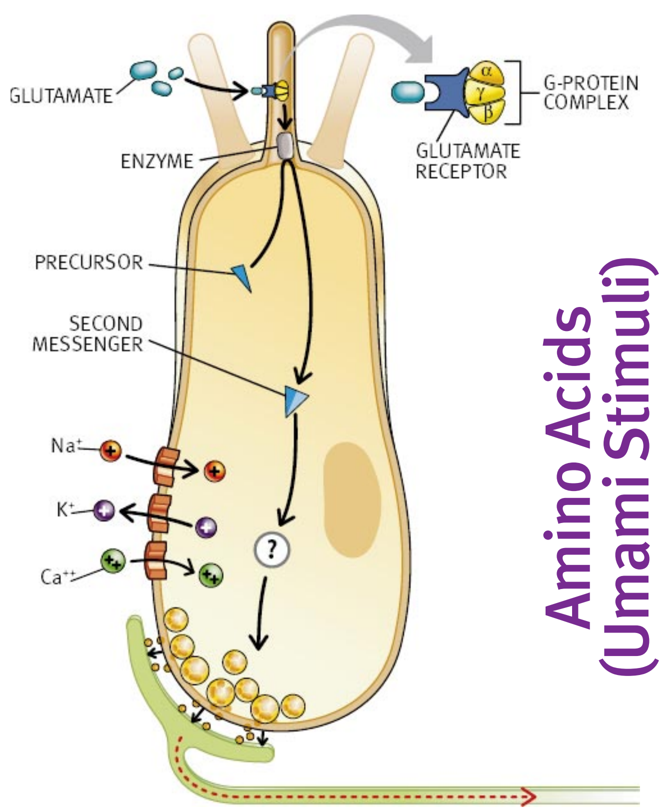
Scientists now know that things that taste alike evoke similar patterns of activity across groups of taste neurons. What is more, they can compare these patterns and use multivariate statistical analysis to plot the similarities in the patterns elicited by various tastants. Taste researchers have generated such comparisons for gustatory stimuli from the neural responses of hamsters and rats. These correspond very closely to similar plots generated in behavioral experiments, from which scientists infer which stimuli taste alike and which taste different to animals. Such data show that the across-neuron patterns contain sufficient information for taste discrimination.

When we block the activity of certain neuron groups, the behavioral discrimination among stimuli—that between the table salt sodium chloride and the salt substitute potassium chloride, for example—is disrupted. This can be shown directly after treating the tongue with the diuretic drug amiloride. Thomas P. Hettinger and Marion E. Frank of the University of Connecticut Health Sciences Center demonstrated that amiloride reduces the responses of some types of pe-

BITTER STIMULI, **such as quinine, also act through G-protein-coupled receptors and second messengers. In this case, however, the second messengers cause the release of calcium ions from the endoplasmic reticulum. The resulting buildup of calcium in the cell leads to depolarization and neurotransmitter release.**



AMINO ACIDS**—such as glutamate, which stimulates the *umami* taste—are known to bind to G-protein-coupled receptors and to activate second messengers. But the intermediate steps between the second messengers and the release of packets of neurotransmitters are unknown.**



What We Learn from Yummy and Yucky

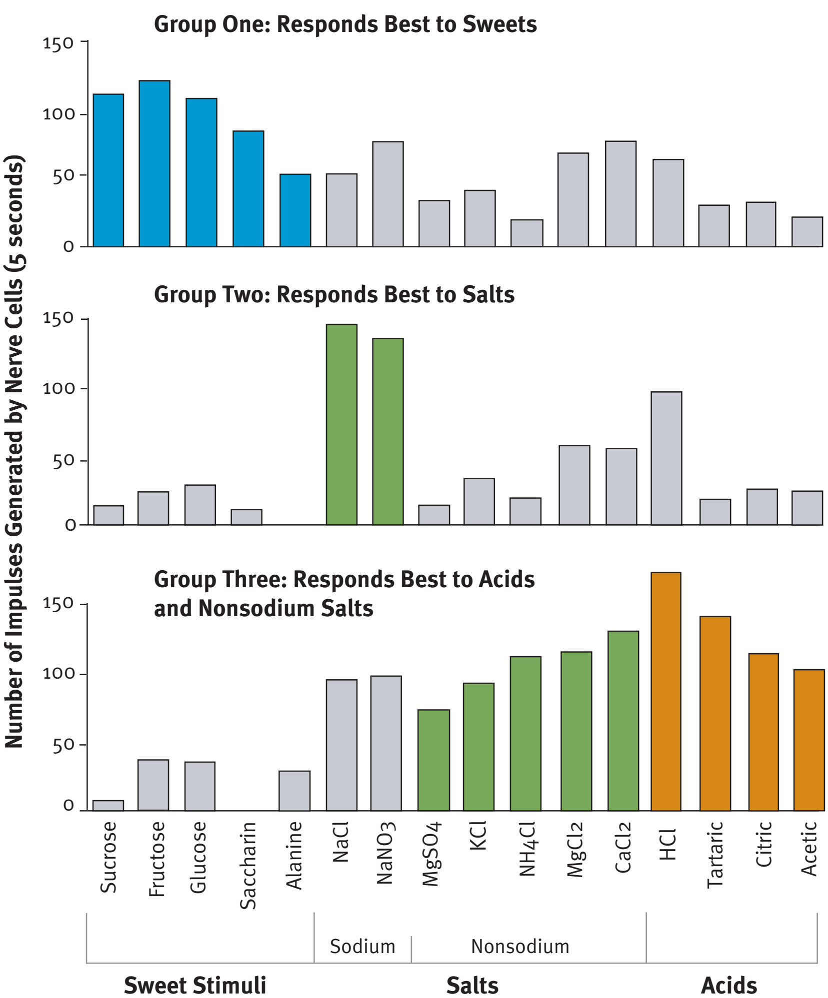
Sensory information from taste cells is critical for helping us to detect and respond appropriately to needed nutrients. The sweet taste of sugars, for example, provides a strong impetus for the ingestion of carbohydrates. Taste signals also evoke physiological responses, such as the release of insulin, that aid in preparing the body to use the nutrients effectively. Humans and other animals with a sodium deficiency will seek out and ingest sources of sodium. Evidence also indicates that people and animals with dietary deficiencies will eat foods high in certain vitamins and minerals.

Just as important as ingesting the appropriate nutrients is not ingesting harmful substances. The universal avoidance of intensely bitter molecules shows a strong link between taste and disgust. Toxic compounds, such as strychnine and other common plant alkaloids, often have a strong bitter taste. In fact, many plants have evolved such compounds as a protective mechanism against foraging animals. The sour taste of spoiled foods also contributes to their avoidance. All animals, including humans, generally reject acids and bitter-tasting substances at all but the weakest concentrations.

The intense reactions of pleasure and disgust evoked by sweet and bitter substances appear to be present at birth and to depend on neural connections within the lower brain stem. Animals with their forebrains surgically disconnected and anencephalic human newborns (those lacking a forebrain) show facial responses normally associated with pleasure and disgust when presented with sweet and bitter stimuli, respectively.

The strong link between taste and pleasure—or perhaps displeasure—is the basis of the phenomenon of taste-aversion learning. Animals, including humans, will quickly learn to avoid a novel food if eating it causes, or is paired with, gastrointestinal distress. Naturally occurring or experimentally induced taste-aversion learning can follow a single pairing of tastant and illness, even if there is a gap of many hours between the two. One side effect of radiation treatments and chemotherapy in cancer patients is loss of appetite; much of this is caused by conditioned taste aversions resulting from the gastrointestinal discomfort produced by these treatments. This mechanism has also made it extremely difficult to devise an effective poison for the control of rats, which are especially good at making the association between novel tastants and their physiological consequences. *—D.V.S. and R.F.M.*

Measuring the Preferences of Taste Neurons



ripheral gustatory neurons but not others. It blocks sodium channels on the apical membranes of taste receptor cells—the membranes that are closest to the opening of the taste pore—and exerts its influence primarily on neurons that respond best to sodium chloride.

Smith and his colleague Steven J. St. John recently demonstrated that treatment with amiloride eliminates the differences in the across-neuron patterns between sodium chloride and potassium chloride in rats. It also disrupts the rats' ability to discriminate behaviorally between these stimuli, as shown by Alan C. Spector and his colleagues at the University of Florida. Reducing the activity in other cell types also abolishes the differences in the across-neuron patterns evoked by these salts, but in a completely different way. These studies showed that it is not a specific cell type that is responsible for taste discrimination but a comparison in the activity across cells. Thus, taste discrimination depends on the relative activity of different neuron types, each of which must contribute to the overall pattern of ac-

NERVE CELL ACTIVITY TESTS demonstrate that taste neurons can respond to different types of taste stimuli—be they sweet, salty, sour or bitter—although the cells usually respond most strongly to one type. (Bitter stimuli not shown.)

EDWARD BELL

The "Taste Map": All Wrong

One of the most dubious "facts" about taste—and one that is commonly reproduced in textbooks—is the oft-cited but misleading "tongue map" showing large regional differences in sensitivity across the human tongue. These maps indicate that sweetness is detected by taste buds on the tip of the tongue, sourness on the sides, bitterness at the back and saltiness along the edges.

Taste researchers have known for many years that these tongue maps are wrong. The maps arose early in the 20th century as a result of a misinterpretation of research reported in the late 1800s, and they have been almost impossible to purge from the literature.

In reality, all qualities of taste can be elicited from all the regions of the tongue that contain taste buds. At present, we have no evidence that any kind of spatial segregation of sensitivities contributes to the neural representation of taste quality, although there are some slight differences in sensitivity across the tongue and palate, especially in rodents.

—*D.V.S. and R.F.M.*

OUTDATED "TONGUE MAP" has continued to appear in textbooks even though it was based on a misinterpretation of research done in the 19th century.

LAURIE GRACE

tivity for an individual to distinguish among different stimuli.

Because taste neurons are so widely responsive, neurobiologists must compare the levels of activity of a range of neurons to get an idea of what sensation they are registering. No single neuron type alone is capable of discriminating among stimuli of different qualities, because a given cell can respond the same way to disparate stimuli, depending on their relative concentrations. In this sense, taste is like vision, in which three types of photoreceptors respond to light of a broad range of wavelengths to allow us to see the myriad hues of the rainbow. It is well known that the absence of one of these photoreceptor pigments disrupts color discrimination, and this disruption extends well beyond the wavelengths to which that receptor is most sensitive. That is, discrimination between red and green stimuli is disrupted when either the "red" or the "green" photopigment is absent.

Although this analogy with color vision provides a reasonable explanation for neural coding in taste, researchers continue to debate whether individual neuron types play a more significant role in taste coding than they do in color vision. Scientists are also questioning whether taste is an analytic sense, in which each quality is separate, or a synthetic sense like color vision, where combinations of colors produce a unique quality. A challenge to elucidating neural coding in this system is the precise determination of the relation between the activity in these broadly tuned neurons and the sensations evoked by taste mixtures.

These diverse experimental approaches to investigating the gustatory system—ranging from isolating taste-cell proteins to studying the neural representation of taste stimuli and the perception of taste quality in humans—are coming together to provide a more complete picture of how the taste system functions. This knowledge will spur discoveries of new artificial sweeteners and improved substitutes for salt and fat—in short, the design of more healthful foods and beverages that taste great, too. SA

The Authors

DAVID V. SMITH and ROBERT F. MARGOLSKEE approach the study of taste from complementary angles. Smith's training is in psychobiology and neurophysiology. He is professor and vice chairman of the department of anatomy and neurobiology at the University of Maryland School of Medicine, where he has been since 1994, and is a member of the program in neuroscience there. He earned his Ph.D. from the University of Pittsburgh and received postdoctoral training at the Rockefeller University. Margolskee's training is in molecular neurobiology and biochemistry. He is an associate investigator of the Howard Hughes Medical Institute and a professor of physiology and biophysics and of pharmacology at the Mount Sinai School of Medicine, where he has been since 1996. He received his M.D. and Ph.D. in molecular genetics from the Johns Hopkins School of Medicine and did postdoctoral research in biochemistry at Stanford University. He founded the biotechnology company Linguagen in Paramus, N.J.

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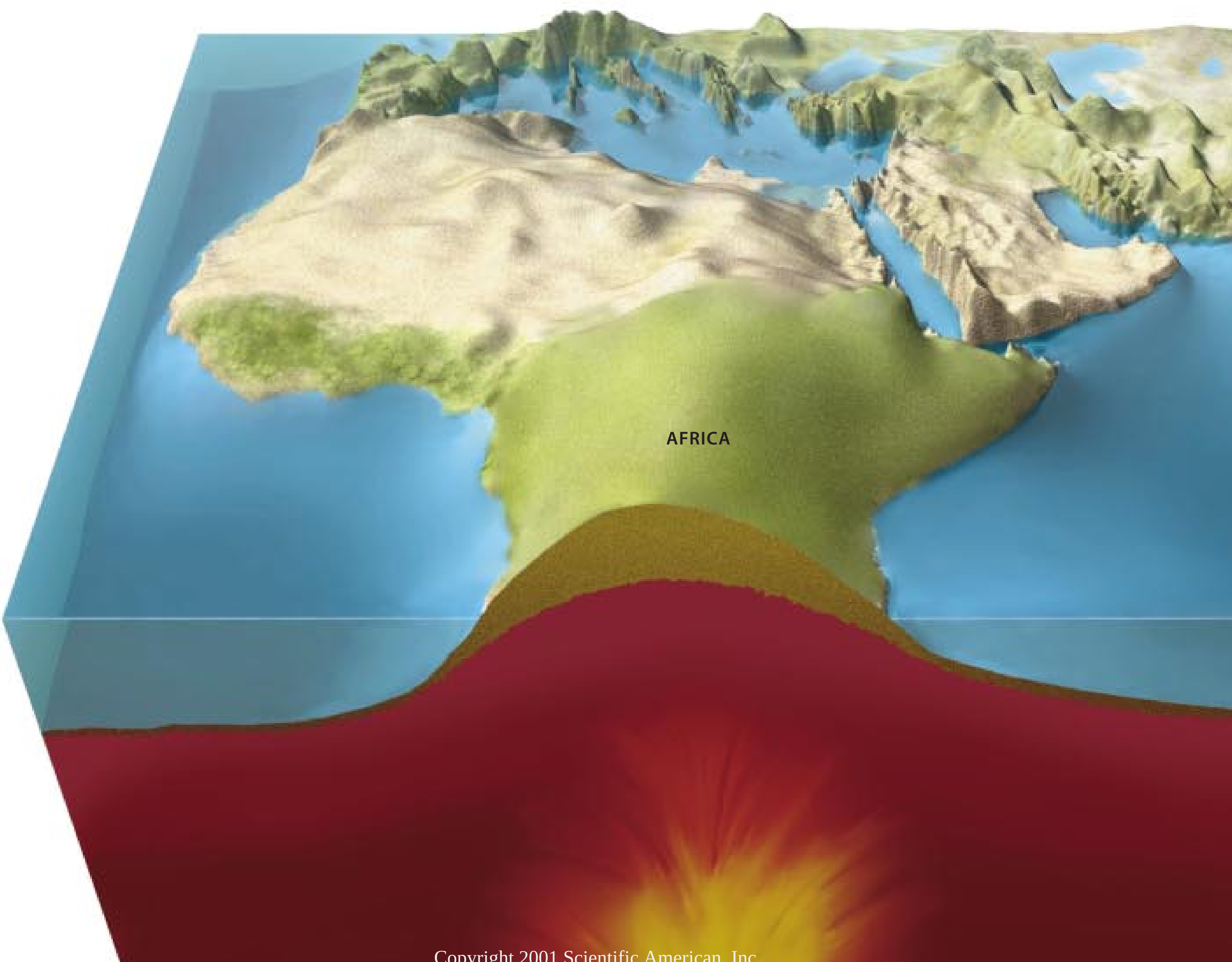
Sculpting the Earth from Inside Out

Powerful motions deep inside the planet do not merely shove fragments of the rocky shell horizontally around the globe—they also lift and lower entire continents

by Michael Gurnis



Credit for sculpting the earth's surface typically goes to violent collisions between tectonic plates, the mobile fragments of the planet's rocky outer shell. The mighty Himalayas shot up when India rammed into Asia, for instance, and the Andes grew as the Pacific Ocean floor plunged beneath South America. But even the awesome power of plate tectonics cannot fully explain some of the planet's most massive surface features.

Take southern Africa. This region boasts one of the world's most expansive plateaus, more than 1,000 miles across and almost a mile high. Geologic evidence shows that southern Africa, and the surrounding ocean floor, has been rising slowly for the past 100 million years, even though it has not experienced a tectonic collision for nearly 400 million years.

The African superswell, as this uplifted landmass is known, is just one example of dramatic vertical movement by a broad chunk of the earth's surface. In other cases from the distant past, vast stretches of Australia and North America bowed down thousands of feet—and then popped up again.

Scientists who specialize in studying the earth's interior have long suspected that activity deep inside the earth was behind such vertical changes at the surface. These geophysicists began searching for clues in the mantle—the middle layer of the planet. This region of scalding-hot rock lies just below the jigsaw configuration of tectonic plates and extends down more than 1,800 miles to the outer edge of the globe's iron core. Researchers learned that variations in the mantle's intense heat and pressure enable the solid rock to creep molasseslike over thousands of years. But they could not initially decipher how it could give rise to large vertical motions. Now, however, powerful computer models that combine snapshots of the mantle today with clues about how it might have behaved in the

ALL ILLUSTRATIONS BY DAVID FIERSTEIN

ENIGMATIC DIPS AND SWELLS have occurred over continent-size swaths of the earth's surface several times in the past. Southern Africa has been lifted about 1,000 feet over the past 20 million years, for example, and a sunken continent's highest peaks today form the islands of Indonesia. Scientists are now finding that the causes of these baffling vertical motions lie deep within the planet's interior.

past are beginning to explain why parts of the earth's surface have undergone these astonishing ups and downs.

The mystery of the African superswell was among the easiest to decipher. Since the early half of the 20th century, geophysicists have understood that over the unceasing expanse of geologic time, the mantle not only creeps, it churns and roils like a pot of thick soup about to boil. The relatively low density of the hottest rock makes that material buoyant, so it ascends slowly; in contrast, colder, denser rock sinks until heat escaping the molten core warms it enough to make it rise again. These three-dimensional motions, called convection, are known to enable the horizontal movement of tectonic plates, but it seemed unlikely that the forces they created could lift and lower the planet's surface. That skepticism about the might of the mantle began to fade away when researchers created the first blurry images of the earth's interior.

About 20 years ago scientists came up with a way to make three-dimensional snapshots of the mantle by measuring vibrations that are set in motion by earthquakes originating in the planet's outer shell. The velocities of these vibrations, or seismic waves, are determined by the chemical composition, temperature and pressure of the rocks they travel through. Waves become sluggish in hot, low-density rock, and they speed up in colder, denser regions. By recording the time it takes for seismic waves to travel from an earthquake's epicenter to a particular recording station at the surface, scientists can infer the temperatures and densities in a given segment of the interior. And by compiling a map of seismic velocities from thousands of earthquakes around the globe they can begin to map temperatures and densities throughout the mantle.

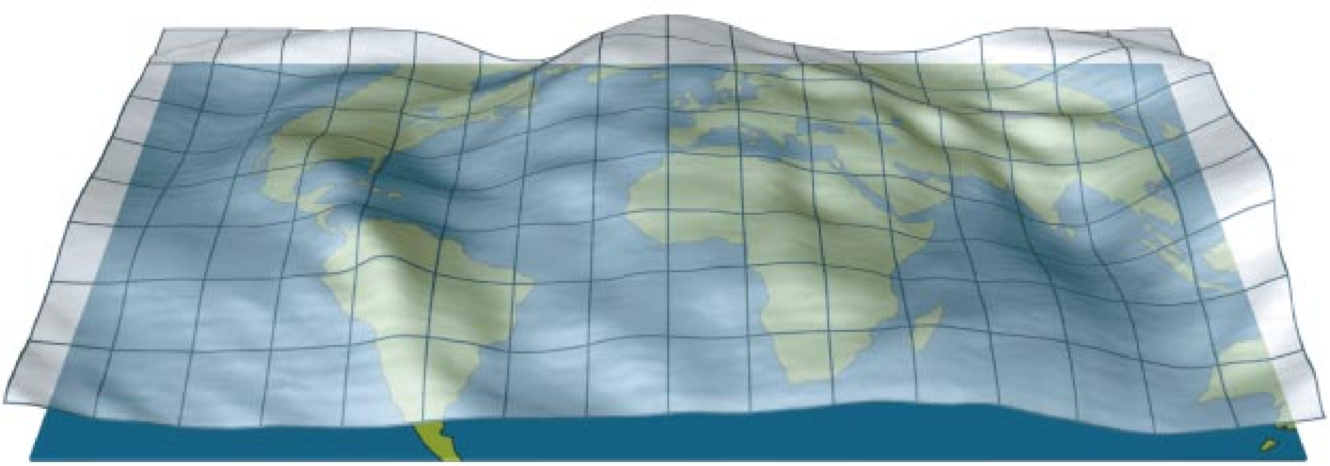
These seismic snapshots, which become increasingly more detailed as researchers find more accurate ways to compile their measurements, have recently revealed some unexpectedly immense formations in the deepest parts of the mantle. The largest single structure turns out to lie directly below Africa's southern tip. About two years ago seismologists Jeroen Ritsema and Hendrik-Jan van Heijst of the California Institute of Technology calculated that this mushroom-shaped mass stretches some 900 miles upward from the core and spreads across several thousand miles [*see illustration on opposite page*].

The researchers immediately began to wonder whether this enormous blob could be shoving Africa skyward. Because the blob is a region where seismic waves are sluggish, they assumed that it was hotter than the surrounding mantle. The basic physics of convection suggested that a hot blob was likely to be rising. But a seismic snapshot records only a single moment in time and thus only one position of a structure. If the blob were of a different composition than the surrounding rock, for instance, it could be hotter and still not rise. So another geophysicist, Jerry X. Mitrovica of the University of Toronto, and I decided to create a time-lapse picture of what might be happening. We plugged the blob's shape and estimated density, along with estimates of when southern Africa began rising, into a computer program that simulates mantle convection. By doing so, we found last year that the blob is indeed buoyant enough to rise slowly within the mantle—and strong enough to push Africa upward as it goes.

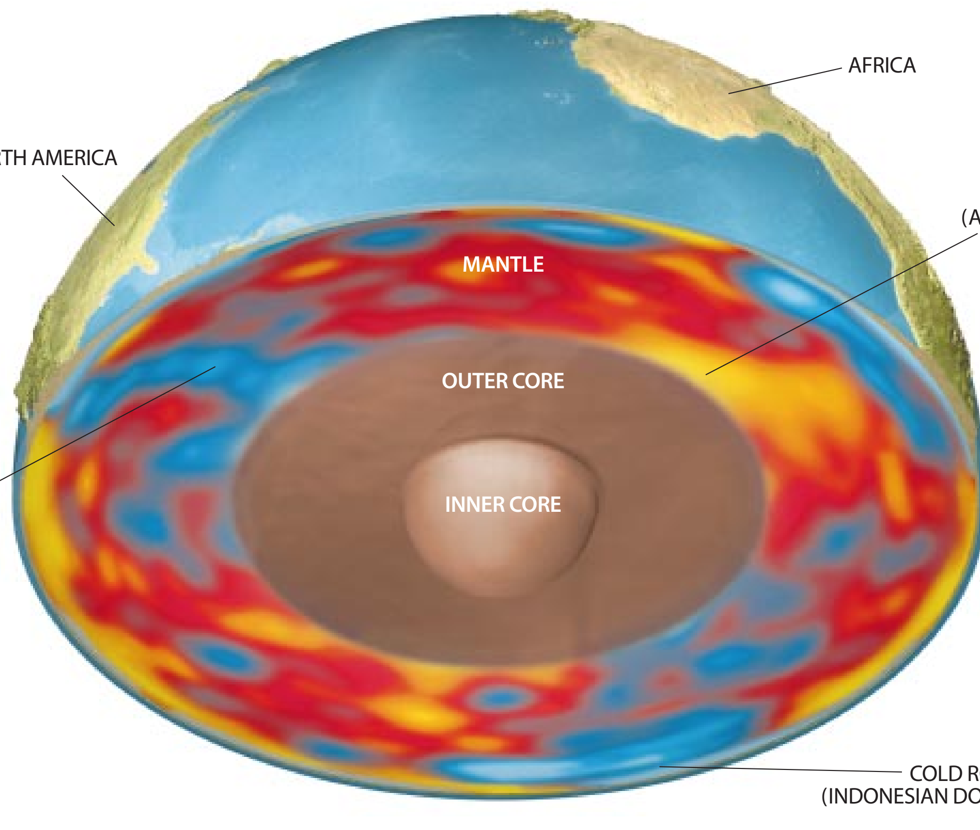
Seismic snapshots and computer models—the basic tools of geophysicists—were enough to solve the puzzle of the African superswell, but resolving the up-and-down movements of North America and Australia was more complicated and so was accomplished in a more circuitous way. Geophysicists who think only about what the mantle looks like today cannot fully explain how it sculpts the earth's surface. They must therefore borrow from the historical perspective of traditional geologists who think about the way the surface has changed over time.

Ghosts from the Past

The insights that would help account for the bobbings of Australia and North America began to emerge with investigations of a seemingly unrelated topic: the influence of mantle density on the earth's gravitational field. The basic principles of physics led scientists in the 1960s to expect that gravity would be lowest above pockets of hot rock, which are less dense and thus have less mass. But when geophysicists first mapped the earth's gravitational variations, they found no evidence that gravity correlated with the cold and hot parts of the mantle—at least not in the expected fashion.



BULGES AND TROUGHS in the transparent surface above the world map represent natural variations in the earth's gravitational field. High points indicate stronger-than-normal gravity caused by a pocket of excess mass within the planet's interior; low areas occur above regions where a deficiency of mass produces a band of low gravity. Such differences in gravity hint at the location of oddities in the structure of the earth's mantle.



MANTLE MAP integrates measurements of thousands of earthquake vibrations, or seismic waves, that have traveled through the planet. Regions where waves moved quickly (*blue*) usually denote cold, dense rock. Regions where waves slowed down (*yellow*) denote hot, less compact rock. Under southern Africa and the South Atlantic lies a pocket of sluggish velocities—a buoyant blob of hot rock called the African superplume. The map also reveals cold, sinking material that is tugging on North America and Indonesia.

SOURCE: JEROEN RITSEMA *California Institute of Technology*

Indeed, in the late 1970s and early 1980s Clement G. Chase uncovered the opposite pattern. When Chase, now at the University of Arizona, considered geographic scales of more than 1,000 miles, he found that the pull of gravity is strongest not over cold mantle but over isolated volcanic regions called hot spots. Perhaps even more surprising was what Chase noticed about the position of a long band of low gravity that passes from Hudson Bay in Canada northward over the North Pole, across Siberia and India, and down into Antarctica. Relying on estimates of the ancient configuration of tectonic plates, he showed that this band of low gravity marked the location of a series of subduction zones—that is, the zones where tectonic plates carrying fragments of the seafloor plunge back into the mantle—from 125 million years ago. The ghosts of ancient subduction zones seemed to be diminishing the pull of gravity. But if cold, dense chunks of seafloor were still sinking through the mantle, it seemed that gravity would be high above these spots, not low, as Chase observed.

In the mid-1980s geophysicist Bradford H. Hager, now at the Massachusetts Institute of Technology, resolved this apparent paradox by proposing that factors other than temperature might create pockets of extra or deficient mass within the mantle. Hager developed his theory from the physics that describe moving fluids, whose behavior the mantle imitates over the long term. When a low-density fluid rises upward, as do the hottest parts of the mantle, the force of the flow pushes up the higher-density fluid above it. This gentle rise atop the upwelling itself creates an excess of mass (and hence stronger gravity) near the planet's surface. By the same token, gravity can be lower over cold, dense material: as this heavy matter sinks, it drags down mass that was once near the surface. This conception explained why the ghosts of subduction zones could generate a band of low gravity: some of that cold, subducted seafloor must still be sinking within the mantle—and towing the planet's surface downward in the process. If Hager's explanation was correct, it meant that the mantle did not merely creep horizontally near the planet's surface; whole segments of its up-and-down movements also reached the surface. Areas that surged upward would push the land above it skyward, and areas that sank would drag down the overlying continents as they descended.

Bobbing Continents

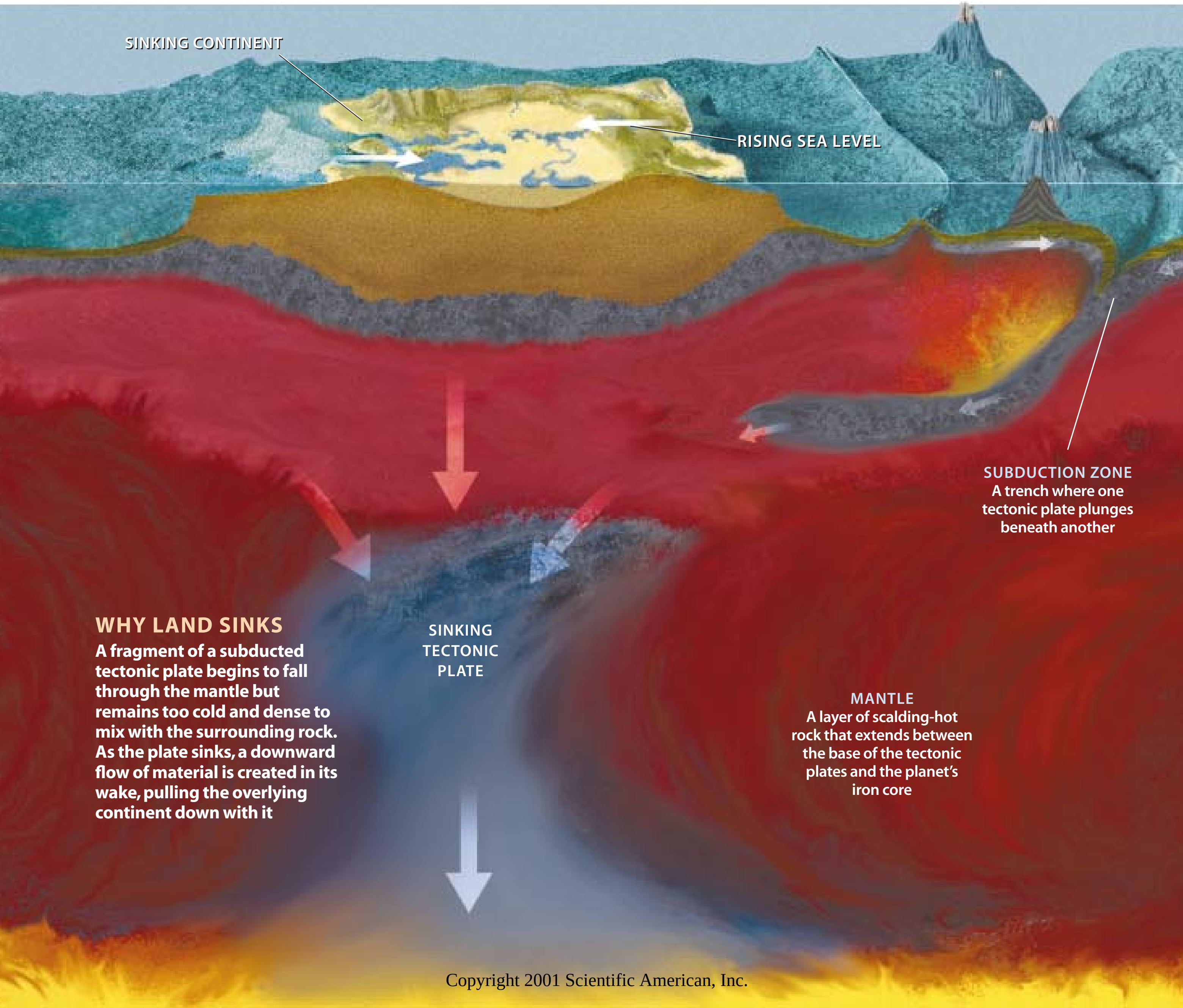
At the same time that Chase and Hager were discovering a mechanism that could dramatically lift and lower the earth's surface, geologists were beginning to see evidence that continents might actually have experienced such dips and swells in the past. Geologic formations worldwide contain evidence that sea level fluctuates over time. Many geologists suspected that this fluctuation would affect all continents in the same way, but a few of them advanced convincing evidence that the most momentous changes in sea level stemmed from vertical motions of continents. As one continent moved, say, upward relative to other landmasses, the ocean surface around that continent would become lower while sea level around other landmasses would stay the same.

Most geologists, though, doubted the controversial notion that continents could move vertically—even when the first indications of the bizarre bobbing of Australia turned up in the early 1970s. Geologist John J. Veevers of Macquarie University in Sydney examined outcrops of ancient rock in eastern Australia and discovered that sometime in the early Cretaceous period (about 130 million years ago), a shallow sea rapidly covered that half of Australia while other continents flooded at a much more leisurely pace. Sea level climaxed around those landmasses by the late Cretaceous (about 70 million years ago), but by then the oceans were already retreating from Australia's shores. The eastern half of the continent must have sunk several thousand feet relative to other landmasses and then popped back up before global sea level began to fall.

Veevers's view of a bobbing continent turned out to be only part of Australia's enigmatic story. In 1978 geologist Gerard C. Bond, now at Columbia University's Lamont-Doherty Earth Observatory, discovered an even stranger turn of events while he was searching global history for examples of vertical continental motion. After Australia's dip and rise during the Cretaceous, it sank again, this time by 600 feet, between then and the present day. No reasonable interpretation based on plate tectonics alone could explain the widespread vertical motions that Bond and Veevers uncovered. Finding a satisfactory explanation would require scientists to link this information with another important clue: Hager's theory about how the mantle can change the shape of the planet's surface.

The first significant step in bringing these clues together was the close examination of another up-and-down example from Bond's global survey. In the late 1980s this work inspired Christopher Beaumont, a geologist at Dalhousie University in Nova Scotia, to tackle a baffling observation about Denver, Colo. Although the city's elevation is more than a

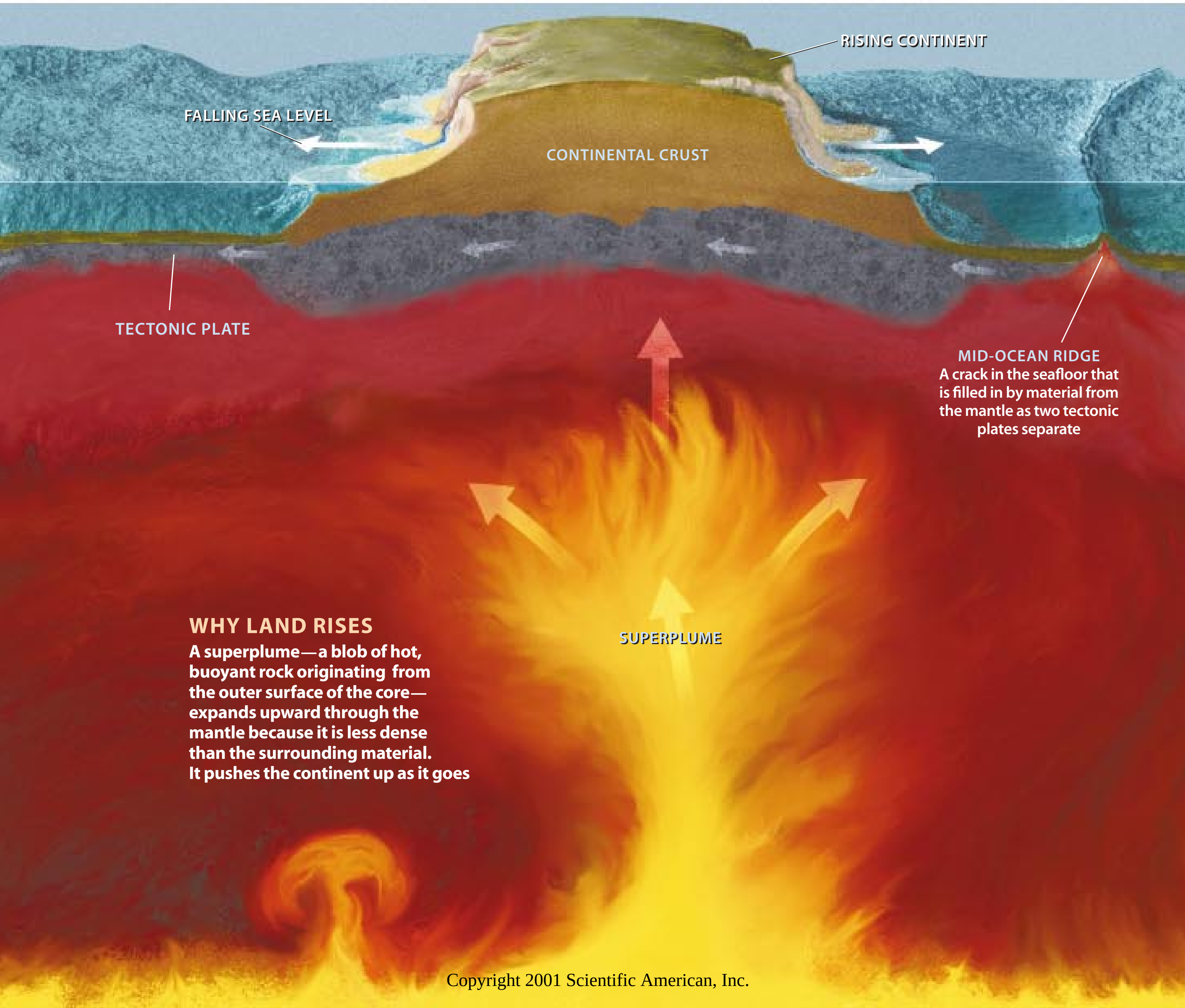
HOW THE MANTLE SHAPES THE EARTH'S SURFACE



mile above sea level, it sits atop flat, undeformed marine rocks created from sediments deposited on the floor of a shallow sea during the Cretaceous period. Vast seas covered much of the continents during that time, but sea level was no more than about 400 feet higher than it is today. This means that the ocean could never have reached as far inland as Denver's current position—unless this land was first pulled down several thousand feet to allow waters to flood inland.

Based on the position of North America's coastlines during the Cretaceous, Beaumont estimated that this bowing downward and subsequent uplift to today's elevation must have affected an area more than 600 miles across. This geographic scale was problematic for the prevailing view that plate tectonics alone molded the surface. The mechanism of plate tectonics permits vertical motions within only 100 miles or so of plate edges, which are thin enough to bend like a stiff fishing pole, when forces act on them. But the motion of North America's interior happened several hundred miles inland—far from the influence of plate collisions. An entirely different mechanism had to be at fault.

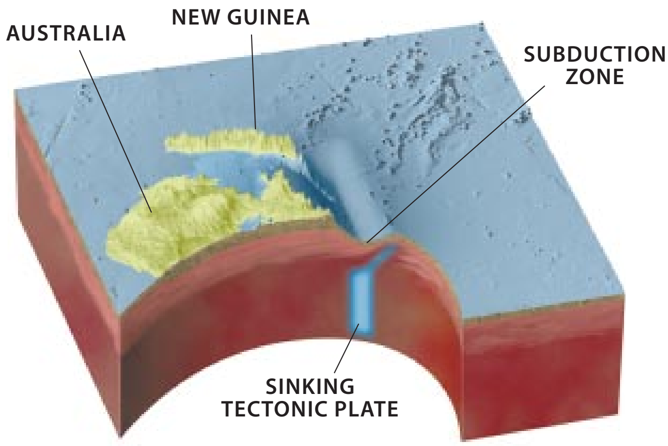
Beaumont knew that subducted slabs of ancient seafloor might sit in the mantle below North America and that such slabs could theoretically drag down the center of a continent. To determine whether downward flow of the mantle could have caused the dip near Denver, Beaumont teamed up with Jerry Mitrovica, then a graduate student at the University of Toronto, and Gary T. Jarvis of York University in Toronto. They found that the sinking of North America during the Cretaceous could have been caused by a plate called the Farallon as it plunged into the mantle beneath the western coast of North America. Basing their conclusion on a computer model, the research team argued that the ancient plate thrust into



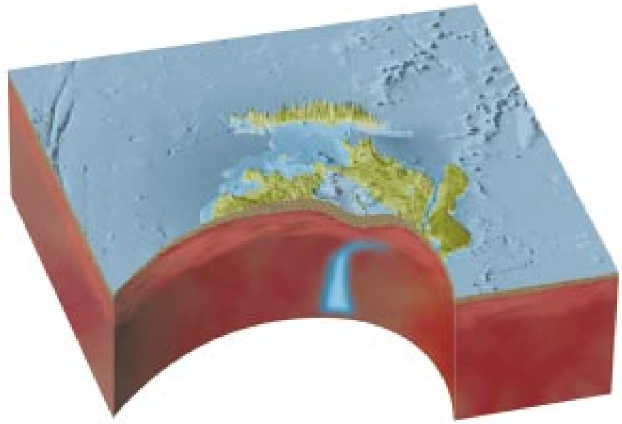
WHY LAND RISES
A superplume—a blob of hot, buoyant rock originating from the outer surface of the core—expands upward through the mantle because it is less dense than the surrounding material. It pushes the continent up as it goes

AUSTRALIA'S UPS AND DOWNS

A computer model reveals how the ghost of an ancient subduction zone dragged down a continent



130 Million Years Ago
Australia is bordered by a subduction zone, a deep trench where the tectonic plate to the east plunges into the mantle. The sinking plate (*blue*) pulls the surrounding mantle and the eastern edge of Australia down with it. Later, subduction ceases and the continent begins to drift eastward.



90 Million Years Ago
The entire eastern half of Australia sinks about 1,000 feet below sea level as the continent passes eastward over the sinking tectonic plate. About 20 million years later the plate's downward pull diminishes as it descends into the deeper mantle. As a result, the continent then pops up again.

the mantle nearly horizontally. As it began sinking, it created a downward flow in its wake that tugged North America low enough to allow the ocean to rush in. As the Farallon plate sank deeper, the power of its trailing wake decreased. The continent's tendency to float eventually won out, and North America resurfaced.

When the Canadian researchers advanced their theory in 1989, the Farallon plate had long since vanished into the mantle, so its existence had only been inferred from geologic indications on the bottom of the Pacific Ocean. At that time, no seismic images were of high enough resolution to delineate a structure as small as a sinking fragment of the seafloor. Then, in 1996, new images of the mantle changed everything. Stephen P. Grand of the University of Texas at Austin and Robert D. van der Hilst of M.I.T., seismologists from separate research groups, presented two images based on entirely different sets of seismic measurements. Both pictures showed virtually identical structures, especially the cold-mantle downwellings associated with sinking slabs of seafloor. The long-lost Farallon plate was prominent in the images as an arching slab 1,000 miles below the eastern coast of the U.S.

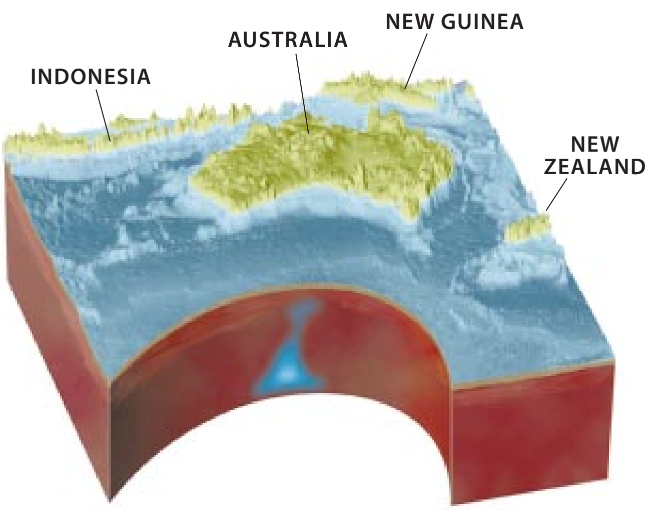
Moving Down Under

Connecting the bobbing motion of North America to the subduction of the seafloor forged a convincing link between ancient sea-level change and goings-on in the mantle. It also became clear that the ancient Farallon slab sits within the band of low gravity that Chase had observed two decades earlier. I suspected that these ideas could also be applied to the most enigmatic of the continental bobbings, that of Australia during and since the Cretaceous. I had been simulating mantle convection with computer models for 15 years, and many of my results showed that the mantle was in fact able to lift the surface by thousands of feet—a difference easily great enough to cause an apparent drop in sea level. Like Chase, Veevers and other researchers before me, I looked at the known history of plate tectonics for clues about whether something in the mantle could have accounted for Australia's bouncing. During the Cretaceous period, Australia, South America, Africa, India, Antarctica and New Zealand were assembled into a vast supercontinent called Gondwana, which had existed for more than 400 million years before it fragmented into today's familiar landmasses. Surrounding Gondwana for most of this time was a huge subduction zone where cold oceanic plates plunged into the mantle.

I thought that somehow the subduction zone that surrounded Gondwana for hundreds of millions of years might have caused Australia's ups and downs. I became more convinced when I sketched the old subduction zones on maps of ancient plate configurations constructed by R. Dietmar Müller, a seagoing geophysicist at Sydney University. The sketches seemed to explain the Australian oddities. Australia would have passed directly over Gondwana's old subduction zone at the time it sank.

To understand how the cold slab would behave in the mantle as Gondwana broke apart over millions of years, Müller and I joined Louis Moresi of the Commonwealth Scientific and Industrial Research Organization in Perth to run a computer simulation depicting the mantle's influence on Australia over time. We knew the original position of the ancient subduction zone, the history of horizontal plate motions in the region and the estimated properties—such as viscosity—of the mantle below. Operating under these constraints, the computer played out a scenario for Australia that fit our hypotheses nearly perfectly [*see box above*].

The computer model started 130 million years ago with ocean floor thrusting beneath eastern Australia. As Australia broke away from Gondwana, it passed over the cold, sinking slab, which sucked the Australian plate downward. The con-



Today
Australia lies north of its former site, having been pushed there by activity in adjacent tectonic plates beginning about 45 million years ago. The entire continent has dropped relative to its greatest elevation as the result of a downward tug in the mantle under Indonesia—a landmass that is also sinking.

tinent rose up again as it continued its eastward migration away from the slab.

Our model resolved the enigma of Australia's motion during the Cretaceous, originally observed by Veevers, but we were still puzzled by the later continentwide sinking of Australia that Bond discovered. With the help of another geophysicist, Carolina Lithgow-Bertelloni, now at the University of Michigan, we confirmed Bond's observation that as Australia moved northward toward Indonesia after the Cretaceous, it subsided by about 600 feet. Lithgow-Bertelloni's global model of the mantle, which incorporated the history of subduction, suggested that Indonesia is sucked down more than any other region in the world because it lies at the intersection of enormous, present-day subduction systems in the Pacific and Indian oceans. And as Indonesia sinks, it pulls Australia down with it. Today Indonesia is a vast submerged continent—only its highest mountain peaks protrude above sea level.

Which brings us back to Africa. In a sense, Indonesia and Africa are opposites: Indonesia is being pulled down while Africa is being pushed up. These and other changes in the mantle that have unfolded over the past few hundred million years are intimately related to Gondwana. The huge band of low gravity that Chase discovered 30 years ago is created by the still-sinking plates of a giant subduction zone that once encircled the vast southern landmass. At the center of Gondwana was southern Africa, which means that the mantle below this region was isolated from the chilling effects of sinking tectonic plates at that time—and for the millions of years since. This long-term lack of cold, downward motion below southern Africa explains why a hot superplume is now erupting in the deep mantle there.

With all these discoveries, a vivid, dynamic picture of the motions of the mantle has come into focus. Researchers are beginning to see that these motions sculpt the surface in more ways than one. They help to drive the horizontal movement of tectonic plates, but they also lift and lower the continents. Perhaps the most intriguing discovery is that motion in the deep mantle lags behind the horizontal movement of tectonic plates. Positions of ancient plate boundaries can still have an effect on the way the surface is shaped many millions of years later.

Our ability to view the dynamics of mantle convection and plate tectonics will rapidly expand as new ways of observing the mantle and techniques for simulating its motion are introduced. When mantle convection changes, the gravitational field changes. Tracking variations in the earth's gravitational field is part of a joint U.S. and German space mission called GRACE, which is set for launch in June. Two spacecraft, one chasing the other in earth orbit, will map variations in gravity every two weeks and perhaps make it possible to infer the slow, vertical flow associated with convection in the mantle. Higher-resolution seismic images will also play a pivotal role in revealing what the mantle looks like today. Over the five- to 10-year duration of a project called USArray, 400 roving seismometers will provide a 50-mile-resolution view into the upper 800 miles of the mantle below the U.S.

Plans to make unprecedented images and measurements of the mantle in the coming decade, together with the use of ever more powerful supercomputers, foretell an exceptionally bright future for deciphering the dynamics of the earth's interior. Already, by considering the largest region of the planet—the mantle—as a chunk of rock with a geologic history, earth scientists have made extraordinary leaps in understanding the ultimate causes of geologic changes at the surface. SA

The Author

MICHAEL GURNIS is a geophysicist who is interested in the dynamics of plate tectonics and the earth's interior. These physical processes, which govern the history of the planet, have intrigued him since he began studying geology as an undergraduate 20 years ago. With his research group at the California Institute of Technology, Gurnis now develops computer programs that simulate the evolving motions of the mantle and reveal how those motions have shaped the planet over time. Gurnis's research highlights over the past three years have been deciphering the mysteries of the present-day African superswell and the bobbings of Australia during the Cretaceous period.

Further Information

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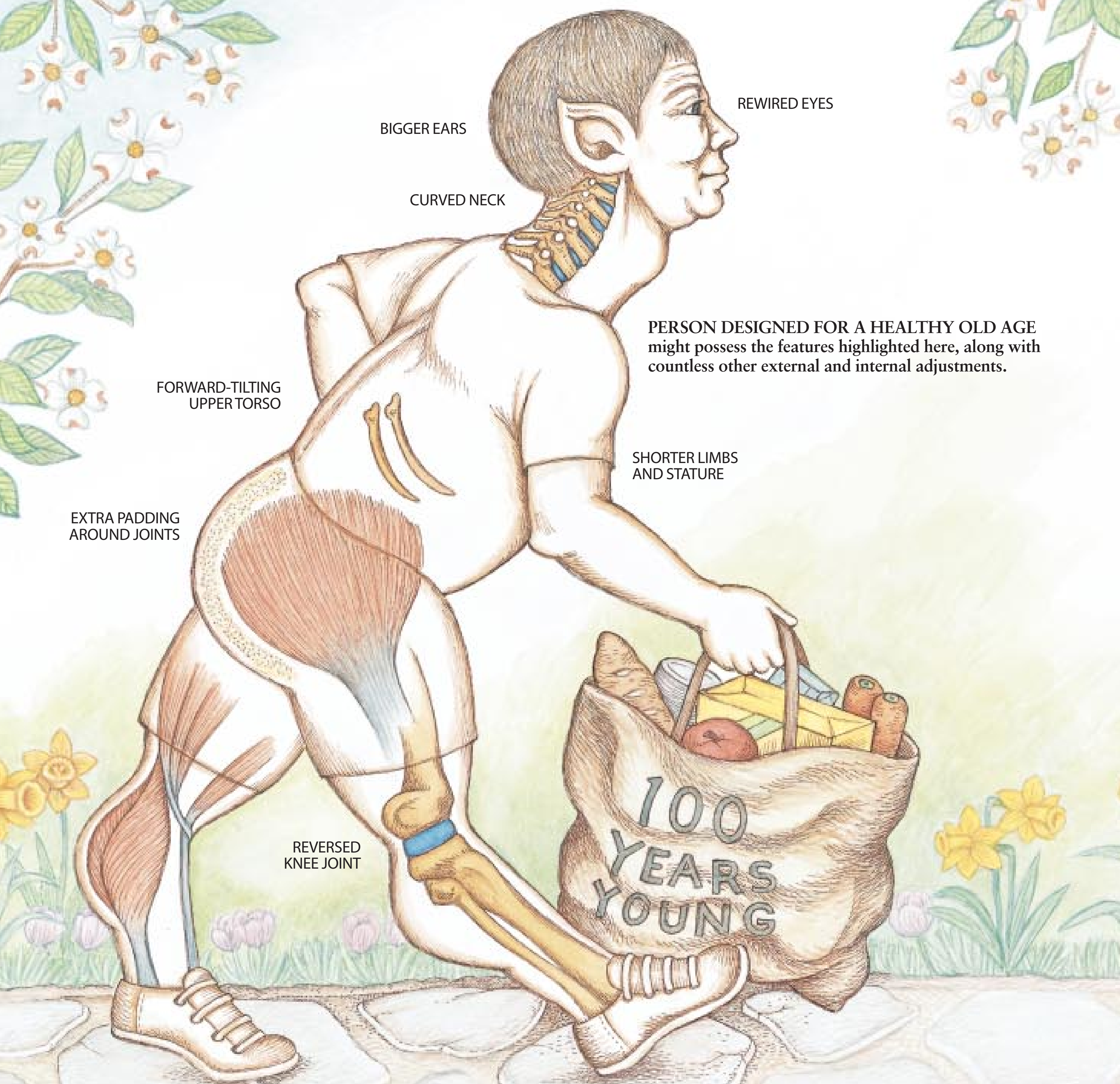
Gurnis's Computational Geodynamics Research Group Web site: www.gps.caltech.edu/~gurnis/geodynamics.html

If Humans Were Built to Last

by S. Jay Olshansky, Bruce A. Carnes and Robert N. Butler



PERSON DESIGNED FOR A HEALTHY OLD AGE might possess the features highlighted here, along with countless other external and internal adjustments.

Bulging disks, fragile bones, fractured hips, torn ligaments, varicose veins, cataracts, hearing loss, hernias and hemorrhoids: the list of bodily malfunctions that plague us as we age is long and all too familiar. Why do we fall apart just as we reach what should be the prime of life?

The living machines we call our bodies deteriorate because they were not designed for extended operation and because we now push them to function long past their warranty period. The human body is artistically beautiful and worthy of all the wonder and amazement it invokes. But from an engineer's perspective, it is a complex network of bones, muscles, tendons, valves and joints that are directly analogous to the fallible pulleys, pumps, levers and hinges in machines. As we plunge further into our postreproductive years, our joints and other anatomical features that serve us well or cause no problems at younger ages reveal their imperfections. They wear out or otherwise contribute to the health problems that become common in the later years.

In evolutionary terms, we harbor flaws because natural selection, the force that molds our genetically controlled traits, does not aim for perfection or endless good health. If a body plan allows individuals to survive long enough to reproduce (and, in humans and various other organisms, to raise their young), then that plan will be selected. That is, individuals robust enough to reproduce will pass their genes—and therefore their body design—to the next generation. Designs that seriously hamper survival in youth will be weeded out (selected against) because most affected individuals will die before having a chance to produce offspring. More important, anatomical and physiological quirks that become disabling only after someone has reproduced will spread. For example, if a body plan leads to total collapse at age 50 but does not interfere with earlier reproduction, the arrangement will get passed along despite the harmful consequences late in life.

We would look a lot different—inside and out—if evolution had designed the human body to function smoothly not only in youth but for a century or more

Had we been crafted for extended operation, we would have fewer flaws capable of making us miserable in our later days. Evolution does not work that way, however. Instead it cobbles together new features by tinkering with existing ones in a way that would have made Rube Goldberg proud.

The upright posture of humans is a case in point. It was adapted from a body plan that had mammals walking on all fours. This tinkering undoubtedly aided our early hominid ancestors: standing on our own two feet is thought to have promoted tool use and enhanced intelligence. Our backbone has since adapted somewhat to the awkward change: the lower vertebrae have grown bigger to cope with the increased vertical pressure, and our spine has curved a bit to keep us from toppling over. Yet these fixes do not ward off an array of problems that arise from our bipedal stance.

What If?

Recently the three of us began pondering what the human body would look like had it been constructed specifically for a healthy long life. The anatomical revisions depicted on the pages that follow are fanciful and incomplete. Nevertheless, we present them to draw attention to a serious point. Aging is frequently described as a disease that can be reversed or eliminated. Indeed, many purveyors of youth-in-a-bottle would have us believe that medical problems associated with aging are our own fault, arising primarily from our decadent lifestyles. Certainly any fool can shorten his or her life. But it is grossly unfair to blame people for the health consequences of inheriting a body that lacks perfect maintenance and repair systems and was not built for extended use or perpetual health. We would still wear out over time even if some mythical, ideal lifestyle could be identified and adopted.

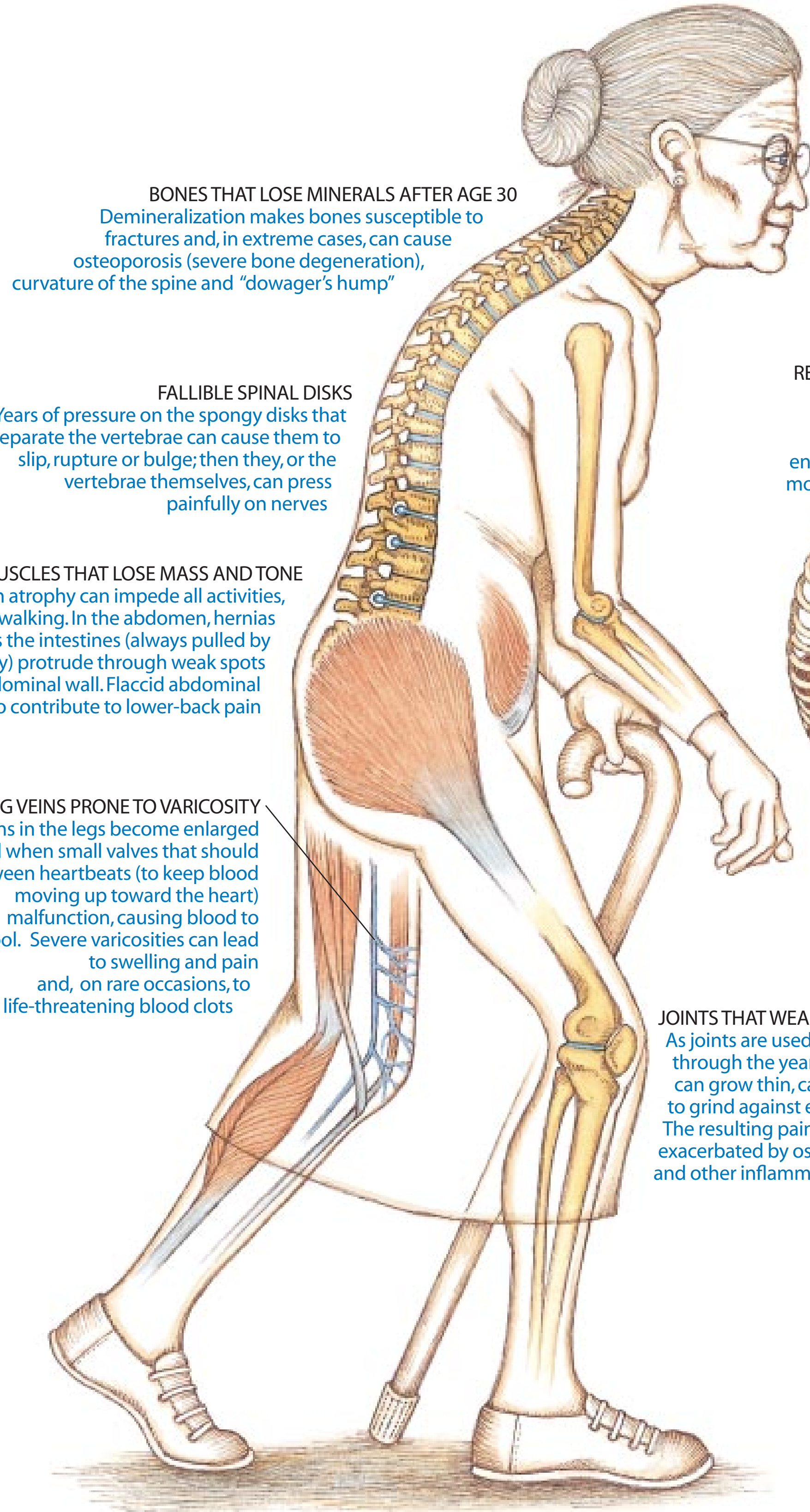
This reality means that aging and many of its accompanying disorders are neither unnatural nor avoidable. No simple interventions can make up for the countless imperfections that permeate our anatomy and are revealed by the passage of time. We are confident, however, that biomedical science will be able to ease certain of the maladies that result. Investigators are rapidly identifying (and discerning the function of) our myriad genes, developing pharmaceuticals to control them, and learning how to harness and enhance the extraordinary repair capabilities that already exist inside our bodies. These profound advances will eventually help compensate for many of the design flaws contained within us all.

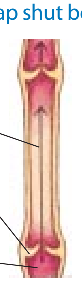
ALL ILLUSTRATIONS BY PATRICIA J. WYNNE

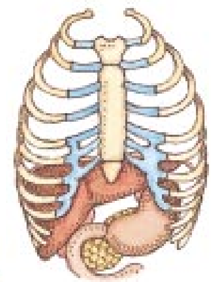
WALK THIS WAY

A number of the debilitating and even some of the fatal disorders of aging stem in part from bipedal locomotion and an upright posture—ironically, the same features that have enabled the human species to flourish. Every step we take places extraordinary pressure on our feet, ankles, knees and back—structures that support the weight of the whole body above them. Over the course of just a single day, disks in the lower back are subjected to pressures equivalent to several tons per square inch. Over a lifetime, all this pressure takes its toll, as does repetitive use

Flaws





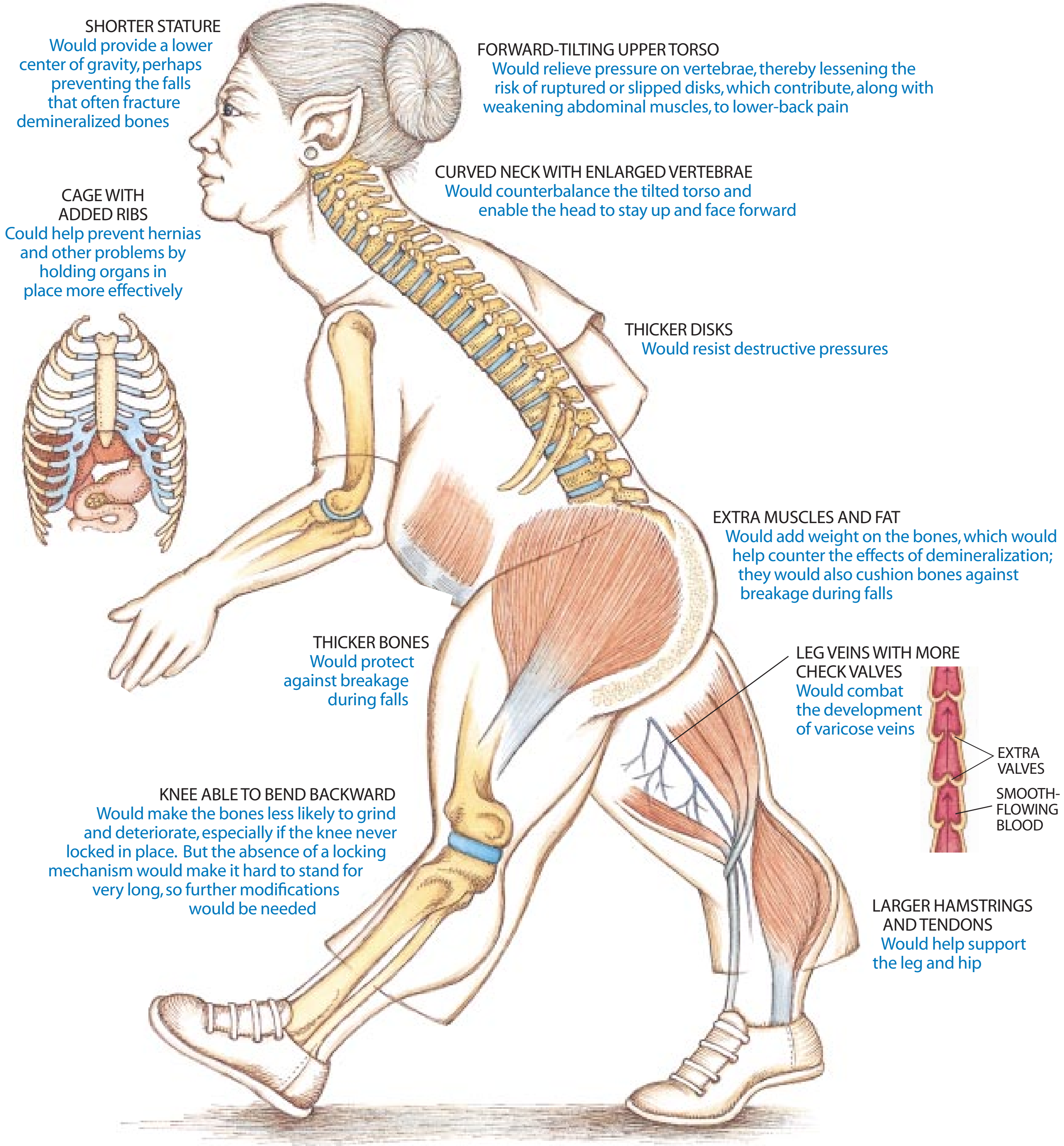


of our joints and the constant tugging of gravity on our tissues.

Although gravity tends to bring us down in the end, we do possess some features that combat its ever present pull. For instance, an intricate network of tendons helps to tether our organs to the spine, keeping them from slumping down and crushing one another.

But these anatomical fixes—like the body in general—were never meant to work forever. Had longevity and persistent good health been the overarching aim of evolution, arrangements such as those depicted below might have become commonplace.

Fixes



PLAN A HEAD

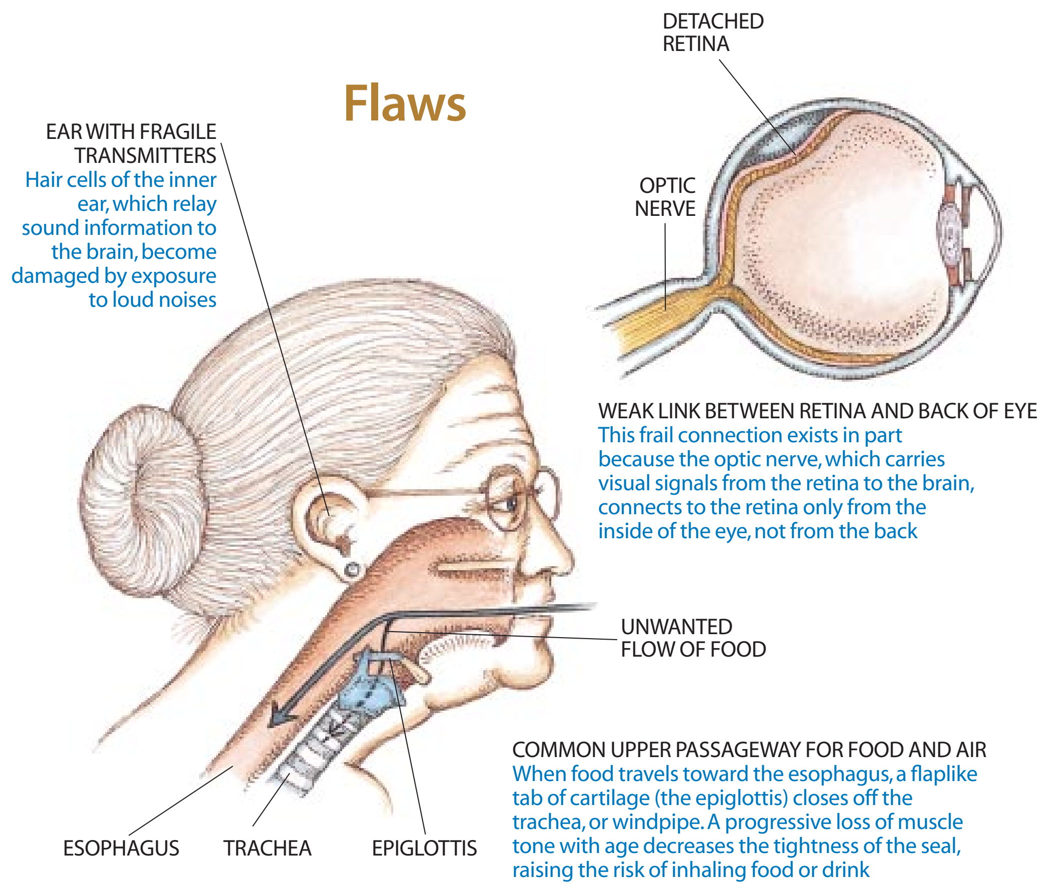
Various parts of the head and neck become problematic with disturbing regularity as people age. Consider the eye. The human version is an evolutionary marvel, but its complexity provides many opportunities for things to go wrong over a long lifetime.

Our vision diminishes as the protective fluid of the cornea becomes less transparent over time. The muscles that control the opening of the iris and the focusing of the lens atrophy and lose responsiveness, and the lens thickens and yellows, impairing visual acuity and color perception. Further, the retina—responsible for transmitting images to the brain—can detach fairly easily from the back of the eye, leading to blindness.

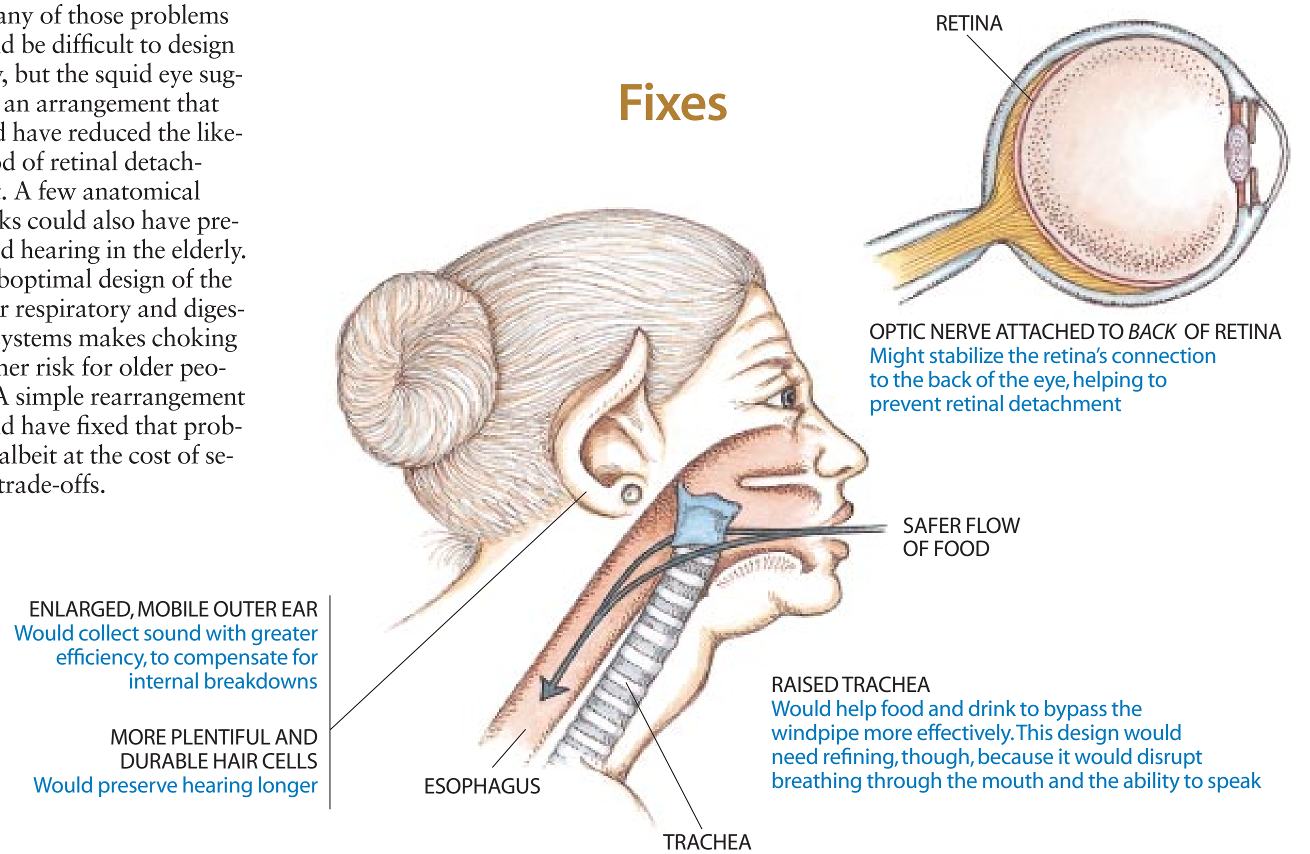
Many of those problems would be difficult to design away, but the squid eye suggests an arrangement that could have reduced the likelihood of retinal detachment. A few anatomical tweaks could also have preserved hearing in the elderly.

Suboptimal design of the upper respiratory and digestive systems makes choking another risk for older people. A simple rearrangement would have fixed that problem, albeit at the cost of severe trade-offs.

Flaws



Fixes

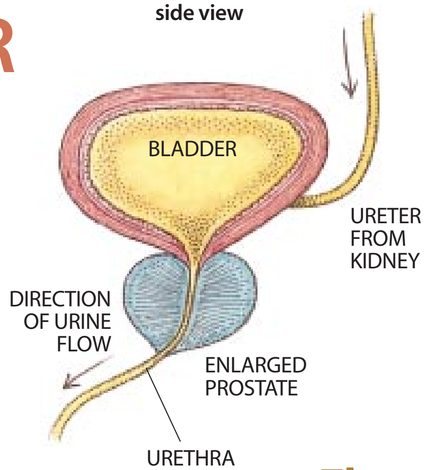


CALL A PLUMBER

An experienced plumber looking at the anatomy of a man's prostate might suspect the work of a young apprentice, because the urethra, the tube leading from the bladder, passes straight through the inside of the gland. This configuration may have as yet unknown benefits, but it eventually causes urinary problems in many men, including weak flow and a frequent need to void.

Women also cope with plumbing problems as they age, particularly incontinence. Both sexes could have been spared much discomfort if evolution had made some simple modifications in anatomical design.

MALE PROSTATE
side view



Flaw

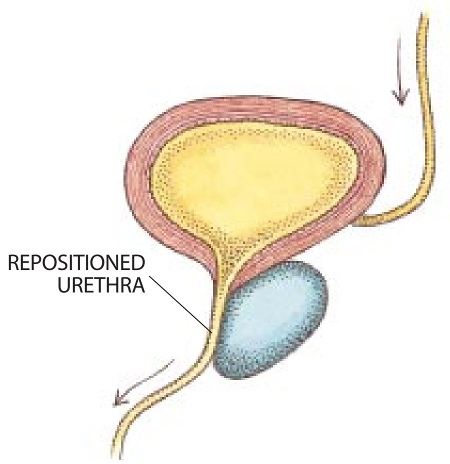
URETHRA PRONE TO CONSTRICTION

The prostate becomes enlarged in one of every two males at some point in life. As it grows, it squeezes the urethra, potentially obstructing the flow of urine. Total obstruction can be fatal

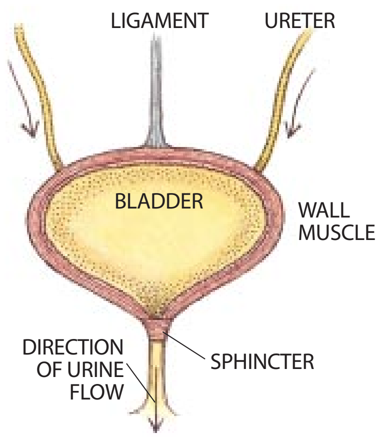
Fix

URETHRA HUGGING OUTSIDE OF PROSTATE

Would not be squeezed if the prostate became enlarged



FEMALE BLADDER
front view



Flaw

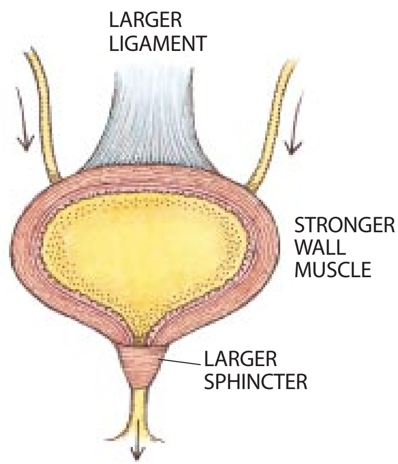
MUSCLES AND LIGAMENTS THAT WEAKEN WITH TIME

Particularly after multiple pregnancies, the muscles of the pelvic floor and the bladder, and the ligaments that support the bladder, can sag, leading to incontinence

Fix

STRONGER SPHINCTER MUSCLES IN BLADDER AND MORE DURABLE LIGAMENTS

Would increase control over bladder function



The Authors

S. JAY OLSHANSKY, BRUCE A. CARNES and ROBERT N. BUTLER all have an enduring interest in the processes that underlie human aging. Olshansky is professor in the School of Public Health at the University of Illinois at Chicago. He and Carnes, both senior research scientists at the National Opinion Research Center/Center on Aging at the University of Chicago, collaborate on studies—funded by the National Institute on Aging (NIA) and the National Aeronautics and Space Administration—of the biodemography of aging (examining the biological reasons for age-related patterns of disease and death in populations). They are co-authors of *The Quest for Immortality: Science at the Frontiers of Aging* (W. W. Norton, 2001). Butler is president of the International Longevity Center in New York City and was founding director of the NIA.

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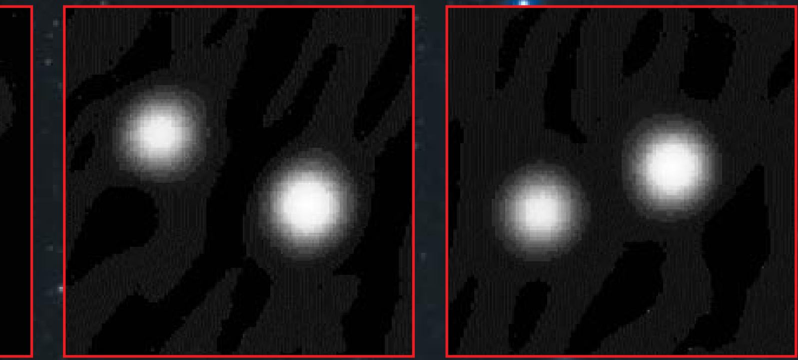
The Olshansky and Carnes Web site is www.thequestforimmortality.com

The International Longevity Center Web site is www.ilcusa.org

A Sharper

A new generation of optical interferometers is letting astronomers study stars in 100 times finer detail than is possible with the Hubble Space Telescope

View of the Stars



CHRISTIAN A. HUMMEL *USNO/NRL Optical Interferometer Project*

FIRST BINARY-STAR SYSTEM imaged with a conventional telescope was Mizar, the middle star in the handle of the Big Dipper. Although Mizar's two components (Mizar A and Mizar B) are less than 0.004 degree apart on the sky, they are themselves each binary stars. In 1996 the Navy Prototype Optical Interferometer (NPOI) resolved the two stars that make up Mizar A, producing the highest-resolution image then made in optical astronomy. These four images show Mizar Aa and Mizar Ab as they execute half an orbit around their common center of gravity.

by Arsen R. Hajian and J. Thomas Armstrong

About 20 years ago one of the authors of this article took his father's binoculars and tiptoed out of the house at night. The budding astronomer decided that he would look for playmates on other planets going around stars in the sky. To his chagrin, the binoculars made no difference whatsoever. The stars appeared as twinkling points of light to his naked eye, and they were pointlike through binoculars as well. Although the largest stars could engulf our entire solar system within their luminous diameters, every star (aside from the sun) is simply too distant to be resolved with binoculars.

Two decades later the same kid can see not just a point of light but a circular disk—at least for some of the brightest stars. This stellar resolution takes advantage of a technique that was suggested more than 130 years ago: interferometry [*see box on page 60 for the history of the technique*]. Instead of looking through binoculars or even a conventional telescope, he must use a computer display connected to a device called an optical interferometer. For more than half a century, interferometry at radio wavelengths has succeeded brilliantly, mapping the structures of distant galaxies and quasars by their radio emissions. Only in the past 15 years, however, has technology allowed interferometry at infrared and visual wavelengths to take off—and the results have been well worth the wait. The Hubble Space Telescope reigns supreme for taking crisp photographs of faint objects, but ground-based optical interferometers can see, for the brightest stars, details 100 times finer than Hubble can.

Optical interferometry is evolving from a difficult laboratory experiment to a mainstream observational technique. Interferometers now coming into operation will

ROGER RESSMEYER *Corbis*

image stellar surfaces, multiple-star systems, clouds or disks of material orbiting stars, and shadows of planets passing in front of stars. Before long, astronomers will have a vast portfolio of new images, including spectacular movies of stars rotating and showing "starspots," the equivalent of sunspots. We will learn more about the birth, structure, activity, evolution and death of stars.

The essence of interferometry is to combine two nearly identical signals to produce interference and thus obtain information that is not available from either signal alone. For example, overlapping the light from two separate telescopes can produce a pattern of light and dark bands. The spacing of those bands and how they vary as the telescopes are moved tell astronomers about the structure of the light source at a much finer resolution than that of the individual telescope images. This method of mapping the spatial structure of the object is called spatial interferometry. (Other types of interferometry can determine properties such as the spectrum of the object's light.)

Spatial interferometry at optical wavelengths is a tricky business, requiring state-of-the-art hardware. In this article we describe how these interferometers work, why it has taken so long for the technique to mature, what we want to look at and what the future holds.

Engineering and the Atmosphere

An astronomer who wants to make a detailed image of a star faces two problems: the limits to telescope size and the turbulence of Earth's atmosphere. Consider one of the most basic questions we can ask: What is the apparent size of a star (that is, the size of the disk that it forms on the sky)?

At closest approach to Earth, the crescent Venus subtends about one arc-

Contributions to Astronomy

Optical interferometry has already become more than a technical curiosity. Almost two dozen interferometers have produced substantial research results in astronomy, including the following:

Single Stars: Stellar Diameters

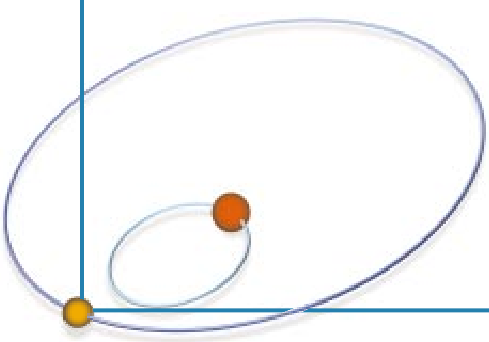
The first measurements of stellar diameters were made in 1920 by Albert A. Michelson and Francis G. Pease, who measured the diameter of Betelgeuse and five other supergiant stars with diameters of 20 to 50 milliarcseconds. If human eyes had this resolving power, you would be able to see the individual atoms composing your hand at arm's length. Roughly half a century later, Robert Hanbury Brown's team at the Intensity Interferometer in Australia measured 32 bright stars ranging from 0.4 to 5.5 milliarcseconds in diameter. Astronomers have now measured the diameters of well over 100 stars, sometimes with about 1 percent precision. Only a few stars have been measured by other techniques, such as studying them as the moon passes in front of them.

A recent image of Betelgeuse

Multiple Stars: Orbits

At least half the stars in the sky in fact consist of two or more stars orbiting around their common center of gravity. Observing the orbits of such double or multiple stars is the only practical way to measure the masses of stars.

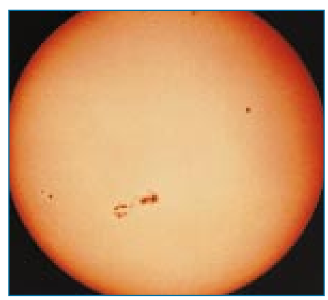
In 1920 John A. Anderson of the Mount Wilson Observatory in California observed the binary star Capella with Michelson's six-meter interferometer and measured the apparent separation of the two component stars at six points around their orbit. Even in 1920 Capella was a well-known spectroscopic binary, meaning that the speed of the two stars in their mutual orbit had been measured by the Doppler shifts of their spectra. Anderson combined his results with those spectroscopic data to deduce the inclination of the orbit (relative to our line of sight) and thereby determined the masses of both stars and the distance to the system.



Modern interferometers have continued to measure binary orbits, with improved precision and higher resolution. The smallest separation between components of a binary star yet measured is about two milliarcseconds for the star TZ Trianguli by Christopher D. Koresko and his colleagues using the Palomar Testbed Interferometer. Today optical interferometry is so precise that it is often the spectroscopic data that limit our knowledge of the stellar masses.

Stellar Surface Structure

Even more difficult than measuring a star's diameter is detecting surface features on its image. This task requires not only better resolution but also greater sensitivity, because surface structure involves relatively small variations of intensity. A simple example of such structure is limb darkening—that is, when the edge of a star's disk, its limb, is not as bright as its center. When one looks at the center of a star, one sees deeper into the stellar atmosphere, where the gas is hotter and brighter. Light from the limb, in contrast, comes from cooler and dimmer gas. Astronomers have observed limb darkening of the sun, and some limb darkening should occur for all stars, depending on their spectral type. Modern optical interferometry can distinguish between a uniform disk and one that is limb-darkened. Studies of limb darkening are needed to test our theories of stellar atmospheres. *—A.R.H. and J.T.A.*



The sun

COURTESY OF JOHN YOUNG CAVENDISH ASTROPHYSICS GROUP (*Betelgeuse*); SLIM FILMS (*illustration*); DENNIS DI CICCO *Corbis* (*sun*) minute, or 1⁄60 of a degree. The best unaided eyes are just capable of resolving a disk that is one arcminute across, that is, of seeing it as a disk and not a point. A telescope with a 15-centimeter mirror can do 60 times better than the finest naked eye, mostly because its aperture is about that much larger than a pupil. In such a telescope, a star appears as a fuzzy disk about one arcsecond in diameter, regardless of the star's size, because the telescope cannot form a smaller image. The fuzziness is caused by diffraction of light passing through the aperture; the smaller the aperture, the larger the image produced.

One arcsecond is the size of a gnat in the centerfield bleachers as seen from home plate or about the size of the largest moons of Jupiter as seen from Earth. But Betelgeuse, the star that forms the largest disk in Earth's sky (aside from the sun), is 1⁄15 that size, about 0.06 arcsecond (60 milliarcseconds) in diameter. The great majority of stars visible to the unaided eye are only a few milliarcseconds or less across.

The resolving power of a telescope—its ability to discriminate small images—improves in proportion to the telescope aperture, so obviously we should use a larger telescope. If a 15-centimeter telescope can resolve a one-arcsecond disk, then a 2.5-meter telescope might resolve Betelgeuse, and one of the 10-meter Keck telescopes on Mauna Kea, Hawaii, might show us details on its surface and resolve many other bright stars. Unfortunately, in practice, increasing the size of the telescope beyond 15 centimeters does no good until we deal with the effects of the turbulent atmosphere.

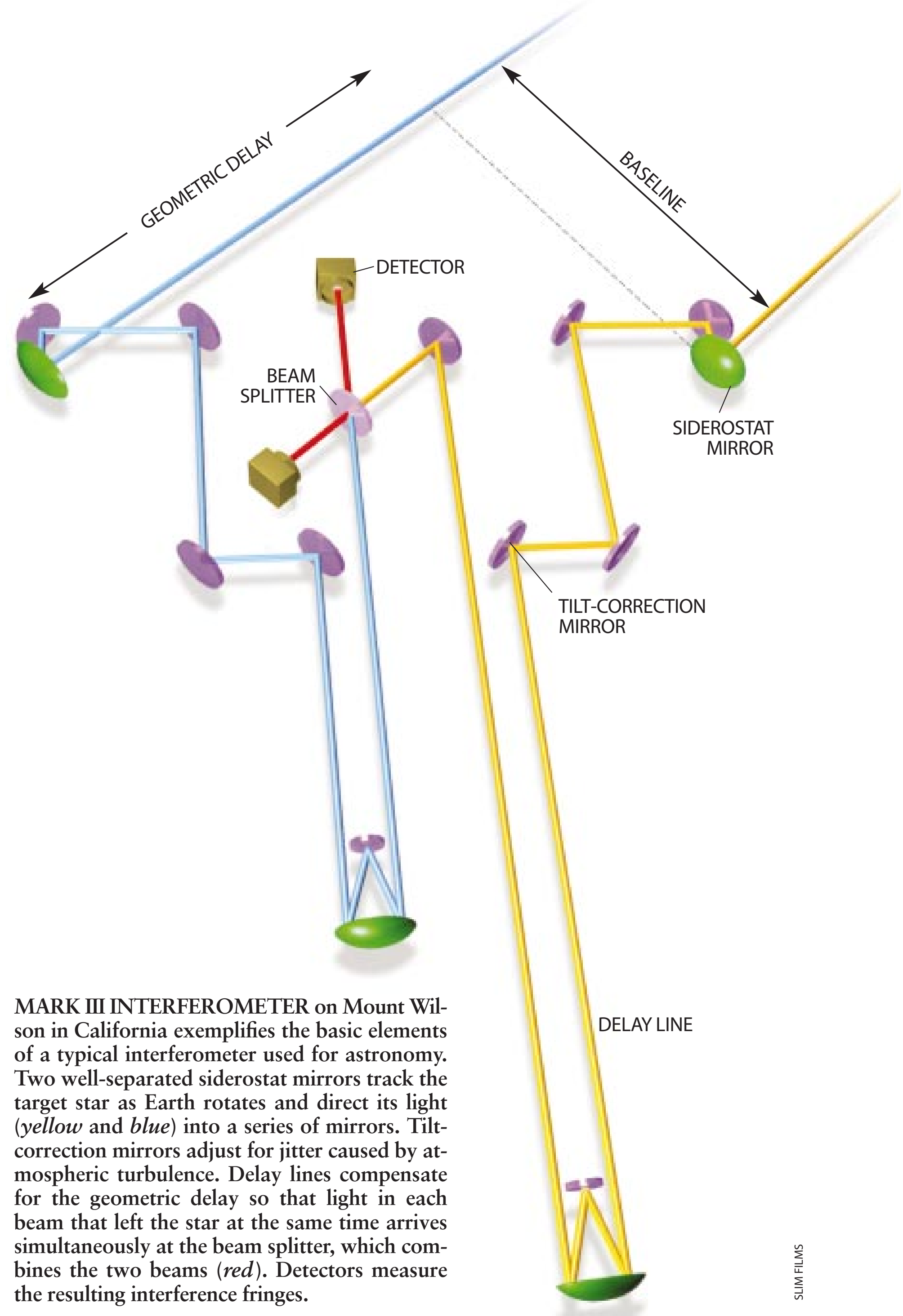
The situation is similar to that of trying to read writing on the bottom of a swimming pool when a strong wind is kicking up waves: the turbulent ripples on the surface distort the light waves coming from the bottom of the pool. Observing the light from stars through Earth's atmosphere is a similar exercise.

Light propagates as a wave. In space above the atmosphere, the light waves from a star arrive as a series of flat planes, like pristine sheets of paper. The turbulent irregularities in the atmosphere distort each wave as it travels to the telescope, making it more like a sheet of paper that someone has wadded up and then tried to smooth out.

The effect of all those wrinkles on the final image turns out to be essentially the same as if the distorted wave were made up of planar sections, each tilted in one direction or another. For light at visible wavelengths, these sections are typically five to 20 centimeters across, depending on the wind and weather, so the segment of the wave arriving at a 10-meter telescope is made up of thousands of such sections. Sections having the same tilt combine to produce an image of the star—a "speckle"—offset according to their tilt. The result is a swarm of speckles moving around rapidly as the atmosphere continually changes. Unless the exposure time is substantially less than one second, the star's image becomes a fuzzy disk that, even in good conditions, is not much smaller than the one produced by a 15-centimeter telescope.

Speckle interferometry deals with atmospheric turbulence by using a conventional telescope and exposure times of about 0.01 second, freezing the speckles' motions. The technique has proved useful for measuring orbits of binary stars, but producing images has turned out to be much harder than practitioners of the technique originally hoped.

In another method, adaptive optics, sensors measure the distortion of the arriving wave, and a computer deforms a mirror to undo as much of the distortion



MARK III INTERFEROMETER on Mount Wilson in California exemplifies the basic elements of a typical interferometer used for astronomy. Two well-separated siderostat mirrors track the target star as Earth rotates and direct its light (*yellow* and *blue*) into a series of mirrors. Tilt-correction mirrors adjust for jitter caused by atmospheric turbulence. Delay lines compensate for the geometric delay so that light in each beam that left the star at the same time arrives simultaneously at the beam splitter, which combines the two beams (*red*). Detectors measure the resulting interference fringes.

as possible. The deformable mirror must be continually adjusted on a timescale of milliseconds. This technique is proving revolutionary in large telescopes, resulting in sharp images with angular resolutions close to the theoretical limit defined by the telescope's aperture [see "Adaptive Optics," by John W. Hardy; Scientific American, June 1994].

But that is still not good enough to discern the size of most stars. Even with the effects of the atmosphere completely removed, a 10-meter telescope could resolve the disks of only a few dozen stars, those that are larger than about 10 milliarcseconds. To measure the diameters of just the stars visible to the unaided eye, for instance, we would need a telescope 500 meters in diameter. Such a large mirror—built to the required precision (a fraction of a micron), supported without distortion and directed to point at specific stars—is far beyond the realms of near-future engineering and economic possibility.

But it turns out we don't need the entire disk of the 500-meter mirror. The trick of interferometry is to place two much smaller telescopes 500 meters apart, correcting for the image motion caused by the atmosphere and combining their light at a central location.

How Interferometry Works

Picture three instruments: a conventional reflecting telescope; the same telescope with all but two small segments of its primary mirror masked off (making it into a so-called sparse-aperture telescope); and an interferometer, consisting of two small primary mirrors and a means of conveying the light that they gather to a detector. Each instrument collects light and delivers it in synchrony to its detector in a different manner.

In the conventional telescope the curvature of its single large mirror assures that all parts of a light wave from a star arrive at the focus at the same time. (In fact, that simultaneous arrival defines the location of the focus.) The sparse-aperture telescope works the same way: its two mirror segments gather light, and each segment simultaneously delivers its part of a wave to the focus. Both telescopes produce an image on a detector (usually a charge-coupled device, or CCD) positioned at the focus, although the image from the sparse-aperture telescope is degraded because of the incompleteness of its primary mirror.

The interferometer resembles the sparse-aperture telescope in having two small mirrors that collect light, but it has several key differences. First, the two mirrors can be on independent mounts instead of being part of a single, large, rigid framework that gets pointed in its entirety at a star. This autonomy is possible because the light-gathering function of each mirror has been separated from

Interferometers for Astronomy across the Ages

1868: French physicist Armand-Hippolyte-Louis Fizeau suggests masking a telescope aperture to perform interferometry. He proposes measuring the sizes of stars by placing a two-hole mask over a telescope and observing the resulting interference pattern.

1876: Édouard Stephan tries Fizeau's technique with the 80-centimeter telescope at Marseilles. But the 65-centimeter separation between the holes that he uses is not enough to measure the stars' sizes. When Stephan looks through his eyepieces at a star, he sees an image of the star from each aperture in the mask. These images are large and usually overlap. The region of overlap is crossed by dark stripes (interference fringes). To measure a star's diameter, one increases the separation between the apertures until the fringes disappear. The larger the separation required, the smaller the star. But Stephan runs out of telescope before the separation becomes large enough. He concludes only that the stars he observes are all smaller than 0.16 arcsecond.

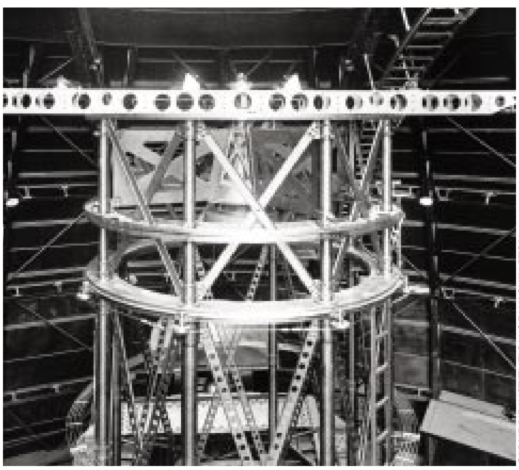
1891: Albert A. Michelson, apparently without knowing of the work of Fizeau and Stephan, tries the same technique, but he looks at the Galilean moons of Jupiter. He succeeds in measuring their sizes because, at diameters between one and two arcseconds, they are considerably larger than stars.

1920: Michelson measures stars by installing a six-meter metal beam with mirrors at each end across the aperture of the 100-inch (2.5-meter) Hooker telescope at Mount Wilson in California, then the biggest in the world (*right*). In the 1930s Michelson's collaborator Francis G. Pease attempts interferometry with mirrors on a 15-meter mount, but he fails, probably because the mount is not mechanically stiff enough.

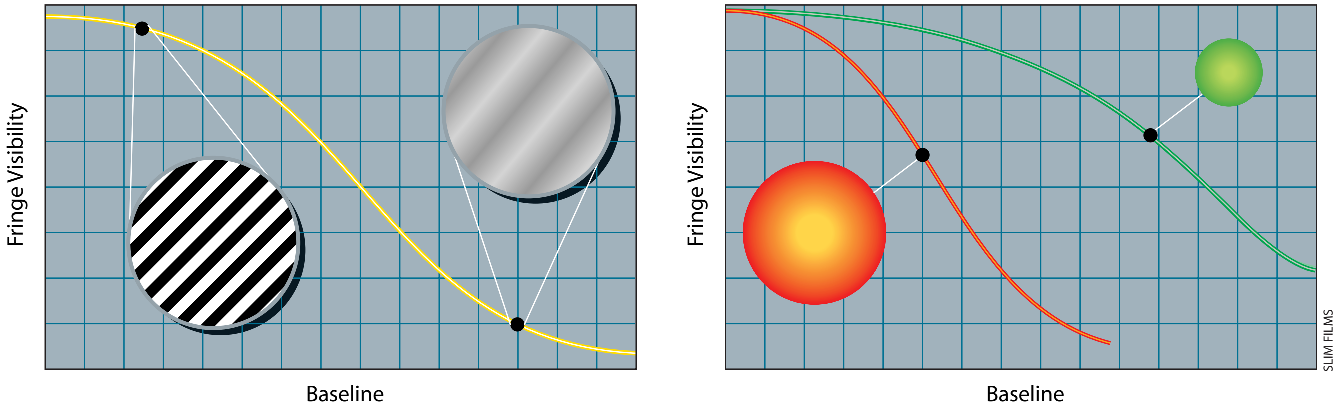
1950s–1960s: Tremendous advances are made in the use of interferometry for astronomical observations using radio wavelengths. Radio interferometry is much easier than optical interferometry because the wavelengths are several thousandfold longer, which reduces the atmosphere's relative effects and eases the engineering precision needed to achieve interference. Further substantial advantages include being able to amplify the radio signals and to record the data at each telescope for combining later.

1958–1976: Robert Hanbury Brown, Richard Q. Twiss and their colleagues take two important steps when they build the Intensity Interferometer near Narrabri, Australia. First, they break the aperture barrier by using two separate telescopes instead of putting a contraption of mirrors across one central telescope. The interferometer's two 6.5-meter telescopes are separated by 10 to 188 meters, a record that has yet to be surpassed. Second, they use electronic detection and data recording, whereas previous researchers observed by eye.

Brown and Twiss also take the novel approach of detecting individual photons at the separate telescopes and correlating their arrival times. This technique has the virtue of simplicity (the light beams from the telescopes are never brought together) but has low sensitivity: even with 100 hours of observation time, the scientists can study


CARNEGIE INSTITUTION OF WASHINGTON

Michelson's 1920 interferometer



SLIM FILMS

INTERFERENCE FRINGES for a single star (*left*) have higher visibility, or contrast, for short baselines and lower visibility for long baselines. The diameter of a star (its angular size on the sky) can be deduced from its fringes (*right*). As the baseline is increased, the fringe visibility of a large star falls faster than that of a small star. Measurements of small stars therefore need larger baselines.

the process that combines their light.

The second difference is how the light is combined in synchrony. In general, one of the primary mirrors is closer than the other to the star under observation [*see illustration on page 59*]. Think of a specific wave of light from the star as a pulse that it has emitted. Unless the star and the mirrors happen to be positioned symmetrically, this pulse will hit one mirror before the other. To compensate for this difference in timing, the light path from each mirror to the common detector includes an adjustable detour, called a delay line, consisting of mirrors on a slide that can be positioned with very high precision.

The third difference is that the light is

stars no dimmer than those of Orion's belt, about magnitude 2.5 in technical terms.

1974: Two groups use the separate-telescope approach with more sensitive detection techniques. Antoine Labeyrie and his colleagues, working at visual wavelengths and using Michelson's technique of combining the two beams before detection, observe the star Vega with a 12-meter baseline. At Kitt Peak, Ariz., a group under Charles H. Townes, working in the midinfrared, borrow a technique from radio astronomy to observe Mercury on a 5.5-meter baseline. Known as heterodyning, the method involves converting the detected high-frequency signal down to lower frequencies in much the same way as a radio receiver converts 100-megahertz FM radio signals down to the frequencies of sound in the human hearing range.

MICHAEL COLLIER AND NATHANIEL WHITE *NPOI*

Navy Prototype Optical Interferometer on Anderson Mesa in Arizona

1980: The Very Large Array (a radio interferometer) is commissioned in Socorro, N.M. It goes on to produce thousands of significant results. [For more on radio interferometry, see "The Very-Long-Baseline Array," by Kenneth I. Kellermann and A. Richard Thompson; Scientific American, January 1988.]

Recent optical work: Following the work of Labeyrie and Townes, activity in optical interferometry picked up speed. Townes has continued the midinfrared development begun in the early 1970s. His group is now operating a two-element heterodyne interferometer with 1.6-meter telescopes on a 32-meter maximum baseline and has studied dust around stars far along in their life cycle. A third telescope and a 75-meter maximum baseline are soon to come.

Since 1974 astronomers have built over a dozen visual and near-infrared interferometers, of which eight are in operation and five are under development. All of these have extended the architecture used by Labeyrie in various ways: baseline length (the current maximum is 80 meters at the Sydney University Stellar Interferometer, Australia); aperture size (1.5 meters, GI2T, France); number of telescopes used at once (four, Cambridge Optical Aperture Synthesis Array, England); and wavelength range (450 to 850 nanometers, Navy Prototype Optical Interferometer, U.S.). The box on page 58 discusses the types of results obtained by these groups.

—A.R.H. and J.T.A.

combined not to produce an image of the star but to detect how the two beams of light interfere. When the peaks and troughs of the two light waves coincide (the waves are "in phase"), constructive interference occurs, producing a high intensity. Light that combines out of phase interferes destructively, producing a low intensity. These oscillations of bright and dark are called fringes.

Astronomers measure the fringes' contrast, or visibility, which varies according to the characteristics of the light source (for example, the size of a star or the separation between two stars in a binary system) and according to the length and orientation of the interferometer's baseline, the line connecting the two mirrors. Astronomers can take measurements from many different baselines, most easily by waiting while Earth rotates. In addition, most of the new interferometers have more than two mirrors in the array and can move the mirrors along tracks.

The researchers analyze the signals by computer, using Fourier transform algorithms to convert the measured fringes into a map of the object under study. That map is actually the same as the imperfect image that would be seen by a sparse-aperture telescope with a diameter equal to the interferometer's baseline. So although the results can have very high resolution, the information they convey is incomplete, somewhat like a view of a house partially hidden behind a tall picket fence. As data from more baselines are combined, the image becomes more complete, as if one saw the house through the fence's blurred pickets while gliding by on a bicycle.

Costs and Complications

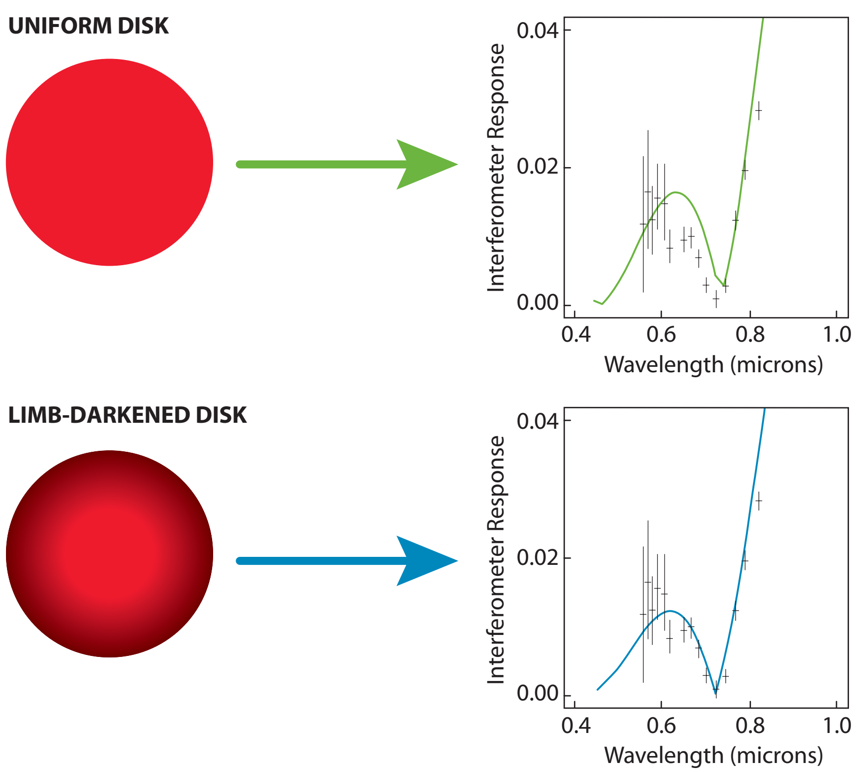
Optical interferometry avoids the costs and difficulties of building a single mammoth telescope but exacts its own price in ways that designers must consider carefully. The light beams from each telescope must be transported dozens or hundreds of meters to the central facility where they are combined. Different wavelengths of light travel at different speeds through air, so the beams must be transported in a vacuum. The expense of the infrastructure grows quickly as the baseline size and number of elements are increased.

An interferometer with more than two telescopes can produce more complete images of objects by simultaneously obtaining fringes for many different baselines. But there are limits to how far this can be pushed. With a 10-telescope interferometer, for instance, one would want to split each light beam into nine beamlets for combining with beamlets from the other telescopes. This dilution lowers the instrument's sensitivity because each set of fringes must be produced with fewer photons. The practical limit is in the range of five to 20 telescopes. In addition, the complexity of the combining optics increases very rapidly because the number of baselines increases roughly as the square of the number of telescopes. For example, two telescopes have a single baseline; 10 would have 45 baselines. Each mirror along a light path saps a percent or so of the beam's photons.

Atmospheric turbulence, the nemesis of large telescopes, also creates problems for an interferometer. Turbulence makes the apparent position of a star on the sky jitter around irregularly. This jitter often causes the beams in two arms of the interferometer to overlap imperfectly or not at all at any given moment. Including sensors and a rapidly responding tilting mirror in each optical path—technology that can be borrowed from adaptive optics—can partially correct the jitter problem.

But turbulence also causes a second problem: it adds a random and very rapidly changing delay to each beam because each telescope looks through a different patch of turbulent atmosphere. This effect degrades the interference needed to produce visible fringes, and it must be removed as much as possible to measure fainter stars and to improve precision.

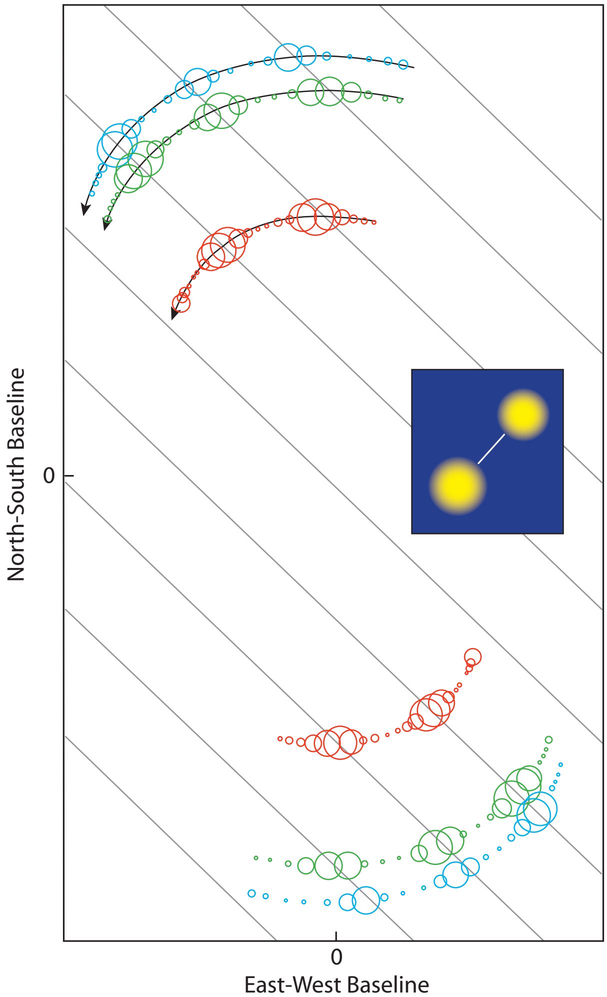
The need for these corrections imposes severe constraints on the interferometer's sensitivity. One cannot get around these constraints by increasing the telescope sizes or using longer data collection times: the information needed to make the corrections—embodied in light from the object under study or another nearby bright star—must be gathered from apertures no bigger than about 20 centimeters (so that the angle tracker has only one speckle to follow) and must be gathered within about 10 milliseconds (so neither the speckles nor the fringes move appreciably). The interference signal itself must also be detected in a gathering time of a few milliseconds to avoid its smearing by the atmospheric fluctuations.



LIMB DARKENING of stars can be detected by interferometers. Data from Alpha Cassiopeiae (*cross shapes*) agree poorly with the theoretical curve for a uniform disk (*top*) but match that expected for a slightly larger but limb-darkened disk (*bottom*). Such results provide information about the atmospheres of stars but require large baselines to achieve resolution finer than the star diameter.

JOHNNY JOHNSON; SOURCE: NPOI

The amalgam of technology needed for all these functions ranges from high-speed photodetectors to computers capable of recording at least several gigabytes of data per night to frequency-stabilized lasers, which precisely monitor delay-line lengths that are changing on millisecond timescales. These tools have become available and mature only in the past 20 to 30 years, and the learning curve to use them effectively has been steep.



BINARY STAR CAPELLA produced this distinctive pattern of fringes at the Mark III Interferometer. As Earth rotates, the interferometer's baseline follows an elliptical arc. The size of each circle indicates the visibility of fringes seen using that baseline, at one of three wavelengths (*colors*). Equally spaced lines pass through the positions of maximum visibility. The two stars in Capella must be oriented at right angles to these lines (*inset*), separated by a distance that depends on the reciprocal of the lines' spacing.

What's Coming

All these problems produce the single largest disadvantage of current optical interferometers: they are barely more sensitive than the naked eye, albeit with much higher resolution. Nevertheless, even limited to the few thousand brightest stars in the sky, interferometers are already amassing a tremendous observational database and producing unique results that justify the effort required [*see box on page 58*]. And these limitations will be overcome in the near future when sophisticated adaptive optics systems are installed on groups of large telescopes.

In recent years, astronomers have been constructing numerous optical and infrared interferometers of ever increasing sophistication. Optical interferometers with several telescopes will soon be online. For example, the Navy Prototype Optical Interferometer (NPOI) on Anderson Mesa in Arizona expects to deploy six apertures within the year, with 15 baselines. In principle, with enough data, astronomers can make a map of a star using methods similar to those used in radio interferometry. In practice, those traditional methods are straightforward in optical interferometry for only the simplest of source structures: binary stars. Custom algorithms are being developed to produce optical maps of sources whose appearance may take any form, such as elliptical stars, stars with spots, and stars with outflowing or flaring material. Optical interferometers have a lot of catching up to do to reach their cousins operating at the longer wavelengths of radio waves.

Interferometers that have advanced adaptive optics, such as the Keck Interferometer (two 10-meter telescopes 85 meters apart) and the Very Large Telescope Interferometer (an array of four eight-meter telescopes in Chile), will image faint astronomical phenomena with superb angular resolution. Both of these facilities will be enhanced with smaller, more widely spaced outrigger telescopes. Proposed space-borne platforms such as the Space Interferometer Mission, the Terrestrial Planet Finder and the MicroArcsecond X-ray Imaging Mission will push astrometry (the science of measuring stellar positions) into the *micro*arcsecond range and will be able to detect planets. Even with optical interferometry, our children still won't be spotting playmates on other planets anytime soon, but nonetheless a profusion of technology and scientific results lies ahead. SA

The Authors

ARSEN R. HAJIAN and J. THOMAS ARMSTRONG share a long-standing interest in optical interferometric techniques. Hajian has been interested in optical interferometry since his early days as a binocular kleptomaniac, and he joined in the NPOI collaboration in 1995. In addition to his work on NPOI, he is building an interferometric spectrometer at the U.S. Naval Observatory, where he is an astronomer. Armstrong, an astronomer at the Naval Research Laboratory in Washington, D.C., has worked in optical interferometry since joining the Mark III collaboration in 1989. He initiated the Mark III binary-star observation program, which has continued with NPOI, and devised the layout of NPOI.

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Links to home pages of current and planned stellar optical interferometry projects and many other resources are at http://huey.jpl.nasa.gov/olbin/links/links.html

JOHNNY JOHNSON; SOURCE: MARK III INTERFEROMETER

Evolution: A Lizard's Tale

by Jonathan B. Losos

On some islands in the Caribbean, evolution seems to have taken the same turn—over and over and over again

Anole lizards can be found everywhere on the islands of the Greater Antilles: in the tops of trees, along their trunks, down among the leaf litter, on fence posts, near flowers. They come in all forms: short, long, blue, brown, green or gray, strong jumpers, poor jumpers, big and brazen, creeping and cautious. This incredible diversity makes the anoles, members of the genus *Anolis,* fascinating creatures to study. For hidden in their myriad forms and dwelling places is the key to an important biological mystery: What drives a creature's evolution to take one path instead of another?

Any visitor to the islands will quickly see that the kinds of anoles that occur together—that is, sympatrically—differ in the habitat they occupy. One species, for example, will be found only in the grass, another only on twigs, a third nearby on the base of tree trunks, sometimes venturing onto the ground. These three species also differ in their morphology. The grass dweller is slender with a long tail, the twig dweller is also thin but with relatively stubby legs, and the tree lizard is stocky with long legs.

What is striking about these lizards is not just that coexisting species differ in morphology and how they use their habitat. Such differences are actually the norm among closely related, sympatric species: Darwin's finches on the Galápagos Islands and the lemurs of Madagascar

ANOLE LIZARDS of the Caribbean islands are a diverse bunch. In the Greater Antilles, about 110 species have evolved to fill nearly every ecological niche, from the crown giant that lives in tree canopies to the long-tailed grass-dwelling anole.

provide two famous examples of animals that adapted into every available niche. What is unusual about the Caribbean anoles is that the same types of habitat specialists occur on each island. If a visitor goes to Puerto Rico and observes the twig species that lives there, he can then travel to each of the other Greater Antillean islands of Cuba, Hispaniola (which encompasses Haiti and the Dominican Republic) and Jamaica, and find a species that looks nearly identical, lives in the same type of habitat and behaves in much the same manner. All four islands also have a base-of-tree specialist, an arboreal specialist and a tree-canopy giant. In addition, grass specialists occur on three islands, and trunk specialists (which have flatter bodies and shorter tails than do base-of-tree lizards) on two.

Biologists are accustomed to finding similar species in similar ecological niches in different parts of the world. The marsupial cat and marsupial wolf of Australia are morphologically and ecologically similar to their feline and canine counterparts on other continents. But convergence of entire communities is an entirely different matter. Although communities in different areas often bear some resemblance to one another, the occurrence of communities composed of the same set of ecological specialists is virtually unparalleled.

Once Was Not Enough

The existence of such communities implies that some deterministic process is responsible for shaping their structure—that something drives the lizards' evolution to take the same course again and again. My colleagues and I have been testing this idea, which has meant testing the three assumptions it is based on: that the specialists evolved independently on each island, that the lizards are indeed adapted for their particular ecological niches and that similar ecological and evolutionary processes operate on each island. In the past 20 years the arsenal of tools available to evolutionary biologists has expanded enormously, allowing us to draw on many disciplines to answer our questions. Using fossil records, field observations, experiments and DNA sequencing, we have begun to figure out what is happening with the anoles of the Greater Antilles.

The presence of similar species on different islands could be explained in several ways. An ancestral species might have adapted to exploit a particular ecological niche on one island and then made its way over water—perhaps by raft or hurricane—to colonize other islands. Or this ancestral specialist might have evolved at a time when the islands were connected, which some of the Caribbean islands may have been. After the islands separated, the isolated lizard populations would have become distinct species, while also retaining the adaptations of their ancestors. Both of these scenarios imply that specialization to each niche occurred only once. Alternatively, each specialist could have arisen independently—or convergently—on each of the Greater Antilles.

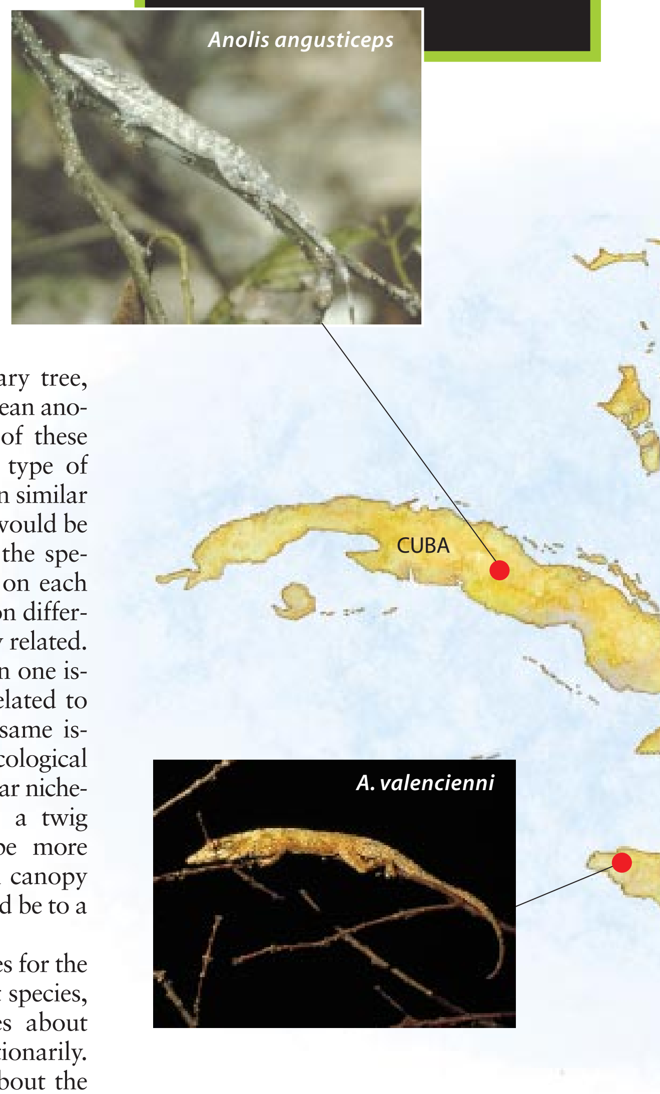
By examining an evolutionary tree, termed a phylogeny, for Caribbean anoles, we can determine which of these possibilities occurred. If each type of specialist evolved just once, then similar specialists on different islands would be closely related. Conversely, if the specialists evolved independently on each island, then similar specialists on different islands would not be closely related. In the latter case, a specialist on one island would be more closely related to other types of lizards on the same island—regardless of their ecological niche—than it would be to similar niche-users on different islands. So a twig dweller on Jamaica would be more closely related to the Jamaican canopy or tree-base lizards than it would be to a Cuban twig dweller.

By comparing DNA sequences for the same gene or genes in different species, biologists can draw inferences about how species are related evolutionarily. Although controversy exists about the best method of deducing phylogenetic relationships from DNA comparisons, researchers agree that species that have more similar DNA are, in most cases, more closely related to each other than to another species whose DNA is less similar. Thus, humans and chimps, which share a great deal of their DNA, had a common ancestor much more recently than did humans and baboons, which share less.

Using this approach, a team including Todd R. Jackman (now at Villanova University), Allan Larson of Washington University and Kevin de Queiroz of the Smithsonian Institution sequenced several genes from more than 50 species of anoles. The data are clear-cut: habitat specialists on one island are not closely related to the same habitat specialists elsewhere. Our findings indicate that specialists evolved independently on each island and that similar communities evolved independently on each island.

The fossil record can often provide another form of evidence for such conclusions. Unfortunately, except for specimens from only the past few thousand years, anole fossils are extremely rare. Perhaps a dozen exist, all of them encased in amber. Presumably these lizards became stuck in the oozing resin of ancient trees that later fell to the ground and became fossilized. Given

GREATER ANTILLES islands, which consist of Cuba, Hispaniola (Haiti and the Dominican Republic), Puerto Rico and Jamaica, each have an anole that has evolved to live primarily on twigs.



ROBERTO OSTI (*map*); JONATHAN B. LOSOS (*photographs*) the popularity of *Jurassic Park,* most of the amber fossils quickly find their way into private hands and remain unavailable for study. Nevertheless, we have examined two specimens found on Hispaniola, dating from the Miocene period, approximately 20 million years ago. These specimens are virtually indistinguishable from the tree-canopy habitat specialists living today and make clear that the phenomenon of anole habitat specialization is an ancient one.

Convergent evolution in similar situa-

tions suggests that features have evolved in response to similar problems posed by the environment. Testing this possibility requires understanding why a particular feature may be favored in certain circumstances. Take leg length as an example. As I mentioned above, Caribbean anoles that live on twigs have very short legs, whereas those occupying lower tree trunks have very long legs. To see whether leg length evolved as a response to differences in the diameter of the surface, we need two kinds of information. We have to discover what the functional consequences of differences in leg length are, and we have to gather data on the relevance of such differences to the behavior and habitat use of the species.

To obtain such information we had to combine laboratory and field approaches. In the laboratory, we investigated functional capabilities by focusing on ecologically relevant measures, such as how fast a lizard can run or how well it can cling. Some of these studies required sophisticated electronic equipment. To record how fast a lizard runs, for example, we built a lizard racetrack—a narrow route two meters in length with infrared beams and detectors positioned every quarter of a meter. Lizards placed at one end of the track usually sprint rapidly toward the dark bag at the opposite end. To determine clinging ability, we placed lizards on a vertical, highly sensitive plate that measures the force their toe pads generate as the lizards attempt to maintain their position while being pulled downward by the experimenter.

Other equipment is not nearly so technologically advanced. To measure maximum jumping capabilities, we put lizards on a flat board 30 centimeters above the ground and induced them to jump by tapping them on the tail. We then measured how far they had jumped.

These various studies have confirmed much of what one would expect. When the effects of the differences in body size are factored out, both running and jumping ability are related to relative hind-limb length. This finding is predictable because long-legged lizards take longer strides and attain higher velocities during jump takeoff. Similarly, larger toe pads confer greater clinging ability.

But the studies also provided some surprises. Most notably, the relation between limb length and sprint speed depends on the surface on which the lizard is running. As surface diameter diminishes, so does the advantage of longer limbs. The long-legged Puerto Rican base-of-trunk specialist *Anolis gundlachi* can run twice as fast as the short-legged Jamaican twig species *A. valencienni* on flat surfaces. But *A. gundlachi*'s speed declines markedly with diminishing surface diameter. On narrow surfaces that are one centimeter in diameter, the species run equally slowly, despite the differences in the lengths of their legs. But whereas the twig anole is very sure-footed on surfaces of all widths, the longer-legged species trips or falls more often than not on narrow surfaces.

This variation in functional capability supports the contention that morphological differences have indeed evolved as adaptations to different environmental niches. But only by examining what animals actually do in nature can we determine whether these capabilities really confer any advantage. Painstaking field studies, conducted primarily by Duncan Irschick, now at Tulane University, reveal that anoles almost always jump distances considerably shorter than the maximum capabilities observed in the laboratory. Therefore, the evolution of long legs is unlikely to have resulted as a response to selection for jumping ability.

In contrast, anoles often do run at top speed—especially when trying to avoid predators. The species that run most frequently are those with the greatest sprinting abilities and the longest legs. Short-legged species rarely run: whether stalking prey or eluding predators, they take the opposite approach, moving stealthily to avoid detection. Given their lack of speed, surefootedness is particularly important, as a stumbling lizard is more likely to attract attention and, once detected, is less likely to escape.

Of Plasticity and Natural Selection

Seeing natural selection at work—that is, seeing a creature adapt to a new habitat and develop a specialization such as short-legged surefootedness—is a rare privilege. Evolution most often occurs over timescales humans cannot experience. But an experiment initiated in the late 1970s by Thomas and Amy Schoener of the University of California at Davis has allowed us a tiny window onto this process. Noticing that certain very small islands in the Bahamas do not naturally harbor anoles, the Schoeners introduced the brown anole, *A. sagrei,* to 20 islands to study the process of extinction. To their surprise, the Schoeners found that the populations survived and even flourished on all but the smallest islands. (The Schoeners' conclusion that the absence of lizards results from the occasional hurricane was verified in 1996 when Hurricane Lili wiped out lizard populations on many small islands.)

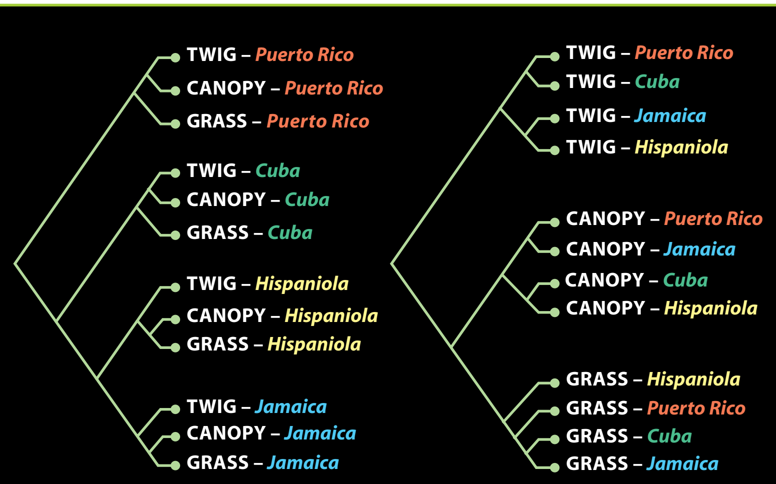
Because the islands differ in vegetation—some have broad tree trunks and others only scraggly bushes—the Schoeners' introduced lizards gave us the chance in 1991 to see whether they had adapted to the different circumstances in which they found themselves. Based on our studies of the anoles of the Greater Antilles, we could make predictions: lizard populations on islands with broad surfaces should have longer legs than do those on islands with only narrow perching surfaces. Our findings corroborated these predictions, indicating that populations had rapidly adapted to environmental differences in just the way we expected. We found that lizards with wider substrates had legs that were several millimeters longer than those raised on narrower surfaces.

A second scenario could also explain these results. The legs of lizards growing up on broader surfaces might simply grow longer than the legs of lizards on narrower surfaces. Such a phenomenon, termed phenotypic plasticity, could even result in individuals that are genetically identical. Studies on bone growth, conducted on mammals and birds, indicate that the bones of individuals experiencing different stresses and strains during growth develop differently. For example, the serving arms of professional tennis players are longer than their nonserving arms. Given that professional tennis players spend hours smashing tennis balls, day after day, during their childhood, these results clearly indicate how differences in activity patterns can lead to differences in limb length.

It is a long way, however, from professional tennis players to lizards growing up on islands with different kinds of vegetation. To see if experience could alter the limb length of the lizards, a number of colleagues and I raised baby *A. sagrei* at the St. Louis Zoo in two environments: on narrow 0.7-centimeter-wide wooden dowels and on broad eight-centimeter-wide boards. What we found, to our surprise, is that the lizards that grew up on the broad surface developed longer limbs than those that grew up on the narrow surfaces—although the differences were not as great as those found between twig users and base-of-tree users in the Greater Antilles.

These findings suggest that the differences observed among the introduced Bahamian populations might result from phenotypic plasticity. To verify this conclusion, we will need to raise lizards from populations with different limb lengths under similar, controlled conditions. If the observed differences in nature are the result of phenotypic plasticity, then differences in limb length should not appear among individuals raised in captivity under identical conditions.

In recent years scientists have begun to consider the possibility that phenotypic plasticity may play an important role in adaptive evolution. By producing morphologies suited to different environments, phenotypic plasticity may allow a population to utilize a habitat in which it otherwise could not survive. Such differences, of course, are not genetically based and do not reflect evolutionary change. But eventually mutations will occur, by chance, in these populations, making the individuals even better adapted to this new habitat. These changes, being genetically based, would lead to evolutionary change. Given enough time, mutation and natural selection could produce species substantially different, and better adapted, than the ancestral form. In this way, phenotypic plasticity could be an important means by which major evolutionary changes are initiated. This hypothesis—first put forth more than 50 years ago but only now receiving serious attention—merits further investigation.



EVOLUTIONARY TREES depict two of many possible hypotheses about the anole lizards' genetic relatedness. At one extreme, each kind of specialist evolved again and again, on different islands (*left*). At the other extreme, each specialist evolved only once and then ended up on various islands (*right*). DNA analysis suggests that a situation similar to the first scenario is more likely.

LAURIE GRACE

An Island Is an Island Is an Island

The last piece of the puzzle that we needed to look at is why specializations evolved in the first place. One explanation posits that two ancestral, unspecialized species became sympatric, perhaps because one colonized an island occupied by the other. Because most species of anoles are quite generalized in their diets, eating a wide variety of different kinds of insects as well as, in some cases, fruits and small vertebrates, two such species are likely to have competed for food. By utilizing different habitats and eating different prey, they could minimize competitive interactions. Natural selection would favor the evolution of features that made each species well adapted to its habitat, producing the specialized species we now see.

Although it is not possible to determine whether, in fact, competition among ancestral anoles led to specialization, we can ascertain whether competition occurs among species today. A large body of work implies that it does. Comparisons of populations of *A. sagrei* in the Bahamas reveal that in areas where the species occurs by itself, it perches higher and uses a broader range of perching sites than it does in areas where other species of anoles are present. Competition with other, more arboreal species seems to force the brown anole to alter

PHENOTYPIC PLASTICITY is evident when *Anolis sagrei* is raised from hatching to adulthood on different substrates. Lizards growing up on thin dowels develop slightly shorter hind limbs (by a few millimeters) than do those growing up on wider boards. (Drawings are not to scale.)

its habitat use. But there are other explanations for this behavior as well. Maybe the habitat differs in places with and without other species.

Fortunately, field experiments can help settle this question. In the Puerto Rican rain forest, graduate students Manuel Leal and Javier A. Rodríguez-Robles (now, respectively, at Union College and the University of California at Berkeley) and I captured and removed all individuals of *A. gundlachi*—the long-legged lizard that lives at the base of the tree—from three 20-by-20-meter plots. We then monitored the population densities of a second species, the Evermann's tree-canopy anole, or *A. evermanni.* Three similar plots in which *A. gundlachi* was not removed served as controls. After eight weeks, population densities of *A. evermanni* were significantly higher in the plots without *A. gundlachi* than they were in the controls.

Similar results were obtained in studies that David Spiller of the University of California at Davis and I conducted on some tiny islands in the Bahamas. We introduced populations of the green anole, *A. carolinensis,* which lives in the canopy, to some of the uninhabited sites. We then compared how they did alone versus how they did on islands where they coexisted with *A. sagrei*. We found that *A. carolinensis* was doing much better when it did not have to compete with *A. sagrei.* These findings and others strongly support the argument that sympatric species of anoles negatively affect one another. Although other processes are possible—such as predation by one anole species on another—competition for resources is by far the most likely explanation. Experiments by Joan Roughgarden and her colleagues at Stanford University indicate that the more ecologically and morphologically similar species are, the stronger the effect they will have on each other. Consequently, it is very plausible that competition was the process leading to habitat specialization.

Unraveling the secrets of evolution is truly like a detective story. Clues exist, but none are definitive. And in the case of the Caribbean lizards, we are still left with the big question: Why did evolutionary diversification lead to such similar outcomes? One possibility is that the islands are relatively biologically impoverished—that is, they have many fewer other species of lizards, birds and other animals than do nearby Central American regions. As a result, anoles have been able to radiate into relatively open ecosystems, unfettered by much competition or predation. Because few other creatures influence the course of evolution and because the environment of each island is quite similar, evolution might take the same course. Indeed, this is seen in the repeated radiation of cichlid fish in different East African lakes [see "Cichlids of the Rift Lakes," by Melanie Stiassny; SCIENTIFIC AMERICAN, February 1999].

But as far as we can tell, replicated adaptive radiation is not the rule but the exception. Only by keeping an open mind and following the data, wherever they lead, can we ultimately hope to solve this mystery of natural history. SA

The Author

JONATHAN B. LOSOS examines the causes and consequences of evolutionary diversification. An associate professor of biology at Washington University and director of the Tyson Research Center there, Losos has focused his studies on lizards because they are well suited for the kinds of multidisciplinary questions he wants to answer. Between his travels around the world looking for lizards, he likes to play ice hockey.

Further Information

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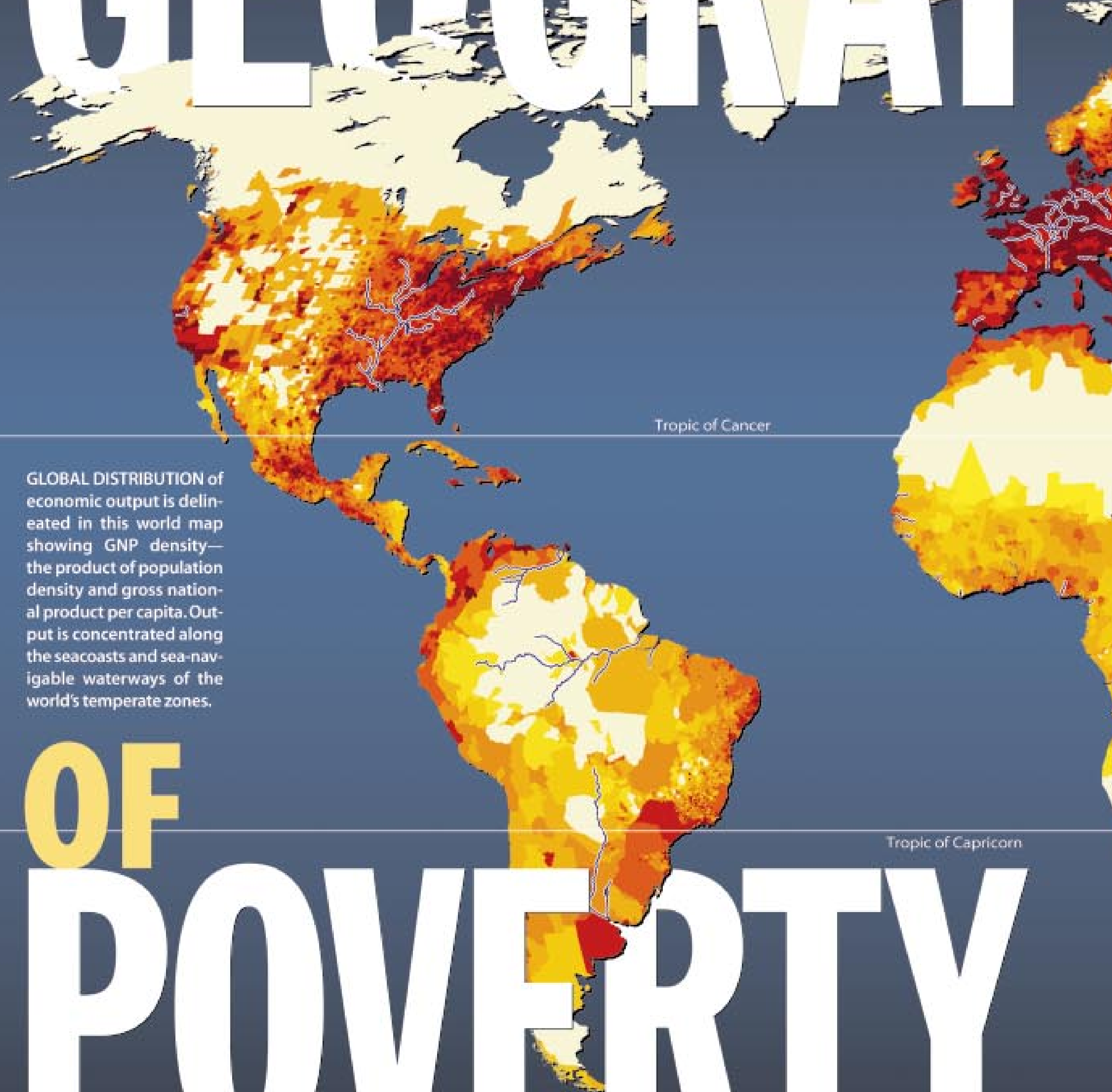
Jonathan B. Losos maintains a Web site at http://biosgi.wustl.edu/~lososlab/

ROBERTO OSTI

THE GEOGRAP



GLOBAL DISTRIBUTION of economic output is delineated in this world map showing GNP density—the product of population density and gross national product per capita. Output is concentrated along the seacoasts and sea-navigable waterways of the world's temperate zones.

OF POVERTY

ILLUSTRATION BY SAMUEL VELASCO; SOURCES: THE WORLD BANK, THE WORLD FACTBOOK (CIA, 1996 AND 1997), THE GLOBAL DEMOGRAPHY PROJECT AND THE ENVIRONMENTAL SYSTEMS RESEARCH INSTITUTE

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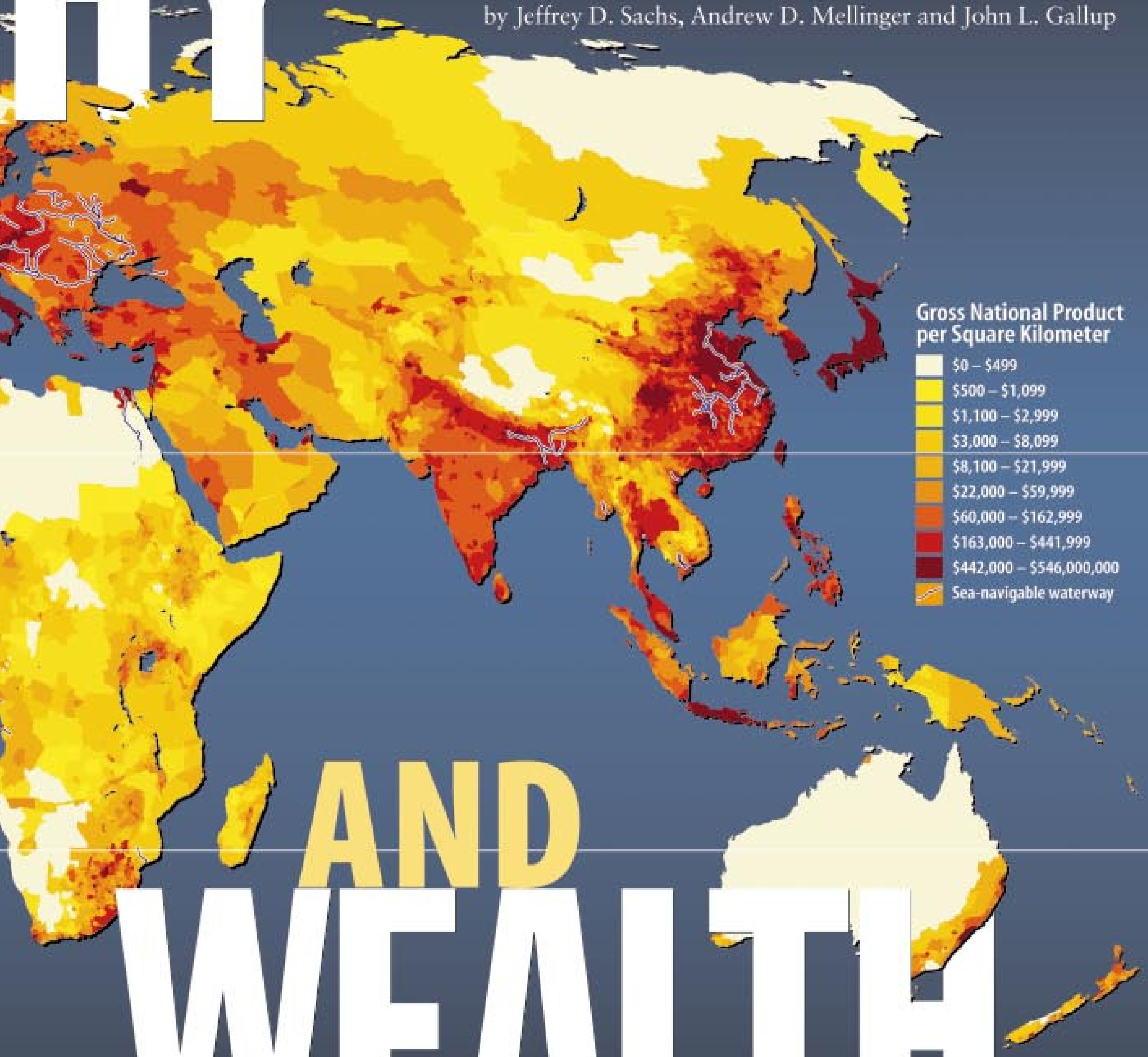
Tropical climate and lack of access to sea trade have hurt the poorest nations. But new aid programs can point the way to prosperity

by Jeffrey D. Sachs, Andrew D. Mellinger and John L. Gallup



AND WEALTH

Why are some countries stupendously rich and others horrendously poor? Social theorists have been captivated by this question since the late 18th century, when Scottish economist Adam Smith addressed the issue in his magisterial work *The Wealth of Nations*. Smith argued that the best prescription for prosperity is a free-market economy in which the government allows businesses substantial freedom to pursue profits. Over the past two centuries, Smith's hypothesis has been vindicated by the striking success of capitalist economies in North America, western Europe and East Asia and by the dismal failure of socialist planning in eastern Europe and the former Soviet Union.

Smith, however, made a second notable hypothesis: that the physical geography of a region can influence its economic performance. He contended that the economies of coastal regions, with their easy access to sea trade, usually outperform the economies of inland areas. Although most economists today follow Smith in linking prosperity with free markets, they have tended to neglect the role of geography. They implicitly assume that all parts of the world have the same prospects for economic growth and long-term development and that differences in performance are the result of differences in institutions. Our findings, based on newly available data and research methods, suggest otherwise. We have found strong evidence that geography plays an important role in shaping the distribution of world income and economic growth.

Coastal regions and those near navigable waterways are indeed far richer and more densely settled than interior regions, just as Smith predicted. Moreover, an area's climate can also affect its economic development. Nations in tropical climate zones generally face higher rates of infectious disease and lower agricultural productivity (especially for staple foods) than do nations in temperate zones. Similar burdens apply to the desert zones. The very poorest regions in the world are those saddled with both handicaps: distance from sea trade and a tropical or desert ecology.

A skeptical reader with a basic understanding of geography might comment at this point, "Fine, but isn't all of this familiar?" We have three responses. First, we go far beyond the basics by systematically quantifying the contributions of geography, economic policy and other factors in determining a nation's performance. We have combined the research tools used by geographers—including new software that can create detailed maps of global population density—with the techniques and equations of macroeconomics. Second, the basic lessons of geography are worth repeating, because most economists have ignored them. In the past decade the vast majority of papers on economic development have neglected even the most obvious geographical realities. Third, if our findings are true, the policy implications are significant. Aid programs for developing countries will have to be revamped to specifically address the problems imposed by geography. In particular, we have tried to formulate new strategies that would help nations in tropical zones raise their agricultural productivity and reduce the prevalence of diseases such as malaria.

The Geographical Divide

The best single indicator of prosperity is gross national product (GNP) per capita—the total value of a country's economic output, divided by its population. A map showing the world distribution of GNP per capita immediately reveals the vast gap between rich and poor nations [*see map on page 74*]. Notice that the great majority of the poorest countries lie in the geographical tropics—the area between the tropic of Cancer and the tropic of Capricorn. In contrast, most of the richest countries lie in the temperate zones.

A more precise picture of this geographical divide can be obtained by defining tropical regions by climate rather than by latitude. The map on page 75 divides the world into five

R. JANKE *Argus Fotoarchiv/Peter Arnold, Inc.*

ECONOMIC DISPARITIES can be partly attributed to geography. Coastal temperate-zone countries such as Germany (*opposite page*) have lower transportation costs and higher farm productivity than landlocked tropical-zone countries such as Uganda (*above*).

R. GILING *Lineair/Peter Arnold, Inc.*

broad climate zones based on a classification scheme developed by German climatologists Wladimir P. Köppen and Rudolph Geiger. The five zones are tropical-subtropical (hereafter referred to as tropical), desert-steppe (desert), temperate-snow (temperate), highland and polar. The zones are defined by measurements of temperature and precipitation. We excluded the polar zone from our analysis because it is largely uninhabited.

Among the 28 economies categorized as high income by the World Bank (with populations of at least one million), only Hong Kong, Singapore and part of Taiwan are in the tropical zone, representing a mere 2 percent of the combined population of the high-income regions. Almost all the temperate-zone countries have either high-income economies (as in the cases of North America, western Europe, Korea and Japan) or middle-income economies burdened by socialist policies in the past (as in the cases of eastern Europe, the former Soviet Union and China). In addition, there is a strong temperate-tropical divide within countries that straddle both types of climates. Most of Brazil, for example, lies within the tropical zone, but the richest part of the nation—the southernmost states—is in the temperate zone.

The importance of access to sea trade is also evident in the world map of GNP per capita. Regions far from the sea, such as the landlocked countries of South America, Africa and Asia, tend to be considerably poorer than their coastal counterparts. The differences between coastal and interior areas show up even more strongly in a world map delineating GNP density—that is, the amount of economic output per square kilometer [*see illustration on pages 70 and 71*]. This map is based on a detailed survey of global population densities in 1994. Geographic information system software is used to divide the world's land area into five-minute-by-five-minute sections (about 100 square kilometers at the equator). One can estimate the GNP density for each section by multiplying its population density and its GNP per capita. Researchers must use national averages of GNP per capita when regional estimates are not available.

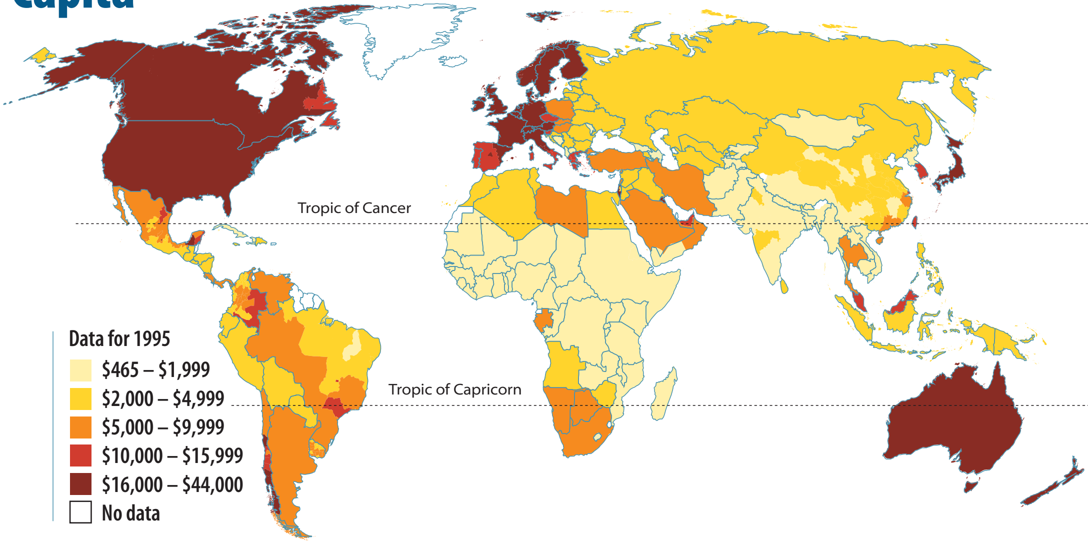
To make sense of the data, we have classified the world's regions in broad categories defined by climate and proximity to the sea. We call a region "near" if it lies within 100 kilometers of a seacoast or a sea-navigable waterway (a river, lake or canal in which oceangoing vessels can operate) and "far" otherwise. Regions in each of the four climate zones we analyzed can be either near or far, resulting in a total of eight categories. The table on the next page shows how the world's population, income and land area are divided among these regions.

The breakdown reveals some striking patterns. Global production is highly concentrated in the coastal regions of temperate climate zones. Regions in the "temperate-near" category constitute a mere 8.4 percent of the world's inhabited land area, but they hold 22.8 percent of the world's population and produce 52.9 percent of the world's GNP. Per capita income in these regions is 2.3 times greater than the global average, and population density is 2.7 times greater. In contrast, the "tropical-far" category is the poorest, with a per capita GNP only about one third of the world average.

Interpreting the Patterns

In our research we have examined three major ways in which geography affects economic development. First, as Adam Smith noted, economies differ in their ease of transporting goods, people and ideas. Because sea trade is less costly than land- or air-based trade, economies near coastlines have a great advantage over hinterland economies. The per-kilometer costs of overland trade within Africa, for example, are often an order of magnitude greater than the costs of sea trade to an African port. Here are some figures we found recently: The cost of shipping a six-meter-long container from Rotterdam, the Netherlands, to Dar-es-Salaam, Tanzania—an air distance of 7,300 kilometers—was about $1,400. But transporting the same container overland from Dar-es-Salaam to Kigali, Rwanda—a distance of 1,280 kilometers by road—cost

GNP per Capita



WEALTH AND CLIMATE are inextricably linked. By comparing world maps showing GNP per capita (*right*) and climate zones (*opposite page*), one notices that temperate-zone countries are generally much more prosperous than tropical-zone nations. And in each climate zone, the regions near seacoasts and waterways are richer than the hinterlands (*table below*).

about $2,500, or nearly twice as much.

Second, geography affects the prevalence of disease. Many kinds of infectious diseases are endemic to the tropical and subtropical zones. This tends to be true of diseases in which the pathogen spends part of its life cycle outside the human host: for instance, malaria (carried by mosquitoes) and helminthic infections (caused by parasitic worms). Although epidemics of malaria have occurred sporadically as far north as Boston in the past century, the disease has never gained a lasting foothold in the temperate zones, because the cold winters naturally control the mosquito-based transmission of the disease. (Winter could be considered the world's most effective public health intervention.) It is much more difficult to control malaria in tropical regions, where transmission takes place year-round and affects a large part of the population.

According to the World Health Organization, 300 million to 500 million new cases of malaria occur every year, almost entirely concentrated in the tropics. The disease is so common in these areas that no one really knows how many people it kills annually—at least one million and perhaps as many as 2.3 million. Widespread illness and early deaths obviously hold back a nation's economic performance by significantly reducing worker productivity. But there are also long-term effects that may be amplified over time through various social feedbacks.

For example, a high incidence of disease can alter the age structure of a country's population. Societies with high levels of child mortality tend to have high levels of fertility: mothers bear many children to guarantee that at least some will survive to adulthood. Young children will therefore constitute a large proportion of that country's population. With so many children, poor families cannot invest much in each child's education. High fertility also constrains the role of women in society, because child rearing takes up so much of their adult lives.

Third, geography affects agricultural productivity. Of the major food grains—wheat, maize and rice—wheat grows only in temperate climates, and maize and rice crops are generally more productive in temperate and subtropical climates than in tropical zones. On average, a hectare of land in the tropics yields 2.3 metric tons of maize, whereas a hectare in the temperate zone yields 6.4 tons. Farming in tropical rain-forest environments is hampered by the fragility of the soil: high temperatures mineralize the organic materials, and the intense rainfall leaches them out of the soil. In tropical environments that have wet and dry seasons—such as the African savanna—farmers must contend with the rapid loss of soil moisture resulting from high temperatures, the great variability of precipitation, and the ever present risk of drought. Moreover, tropical environments are plagued with diverse infestations of pests and parasites that can devastate both crops and livestock.

The Wealth of Regions

Climate Zone (percent of world total)		Near*	Far*
Tropical			
Land area	19.9%	5.5%	14.4%
Population	40.3%	21.8%	18.5%
GNP	17.4%	10.5%	6.9%
Desert			
Land area	29.6%	3.0%	26.6%
Population	18.0%	4.4%	13.6%
GNP	10.1%	3.2%	6.8%
Highland			
Land area	7.3%	0.4%	6.9%
Population	6.8%	0.9%	5.9%
GNP	5.3%	0.9%	4.4%
Temperate			
Land area	39.2%	8.4%	30.9%
Population	34.9%	22.8%	12.1%
GNP	67.2%	52.9%	14.3%

* *"Near" means within 100 kilometers of seacoast or sea-navigable waterway; "far" means otherwise.*

SOURCE: ANDREW D. MELLINGER

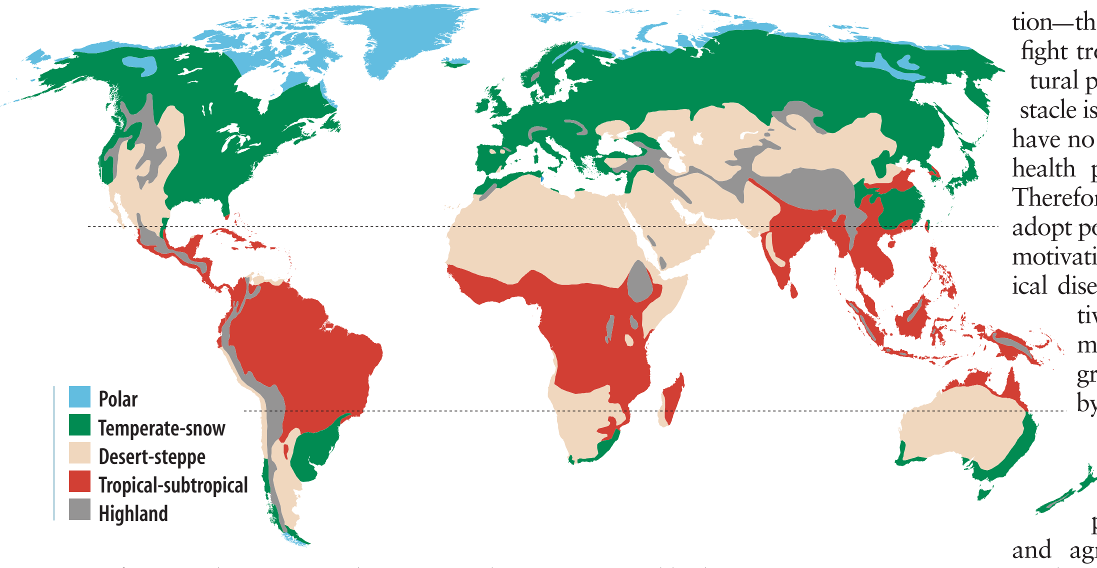
Many of the efforts to improve food output in tropical regions—attempted first by the colonial powers and then in recent decades by donor agencies—have ended in failure. Typically the agricultural experts blithely tried to transfer temperate-zone farming practices to the tropics, only to watch livestock and crops succumb to pests, disease and climate barriers. What makes the problem even more complex is that food productivity in tropical regions is also influenced by geologic and topographic conditions that vary greatly from place to place. The island of Java, for example, can support highly productive farms because the volcanic soil there suffers less nutrient depletion than the nonvolcanic soil of the neighboring islands of Indonesia.

Moderate advantages or disadvantages in geography can lead to big differences in long-term economic performance. For example, favorable agricultural or health conditions may boost per capita income in temperate-zone nations and hence increase the size of their economies. This growth encourages inventors in those nations to create products and services to sell into the larger and richer markets. The resulting inventions further raise economic output, spurring yet more inventive activity. The moderate geographical advantage is thus amplified through innovation.

In contrast, the low food output per

ILLUSTRATIONS BY SAMUEL VELASCO; SOURCES: THE WORLD BANK, *THE WORLD FACTBOOK* (CIA, 1996 AND 1997) AND *MODERN PHYSICAL GEOGRAPHY*, BY ALAN H. STRAHLER AND ARTHUR N. STRAHLER (JOHN WILEY & SONS, 1992)

Climate Zones



farm worker in tropical regions tends to diminish the size of cities, which depend on the agricultural hinterland for their sustenance. With a smaller proportion of the population in urban areas, the rate of technological advance is usually slower. The tropical regions therefore remain more rural than the temperate regions, with most of their economic activity concentrated in low-technology agriculture rather than in high-technology manufacturing and services.

We must stress, however, that geographical factors are only part of the story. Social and economic institutions are critical to long-term economic performance. It is particularly instructive to compare the post–World War II performance of free-market and socialist economies in neighboring countries that share the same geographical characteristics: North and South Korea, East and West Germany, the Czech Republic and Austria, and Estonia and Finland. In each case we find that free-market institutions vastly outperformed socialist ones.

The main implication of our findings is that policymakers should pay more attention to the developmental barriers associated with geography—specifically, poor health, low agricultural productivity and high transportation costs. For example, tropical economies should strive to diversify production into manufacturing and service sectors that are not hindered by climate conditions. The successful countries of tropical Southeast Asia, most notably Malaysia, have achieved stunning advances in the past 30 years, in part by addressing public health problems and in part by moving their economies away from climate-dependent commodity exports (rubber, palm oil and so on) to electronics, semiconductors and other industrial sectors. They were helped by the high concentration of their populations in coastal areas near international sea lanes and by the relatively tractable conditions for the control of malaria and other tropical diseases. Sub-Saharan Africa is not so fortunate: most of its population is located far from the coasts, and its ecological conditions are harsher on human health and agriculture.

The World Bank and the International Monetary Fund, the two international agencies that are most influential in advising developing countries, currently place more emphasis on institutional reforms—for instance, overhauling a nation's civil service or its tax administration—than on the technologies needed to fight tropical diseases and low agricultural productivity. One formidable obstacle is that pharmaceutical companies have no market incentive to address the health problems of the world's poor. Therefore, wealthier nations should adopt policies to increase the companies' motivation to work on vaccines for tropical diseases. In one of our own initiatives, we called on the governments of wealthy nations to foster greater research and development by pledging to buy vaccines for malaria, HIV/AIDS and tuberculosis from the pharmaceutical companies at a reasonable price. Similarly, biotechnology and agricultural research companies need more incentive to study how to improve farm output in tropical regions.

The poorest countries in the world surely lack the resources to relieve their geographical burdens on their own. Sub-Saharan African countries have per capita income levels of around $1 a day. Even when such countries invest as much as 3 or 4 percent of their GNP in public health—a large proportion of national income for a very poor country—the result is only about $10 to $15 per year per person. This is certainly not enough to control endemic malaria, much less to fight other rampant diseases such as HIV/AIDS, tuberculosis and helminthic infections.

A serious effort at global development will require not just better economic policies in the poor countries but far more financial support from the rich countries to help overcome the special problems imposed by geography. A preliminary estimate suggests that even a modest increase in donor financing of about $25 billion per year—only 0.1 percent of the total GNP of the wealthy nations, or about $28 per person—could make a tremendous difference in reducing disease and increasing food productivity in the world's poorest countries. SA

The Authors

JEFFREY D. SACHS, ANDREW D. MELLINGER and JOHN L. GALLUP conducted the research for this article under the auspices of Harvard University's Center for International Development (CID). Sachs is CID's director and serves as an economic adviser to governments in eastern Europe, the former Soviet Union, Latin America, Africa and Asia. Mellinger is a research associate at CID specializing in the multidisciplinary application of geographic information systems. Gallup is founder of developIT.org, which provides free technical support for information technology users and e-commerce in developing countries, and was recently a research fellow at CID.

Further Information

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Additional data and research papers are available at www.cid.harvard.edu and sedac.ciesin.org on the Web.

RADAR_GUNS

Gotcha!

You're zipping along the highway. Suddenly you see the patrol car up ahead. You slam on the brakes. Too late—the radar gun already has a bead on you. You're busted.

Radar has snared speeding drivers since the early 1950s. Handheld radar guns have evolved ever since to increase range, improve targeting and outwit radar detectors. Radar's microwaves, which reflect off objects to indicate speed, have climbed in frequency from the original X band (10.525 gigahertz) to K band (24.150 GHz) in the 1970s to Ka band (33.4 to 36.0 GHz) in the late 1980s. The microwave power output is a relatively harmless 15 to 50 milliwatts.

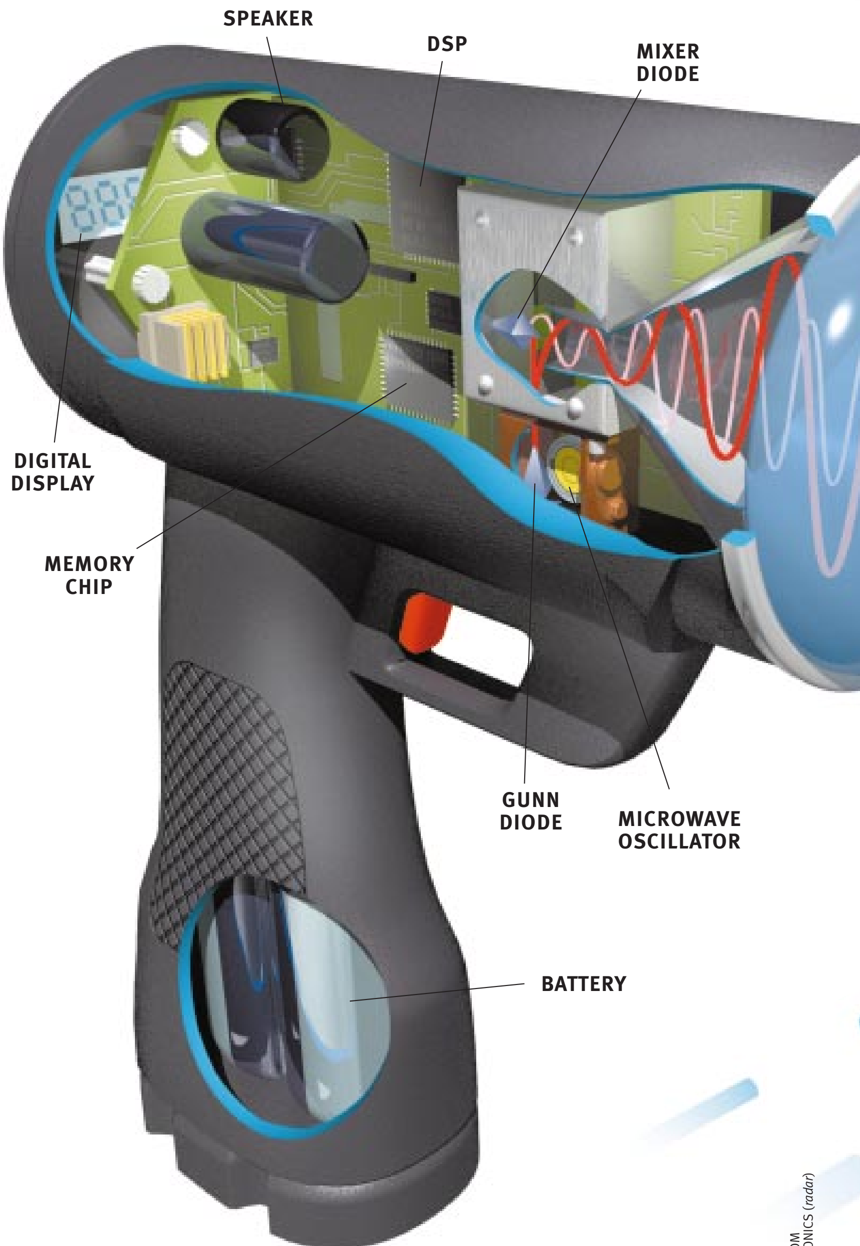
In 1991 manufacturers unveiled laser radar, or lidar. It nails motorists with 904-nanometer infrared light. Lidar's chief advantage is its narrow beam, only three feet wide at 1,000 feet downfield, enabling an officer to pick out a speeding car or motorcycle among three vehicles abreast, says Steve Hocker, product manager at Kustom Signals, a radar and lidar manufacturer in Lenexa, Kan. The microwave cone emitted by a radar gun is about 12 degrees, or 210 feet wide at 1,000 feet. Fog, rain and snow, however, reduce lidar's accuracy; they do not affect radar's accuracy, although they might reduce its range. The average lidar unit costs $3,500, whereas the average handheld radar gun costs $1,300.

Four U.S. manufacturers produce almost all domestic police radar guns. They also make devices to measure the velocity of baseballs and speedboats, to regulate speed in the automatic coupling of railroad boxcars and to determine scientific data such as the flow rate of rising rivers, used to predict flooding. A typical radar unit has a 0.75-mile range and lasts 15 years, according to Jim Hester, general manager of Decatur Electronics's radar manufacturing division in Fort Collins, Colo. The total radar gun market is about $30 million a year.

Despite rumors to the contrary, radar detectors are legal in all U.S. states except Virginia and Washington, D.C. The units sound an alarm when they sense an incoming signal that matches standard radar frequencies, supposedly giving drivers time to slow down. Radar jammers are illegal nationwide, carrying a charge of obstruction of justice, but motorists are known to use them. They emit a strong microwave frequency, which the driver tunes to represent a legal speed; a down-road radar gun will select that signal because it is more powerful than the gun's signal that the car is reflecting. Lidar detectors and jammers are sold as well, many sporting militaristic names.

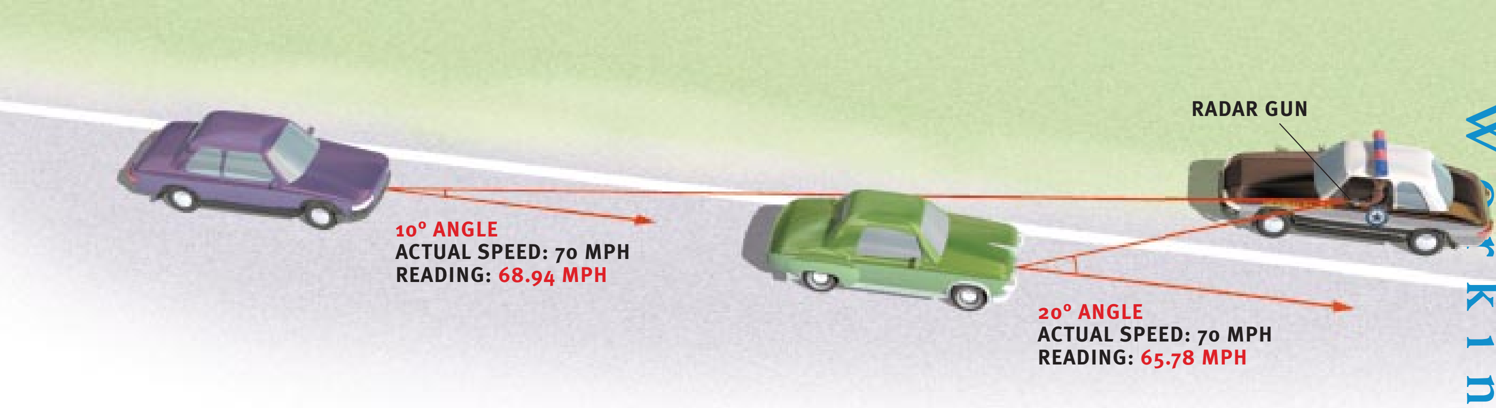
—Mark Fischetti

RADAR GUNS emit a continuous stream of microwaves at a preset frequency. According to the Doppler effect, when the waves reflect off an object moving toward the source, their frequency is shifted higher (objects moving away shift the frequency lower). A stationary gun measures the degree of shift, which determines velocity.

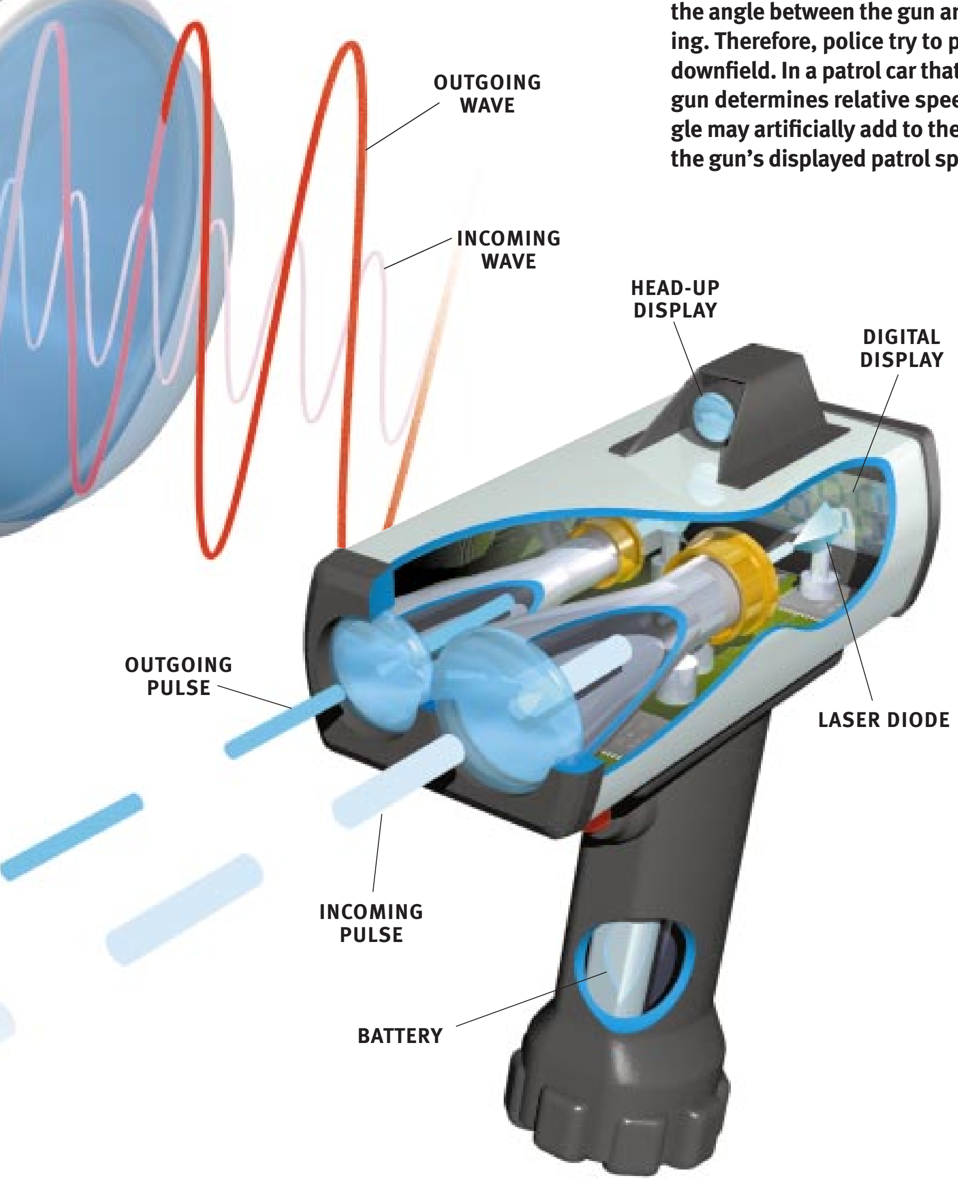


BATTERIES POWER a Gunn diode, part of a microwave oscillator. It emits microwaves that are focused into a beam by a horn and lens (together, the "antenna"). The antenna receives waves reflected by objects in the beam's path. A mixing diode compares the outgoing and incoming signals and sends the difference through an analog-to-digital converter to a digital-signal-processing (DSP) chip. The DSP analyzes the incoming signal frequencies and sends the speed value of the strongest return (typically the closest vehicle) to the gun's display.

ILLUSTRATIONS BY BRYAN CHRISTIE, BASED ON INFORMATION FROM LASERCRAFT AND KUSTOM SIGNALS (*lidar*) AND DECATUR ELECTRONICS (*radar*)



ANY OFFSET between a stationary radar gun and a moving target creates a "cosine effect" that reduces the return frequency by the cosine of the angle between the gun and the vehicle, thus lowering the speed reading. Therefore, police try to park close to the road and detect vehicles far downfield. In a patrol car that is cruising with traffic, however, the moving gun determines relative speed between the car and a target, and any angle may artificially add to the speed reading. Officers are trained to check the gun's displayed patrol speed against their own car's speedometer.



IN A LIDAR GUN, electronics ramp up battery power to high voltage that drives a laser diode. The diode emits infrared laser pulses every five milliseconds. Filters receive pulses reflecting off a target object and focus them onto an avalanche diode, which converts them to electronic signals. High-speed timing circuitry tracks the time it takes for a pulse to reflect and return from the target, and algorithms use the data to determine the object's distance. The algorithms calculate distance again for subsequent pulses and then compute velocity by dividing the change in distance by the change in time.

DID YOU KNOW ...

- **SPEEDING PALM TREE**
  A 1979 Miami TV report showing a radar gun clocking a palm tree at 86 mph brought radar errors to national attention. Error correction has improved, but units can occasionally be foiled by interference from nearby airport radars, CB radios, cellular phones, mercury vapor lights or other police radars, as well as harmonics from a running patrol car's air conditioner, heater or engine fan. But forget telling a judge the unit was wrong; if calibrated and used properly, they seldom are.

- **MUSIC TO THEIR EARS**
  Police radars emit an audio tone that rises in proportion to the target's speed. In the third octave above middle C, the note C-sharp corresponds to 60 mph for Decatur's K-band unit, D-sharp to 70 mph and F-sharp to 80 mph. Some officers become so trained to pitch that they can estimate speed to within 1 mph.

- **FIRSTS**
  Hartford, Conn., claims the first auto-speed regulation; its 1901 law limited automobiles to 12 mph in the country and 8 mph in the city. New Amsterdam (now New York City) passed the first American "traffic" law on June 12, 1652; it prohibited the riding or driving of horses at a gallop within city limits.

MICRO_GRAVITY

Geotropism, One Last Time

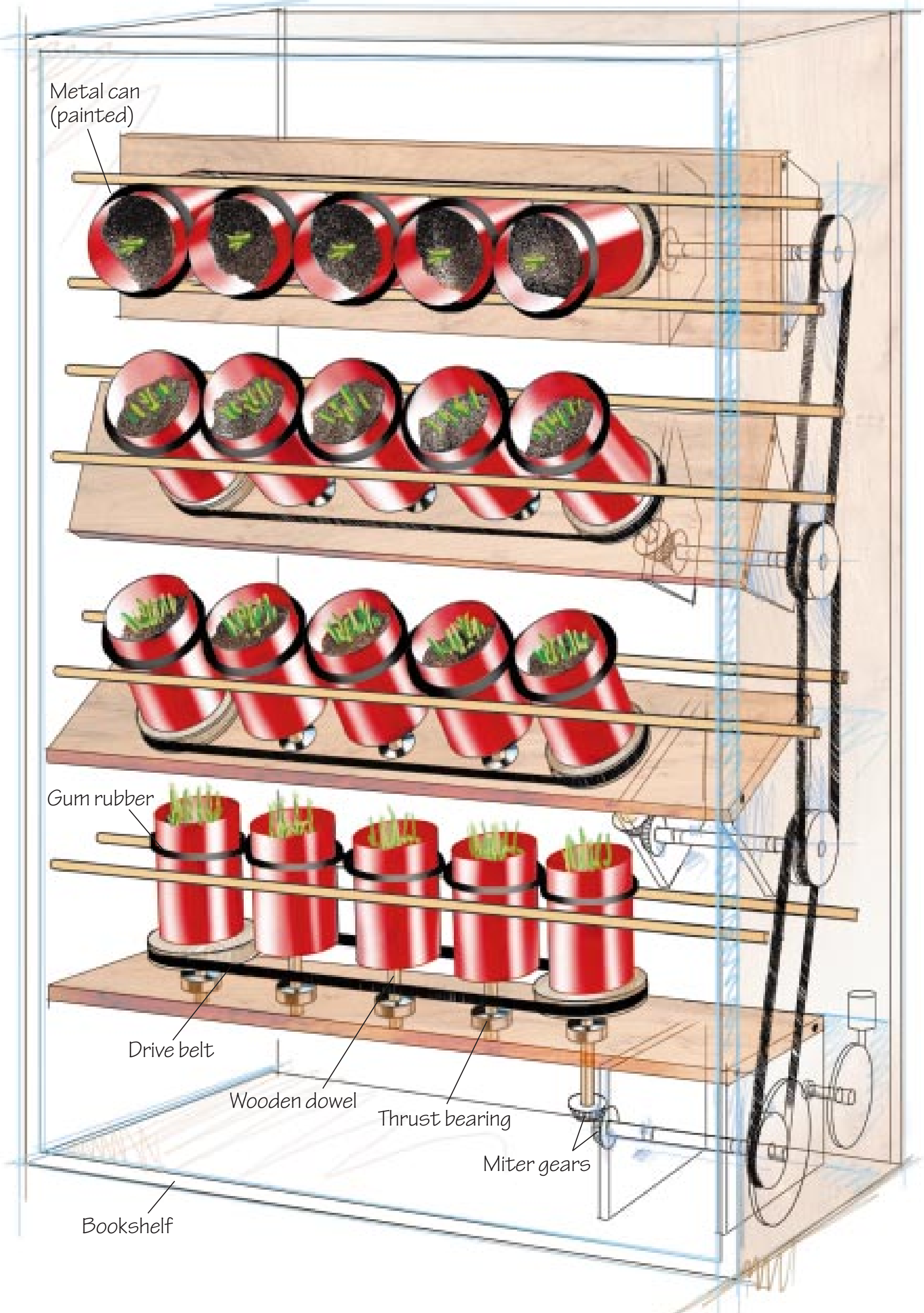
Shawn Carlson investigates how plants grow in reduced gravity

In June 1970, when I was just 10 years old, a delightful exploration into geotropism (the response of plants to gravity) appeared in the Amateur Scientist. Believe it or not, it was contributed by my grandfather, George Donald Graham. When I was a boy, sitting on his knee and listening to how he created this experiment ignited my interest in science. Thirty years later, now writing this column myself (for the last time, I regret to say), I have a new contribution to this topic that I want to share.

My recent advance builds directly on Grandpa Don's early insight. He germinated corn seeds in simulated weightlessness by taking advantage of the fact that plants respond only sluggishly to gravity: it typically requires about a minute for growth hormones called auxins to shift position, thereby allowing a tipped-over plant to start righting itself by adjusting its growth. So, Grandpa reasoned, if he continuously tumbled a plant such that it made a complete revolution in less than a minute, the specimen would be unable to tell up from down. He was right. And his experiments with corn seedlings proved that this plant would fare poorly in a spaceship.

My grandfather's apparatus averaged the earth's field to zero by slowly rotating the seedlings in the vertical plane. In February 1996 I described a more elaborate apparatus, one that spins the seedlings slowly in one plane (to cancel gravity) and quickly in another (to create a centrifugal force). That column sparked hundreds of science-fair projects, several of which earned honors for their creators at national competitions. The device was, however, rather difficult to construct.

But there's an easier approach. Slowly rotating the seedlings in a vertical plane cancels gravity completely; slowly rotating them in a horizontal plane does nothing special. So if the plants rotate at some intermediate angle, the seedlings experience on average an intermediate amount of gravity.



ROTATING CANS simulate reduced gravity for seedlings growing within them. Varying the tilt angle changes the effective pull of gravity from zero (*top*) to its full value (*bottom*).

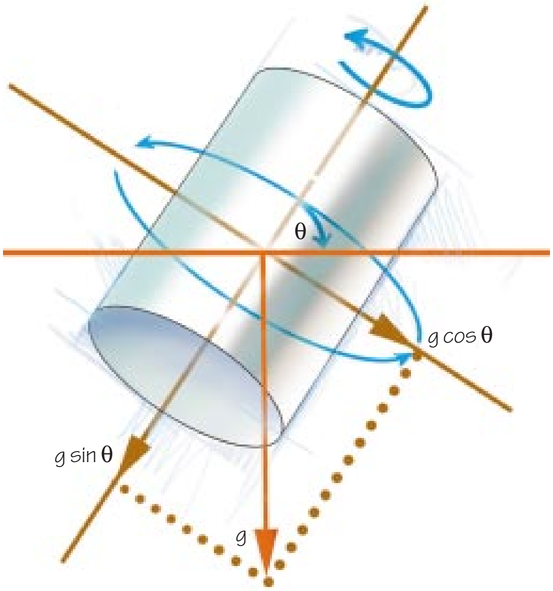
ALL ILLUSTRATIONS BY DANIELS & DANIELS

Why? When something is tilted at an angle and spun around (as in the device shown above), part of the gravitational force pulls along the axis of rotation and part pulls across it. The cross-axis component averages to zero, yet the along-axis component remains unaffected. So seeds germinated in a canted, rotating chamber experience an effective gravity that is reduced by a factor equal to the sine of the tilt angle (θ).

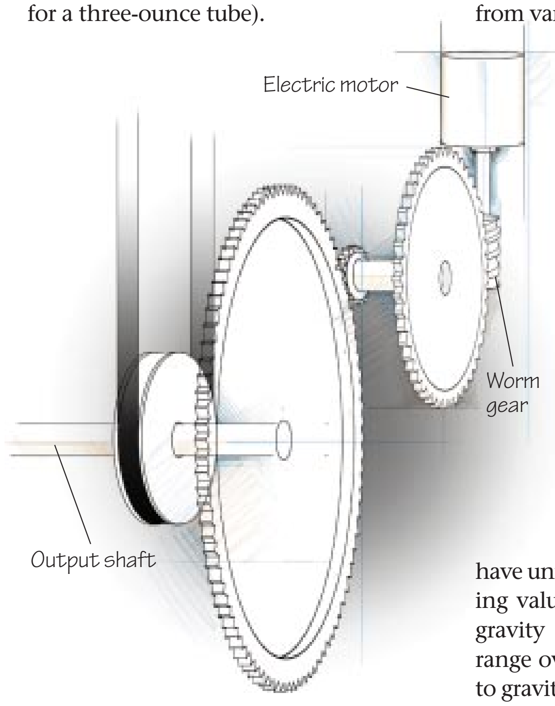
This fact makes it easy to experiment with geotropism. Just attach a surplus clock motor to a juice can and set up the contraption at an angle. Stuff the toe of a nylon stocking with moist potting soil and a few test seeds, then wedge it inside the can. That's all there is to it.

You can easily adapt the rotating-can technique to germinate many seeds simultaneously at several different effective gravities. My first step in this direction is shown in the illustration on the opposite page. The apparatus has 20 half-pint cans (McMaster-Carr, Los Angeles, 562-692-5911; www.mcmaster.com; part no. 4084T42; about $10 per dozen) positioned on four shelves inside an old bookcase. Each shelf holds five cans canted at an angle. I chose to mount them at 0, 30, 60 and 90 degrees (for my control plants). A drive belt rotates the two outer cans. Friction drives the three inner ones.

To make the axles, use a wood screw to hold the center of each can to a half-inch-diameter wooden dowel. Next, use a hole saw and your electric drill to create openings in the base for thrust bearings (McMaster-Carr, part no. 5906K512; 33 cents each). Slip the bearings over each dowel and secure them through the holes. Create the rims from a small sheet of gum rubber (McMaster-Carr, part no. 8633K32; about $4 for a 12-by-24-inch sheet) and an appropriate adhesive (McMaster-Carr, part no. 7587A35; about $3 for a three-ounce tube).



GRAVITATIONAL ACCELERATION (g, about 10 meters per second per second) has one component along the axis of rotation and one component perpendicular to it. The latter averages to zero as the can rotates.



REDUCTION GEARING allows a 1,600-rpm electric motor to turn the output shaft at a rate of just one revolution per minute.

In my latest device, a single motor drives all 20 cans. The $24 I paid to a dealer in surplus electronics bought me a 1/8-horsepower electric motor, which runs at 1,600 revolutions per minute. Turning the cans at one revolution per minute required two sets of reduction gears: a worm gear and wheel with a ratio of 80 to 1 and another pair of gears with a ratio of 20 to 1. The cans are driven through a belt and miter gear assembly, as shown in the illustration. I rescued all the gears from various surplus stores and purchased the belts from McMaster-Carr.

I'm so happy with my current setup that I'm already making plans for my next model. It will contain 10 shelves with nine cans on each shelf. Two of the shelves will be adjustable so that they can be set at any angle. This provision will help me explore the threshold of geotropic response.

I plan to analyze all the results in terms of the angularity of the seedlings, the sum of all the bend angles in the stem divided by its length. Seedlings germinated at low effective gravities are often quite contorted and so have unnaturally high angularities. Graphing values of angularity against effective gravity should allow me to identify the range over which a given plant responds to gravity.

In some of my early experiments, I had to kill the seedlings to measure their angularities accurately. No longer. Now I position the plants on a digital scanner, cover them with a sheet of graph paper and gently press them to the glass. The scanned image contains the complete plant atop a reference grid. Of course, this procedure flattens the three-dimensional structure into a two-dimensional representation. But you'll still arrive at a fairly accurate number.

A plant germinated in a low-gravity environment may have more problems than just a crooked stem. If you want to measure floral metabolism, too, the December 1958 Amateur Scientist column explains how. But the scheme described there requires you to know the surface area of the plant—something that is notoriously hard to compute. Fortunately, once you have scanned the specimen, you'll have several options. Most simply, you can count the squares on the graph paper that are covered by the leaves. You can also print the image, cut out the silhouetted plant and weigh the paper. Or perhaps you can find a way to have your computer tally up the pixels covered by the plant, a number that is proportional to area. This approach seems the most elegant to me, but I haven't found satisfactory means to carry it out with standard software. If you know a simple way, please share your ideas in the online discussion area hosted by the Society for Amateur Scientists.

Armed with these techniques, any ambitious amateur can begin to search out the secret dependencies that plants have on gravity. In this field, it's easy to stand shoulder to shoulder with the professionals. What food plants might one day support human settlements on the moon or Mars? Perhaps your own research may help to develop them. SA

For more information about this and other projects for amateur scientists, check out the online discussions on the Society for Amateur Scientists's Web site. Link to www.sas.org and click on the "Forum" button. You may write the society at 5600 Post Road, Suite 114-341, East Greenwich, RI 02818 or call 401-823-7800. To purchase a CD-ROM containing every project published in this department through the end of 1999 (more than 1,000 projects in all), call 888-875-4255 or consult www.tinkersguild.com

ALGORITHMS_CALENDAR CALCULATIONS

Easter Is a Quasicrystal

Ian Stewart reveals the divine mathematics of a holiday

Ten years ago my first Mathematical Recreations column was about Fermat's Christmas Theorem. With the Lenten season upon us, it seems only fitting to devote this 96th, and my final, column to Easter.

Christmas always falls on December 25, but Easter is quite another matter. The holiday can fall on any date between March 22 and April 25, a five-week window. The date changes from year to year for a number of reasons. First, the date has to be a Sunday because the crucifixion occurred on a Friday and the resurrection on a Sunday. Second, the New Testament says the crucifixion took place during the Jewish holiday of Passover, which is celebrated for eight days following the first full moon of spring.

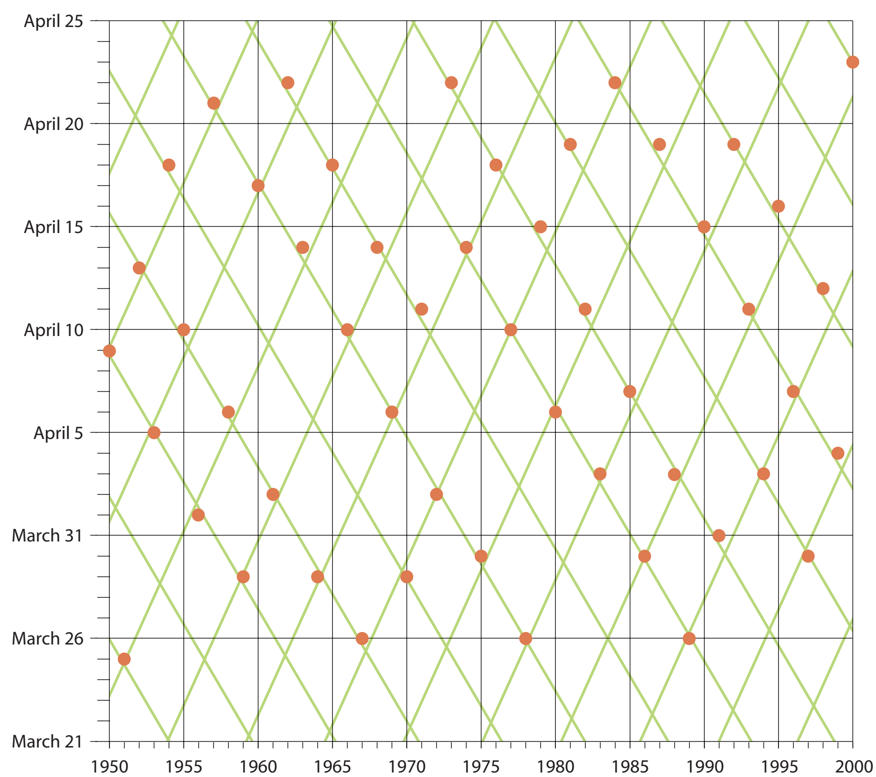
The date of Easter is thus linked to several astronomical cycles, and it is here that the difficulties arise. The lunar month is currently about 29.53 days long, and the solar year about 365.24 days long. This leads to 12.37 lunar months per year, an inconvenient relationship because it is not an integer. It so happens that 235 lunar months are very close to 19 solar years, and the church's system for assigning a date to Easter exploits this coincidence. In A.D. 325 at the Council of Nicaea, church leaders decided that Easter should fall on the first Sunday after the first full moon occurring on, or after, the spring equinox (the date in March on which day and night have equal length).

The year was based on the Julian calendar back then, with one leap year in every four. The dates of full moons were assumed to repeat every 19 Julian years; a bit of juggling with the calendar made this period equal to 235 lunar months. The 19-year period was called the lunar cycle, and each year's position in this cycle was indicated by its Golden Number, which ran from 1 to 19. The entire cycle of the Julian calendar would repeat every 76 years—after four lunar cycles of 19 years each, the pattern of leap years would repeat. The mathematical principle here is that the length of a cycle is equal to the lowest common multiple of the lengths of its constituent subcycles (76 is the lowest common multiple of 19 and 4).

Easter dates repeated in a 532-year cycle, because 532 is the lowest common multiple of 76 (the Julian calendar's cycle) and 7 (the cycle of days in the week). It was a tidy system, but unfortunately it did not accurately account for the true lengths of the lunar month and solar year. As the centuries passed, the calendar started to slip relative to the seasons. (Dante, the medieval Italian poet, pointed out that eventually January would cease to be part of winter.) Finally, in 1582 Pope Gregory XIII reformed the calendar by omitting the leap day in all years that are multiples of 100, except for years that are multiples of 400 (such as the year 2000, for example). To correct for the previous slippage, the Gregorian calendar for 1582 skipped the 10 days between October 4 and 15.

The church's new procedure for calculating the date of Easter assigned each year a number called the Epact, an integer between 0 and 29. This number reveals the phase of the moon on January 1 of each year, with 0 indicating a new moon and 15 a full moon. Every so often the cycle of Epacts must be revised to account for the fact that 235 lunar months do not exactly equal 19 solar years. The last such correction occurred in 1900, and the next will be needed in 2200.

Using the Golden Number and Epact for any given year, one can calculate the date of the first full moon of spring. To determine the date of Easter—the first Sunday



EASTER QUASICRYSTAL is created by graphing the dates of the holiday for the years 1950 to 2000. The graph resembles a regular lattice (*green*), although the plot points (*orange*) vary slightly from the lattice intersections, like the arrangement of atoms in a quasicrystal.

ALL ILLUSTRATIONS BY BRYAN CHRISTIE

after the full moon—the church assigned each year a dominical letter, from A to G, indicating the date of that year's first Sunday: A for January 1, B for January 2, and so on. Every leap year has two dominical letters, one for January and February and the other for the remaining months.

The system has its flaws. The church considers March 21 to be the perennial date of the vernal equinox, but the real astronomical equinox can occur as early as March 19 (as will happen in 2096). Also, the moon does not slavishly follow ecclesiastical conventions. In 1845 and 1923 the first full moon of spring occurred after Easter Sunday in the world's easterly longitudes.

In 1800 German mathematician Carl Friedrich Gauss invented a simple algorithm that incorporated the church's rules for calculating Easter's date. Unfortunately, Gauss's work contained a minor oversight: it gives April 13 for the year 4200 when the correct date should be April 20. He corrected this error by hand in his own copy of the published paper. The first flawless algorithm was presented in 1876 in the journal *Nature* by an anonymous American. In 1965 Thomas H. O'Beirne of Glasgow University published two such procedures in his book *Puzzles*

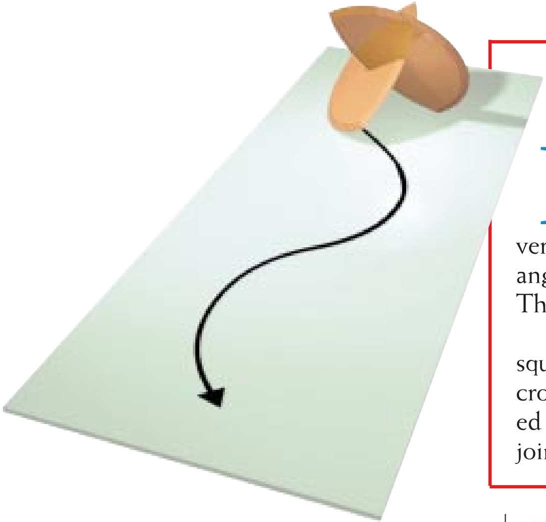
Calculating Easter

Choose any year of the Gregorian calendar and call it x. To determine the date of Easter, carry out the following 10 calculations (it's easy to program them on a computer):

1. Divide x by 19 to get a quotient (which we ignore) and a remainder A. This is the year's position in the 19-year lunar cycle. ($A + 1$ is the year's Golden Number.)
2. Divide x by 100 to get a quotient B and a remainder C.
3. Divide B by 4 to get a quotient D and a remainder E.
4. Divide $8B + 13$ by 25 to get a quotient G and a remainder (which we ignore).
5. Divide $19A + B - D - G + 15$ by 30 to get a quotient (which we ignore) and a remainder H. (The year's Epact is $23 - H$ when H is less than 24 and $53 - H$ otherwise.)
6. Divide $A + 11H$ by 319 to get a quotient M and a remainder (which we ignore).
7. Divide C by 4 to get a quotient J and a remainder K.
8. Divide $2E + 2J - K - H + M + 32$ by 7 to get a quotient (which we ignore) and a remainder L.
9. Divide $H - M + L + 90$ by 25 to get a quotient N and a remainder (which we ignore).
10. Divide $H - M + L + N + 19$ by 32 to get a quotient (which we ignore) and a remainder P.

Easter Sunday is the Pth day of the Nth month (N can be either 3 for March or 4 for April). The year's dominical letter can be found by dividing $2E + 2J - K$ by 7 and taking the remainder (a remainder of 0 is equivalent to the letter A, 1 is equivalent to B, and so on).

Let's try this method for $x = 2001$: (1) $A = 6$; (2) $B = 20$, $C = 1$; (3) $D = 5$, $E = 0$; (4) $G = 6$; (5) $H = 18$; (6) $M = 0$; (7) $J = 0$, $K = 1$; (8) $L = 6$; (9) $N = 4$; (10) $P = 15$. So Easter 2001 is April 15.



READER_FEEDBACK

Readers continue to comment on the solid known as the sphericon ["Cone with a Twist," October 1999]. John D. Determan of Alhambra, Calif., and Cecil Deisch of Warrenville, Ill., suggested using a cone with a 60-degree vertex. When sliced in half, this figure has a cross section that is an equilateral triangle, and two such half-cones can be glued together with a 120-degree twist. The resulting object rolls, but not very far, unfortunately.

David Racusen of Shelburne, Vt., suggested starting with a cylinder with a square cross section and joining two halves with a 90-degree twist. And Don Bancroft of Brookfield, Ill., sent me a copy of his U.S. patent (number 4,257,605, dated March 24, 1981) describing a rolling device made from two semicircles that are joined at the middle of their straight sides with a 90-degree twist (*left*). —*I.S.*

and Paradoxes (Oxford University Press). O'Beirne's method puts the various cycles and adjustments into an arithmetical scheme [*see box on opposite page*].

In general terms, the date of Easter slips back by about eight days each year until it hops forward again. The pattern looks irregular but actually follows the arithmetical procedure just described. In 1990 Alan Mackay, a crystallographer at the University of London, realized that this near-regular slippage ought to show up in a graph that compared the date of Easter with the number of the year [*see illustration on page 80*]. The result is approximately a regular lattice, like the arrangement of atoms in a crystal.

The peculiarities of the calendar, however, make the dates vary slightly as compared with the lattice. The graph more closely resembles a quasicrystal, a molecular structure built for the first time in the early 1980s. Quasicrystals are not as regular as crystals, but their arrangement of atoms is by no means random. The structure is similar to a curious class of tilings discovered by University of Oxford physicist Roger Penrose; these tilings cover the plane without repeating the same pattern periodically. The atoms of quasicrystals have the same near regularity, as do the dates of Easter. The holiday is a quasicrystal in time rather than space.

Under the rules of the Gregorian calendar, the cycle of Easter dates repeats exactly after 5,700,000 years. Long before the first repeat, though, the rules will have slipped relative to astronomical realities: the lengths of the month and day are slowly changing, mainly because of tidal friction. Just for the fun of it, though, try to calculate Easter's date for the year 1000000. SA

(ANSWER: April 16)

REVIEWER_RICK WEISS

Who Owns Your Body?

Lori Andrews and **Dorothy Nelkin** uncover some disturbing answers

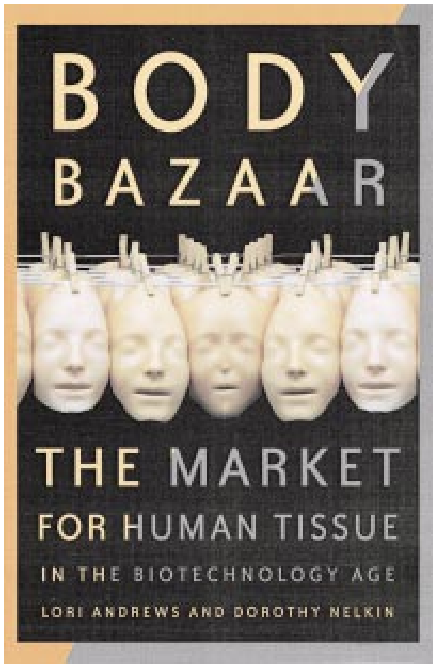
It seems that scientists have been struggling forever to make a mechanical heart that really works. Or a trouble-free hearing aid. Or a prosthetic hand that's half as good as the real thing. From wooden legs to silicone breasts, the history of human corporeal reengineering has largely been one of clumsiness and frustration, despite relentless innovation.

But what if we could take a tip from nature and grow the things we cannot build? Imagine little slabs of cardiac muscle cultivated in a dish, ready to be sewn over your aging heart. Homegrown blood vessels that naturally bypass clogged arteries. Medicines that work perfectly because they are made by your own cells. Imagine hair that sprouts in skeins from once withered follicles. Or being able to *grow,* as advertised, those perfect pecs and abs.

The dream of harnessing biology's regenerative powers for curative, life-extending and even cosmetic purposes has begun to become a reality, write Lori Andrews and Dorothy Nelkin in *Body Bazaar: The Market for Human Tissue in the Biotechnology Age*. But, the authors warn, this new and promising era has a dark side. People's tissues, cells and genes are increasingly being perceived as natural resources to be harvested and transformed into value-added commodities. And the economy that has evolved around this burgeoning industry threatens to wreak ethical havoc.

"The body is more than a utilitarian object: it is also a social, ritual, and metaphorical entity, and the only thing many people can really call their own," the authors write in this fascinating if somewhat polemical overview of the new millennium's hottest biological frontier. "When commercial interests and the quest for profits are a driving force, questions of human safety and respect for the human sources of tissue—the person in the body—take second place."

Let's set aside for a moment the oft-overlooked truth about biotech medicine: that despite all the hoopla surrounding recent advances, including the sequencing of the human genome, it's probably not going to be all that easy to wrest control of Mother Nature's biomolecular operating system to cure inherited diseases and grow replacement parts. Still, vaccines and pharmaceuticals are increasingly being produced with the help of human cells and genes. And DNA is making itself more and more at home in law-enforcement, employment and insurance decisions. As Andrews and Nelkin convincingly point out, even these first steps have already led to some worrisome legal and ethical precedents.



Body Bazaar: The Market for Human Tissue in the Biotechnology Age
by Lori Andrews and Dorothy Nelkin
Crown Publishers, New York, 2001 ($24)

Consider the case of John Moore, who in the 1980s was being treated by a Los Angeles specialist for hairy-cell leukemia. Unbeknownst to Moore, his doctor had discovered in the businessman's spleen cells a natural compound that appeared to have great therapeutic potential. When Moore learned that his doctor had taken out a patent on his cells and had sold the commercial rights to a biotechnology company for millions of dollars, he sued for property theft. But in a landmark 1990 decision, the California Supreme Court ruled 5 to 4 that Moore did not have a property interest in his body parts. Thus, the stage was set for what the biotechnology industry now sees as a crucial right of access to human tissues and what critics like Andrews and Nelkin see as an invitation to wholesale biocolonialism and human exploitation.

Andrews, a legal scholar and bioethicist at the Illinois Institute of Technology, and Nelkin, a New York University professor of law, offer a rogues' gallery of other examples in which people's rights appear to have been trampled or the sanctity of life diminished by gene-hunting bioprospectors and profiteers.

Meet Daniel and Debbie Greenberg, who transformed the deaths of their son and daughter from Canavan disease into a biomedical blessing. They initiated a research program that led to the discovery of that disease's causative gene—only to learn that the university that co-sponsored the research had quickly patented the gene and made it unavailable or unaffordable to researchers who wanted to use it to help parents and patients.

Meet the helpful but perhaps naive citizens of the South Atlantic island of Tristan da Cunha, who, after giving "informed consent" that may have been tainted by language barriers and cultural differences, donated their blood to scientists developing gene-based medicines that the poor volunteers were unlikely ever to afford.

Then there is the sad story of Susan Sutton, whose parents tried to make sense of her suicide by granting permission for her heart, liver, cornea, bones and skin to be used for transplantation. Only later did they discover that although they could not even afford a headstone for their daughter's grave, others had made tens of thousands of dollars brokering the distribution of her body parts.

What are we to make, Andrews and Nelkin ask, of a legal system that stores people's DNA profiles in huge databases without adequate assurance that the information will not be abused? A national transplantation system that precludes buying and selling organs yet allows middlemen to skim profits from their priceless trade? A medical system that (in many states) rules out payments for surrogate mothers but allows women to sell their gene-screened eggs to fertility clinics for thousands of dollars?

Body Bazaar offers compelling evidence that federal regulators and the courts are lagging in their patchwork efforts to deal with biotechnology's entrepreneurial push. Yet although the authors thoroughly document the scope of the problem, they lose some credibility through their unwillingness to acknowledge that many of these quandaries have two sides and by failing to offer more creative solutions.

They seem unwilling to concede, for example, that patents on at least some living things are most assuredly here to stay. The biotechnology industry has little incentive to create the cures that people want if it has no hope of profiting from its efforts. And the authors are right to raise an eyebrow about a company

> *Even science-savvy readers may be only vaguely aware of the biological gold rush now under way.*

that, instead of cleaning up the workplace, turns away applicants whose genes put them at risk of toxic chemicals. But they ignore the more difficult underlying question of whether it's preferable to set environmental protection standards so high as to protect even those whose rare genetic makeups leave them unusually sensitive to certain substances.

One wishes that the last chapter, which seeks to answer the question of how to sequester our warm bodies from the coldhearted bazaar, were longer than seven pages. Nevertheless, at a time when even science-savvy readers may be only vaguely aware of the biological gold rush now under way around the world, *Body Bazaar* does a great service by collecting in very readable form a comprehensive overview of the trend. It offers a prescient look at how our culture is likely to struggle and change as our craving for better and longer lives and more effective law enforcement comes up against long-standing economic, scientific, cultural and even spiritual traditions regarding the body.

Today, 10,000 years after human beings learned to farm the land for food, we are learning how to farm our own bodies for biological products. For the first time ever, our very bodies may be worth more in the marketplace than the products produced by those bodies in a lifetime of agricultural or factory work.

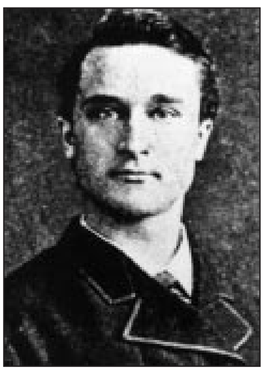
As *Body Bazaar* makes so frighteningly clear, it may be a long time before we—the farmers and the farmed—adjust to that peculiar economic reality. SA

RICK WEISS, a science and medicine reporter at the Washington Post, *has written extensively about genetics and biotechnology.*

THE EDITORS_RECOMMEND

PAT SHIPMAN'S *The Man Who Found the Missing Link: Eugene Dubois and His Thirty-Year Struggle to Prove Darwin Right.* Simon & Schuster, New York, 2001 ($27).

Shipman presents a biography written in the present tense, a technique that gives the reader the sense of accompanying the subject through life. Her subject, Eugene Dubois (1858–1940), was a Dutch physician and anatomist who gave up a promising post at the University of Amsterdam to go to the Dutch East Indies with the aim of finding a fossil of a prehuman that would be demonstrably the "missing link" in the evolutionary trail from ape to human. In 1892, at Trinil in Java, he found what he believed to be such a fossil. Shipman portrays him as he writes his report: "There is only one name that can be given to this creature.... He will call it *erectus, Pithecanthropus erectus,* a name that will honor both the marvelously manlike femur and the capacious but strangely apelike skull. His missing link will be known as the ape-man who walks erect, *Pithecanthropus erectus.*"



FROM THE MAN WHO FOUND THE MISSING LINK

It was a time of uncertainty and confusion in paleontology, and Dubois had to spend years defending his claim. Shipman, adjunct professor of anthropology at Pennsylvania State University, relates that struggle as carefully as she describes his work in Sumatra. "Dubois," she writes, "has been an underestimated man."

JUDITH SHAPIRO'S *Mao's War against Nature: Politics and the Environment in Revolutionary China.* Cambridge University Press, Cambridge, England, 2001 ($18.95).

In China during the Mao years, Shapiro writes, "coercive state behavior such as forcible relocations and suppression of intellectual and political freedoms contributed directly to a wide range of environmental problems ranging from deforestation and desertification to ill-conceived engineering projects that degraded major river courses." Indeed, "few cases of environmental degradation so clearly reveal the human and environmental costs incurred when human beings, particularly those who determine policy, view themselves as living in an oppositional relationship to nature."

Shapiro, who teaches environmental politics at American University in Washington, D.C., examines closely such disastrous Mao projects as the Three Gate Gorge Dam on the Yellow River and the devastation of agriculture through campaigns that imposed a uniform agricultural model on the entire country regardless of local conditions. China's environmental problems continue today, 25 years after Mao's death, although Shapiro sees some "apparently serious efforts" by the central government to deal with them. She also sees the possibility that "a government may yet evolve that is environmentally responsible and responsive."

RICHARD FORTEY'S *Trilobite! Eyewitness to Evolution.* Alfred A. Knopf, New York, 2000 ($26).

Fortey found his first trilobite fossil on the coast of South Wales when he was 14. "The long thin eyes of the trilobite regarded me and I returned the gaze." He found the eyes "compelling" and felt "a shiver of recognition across 500 million years." He fell in love with trilobites on the spot and now, as a senior paleontologist at the Natural History Museum in London, is one of the world's experts on these ancient, extinct marine arthropods. He is also an engaging writer, making not only the story of trilobites but also his view of "the seductions of the scientific method" a splendid read. The drawings and photographs that accompany his tale illuminate the complex, transfixing architecture of the trilobites.


FROM TRILOBITE! EYEWITNESS TO EVOLUTION

"I want to invest the trilobite with all the glamour of the dinosaur and twice its endurance," Fortey writes. "I want you to see the world through the eyes of trilobites, to help you make a journey back through hundreds of millions of years."

DAVID LINDLEY'S *Boltzmann's Atom: The Great Debate That Launched a Revolution in Physics.* Free Press, New York, 2001 ($24).

"I don't believe that atoms exist," physicist Ernst Mach declared after hearing fellow physicist Ludwig Boltzmann talk about them at a meeting in Vienna of the Imperial Academy of Sciences in 1897. Mach was not alone in that opinion, for it was a time when the only evidence for the existence of atoms was circumstantial. But Boltzmann believed in them and had done groundbreaking work on the distribution of atomic velocities in a gas. His paper of 1872 on that subject "signified the arrival of a true genius of physics," Lindley writes.

Lindley, who has worked as a theoretical physicist and is now an editor at *Science News,* is superb at describing Boltzmann's work, which focused on kinetic theory and thermodynamics and fruitfully applied statistics and probability to physics. He is also a talented biographer, painting a vivid picture of Boltzmann the man. Boltzmann, he writes, "left a legacy of scientific achievement that laid the groundwork for quantum theory and held clues to chaotic dynamics."

JON KALB'S *Adventures in the Bone Trade: The Race to Discover Human Ancestors in Ethiopia's Afar Depression.* Copernicus Books, New York, 2001 ($29).

The inhospitable Afar Depression in Ethiopia has produced one of the longest

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Scientific American Frontiers
The magazine's PBS television series is hosted by actor and lifelong science buff Alan Alda. New with the Fall 2000 broadcast season, there are 10 one-hour episodes each season, with Frontiers becoming an integral part of a new PBS science programming initiative. Visit the SCIENTIFIC AMERICAN FRONTIERS Web site at www.pbs.org/saf

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records of human habitation. Kalb, a geologist and paleontologist who is now a research fellow at the University of Texas at Austin, compiled much of that record with his fossil and tool discoveries in the Afar during many years of work there. But he also found that all was not sweetness and light in the relations of paleontological workers in the area. "Intense competition developed among scientists and scientific teams, which resulted in treachery and bloodletting reminiscent of the exploration duels of the nineteenth century." Kalb tells the story of his work, the scientific infighting, and the political turmoil in Ethiopia during his years there with verve and thoroughness.

SHERWIN B. NULAND'S *Leonardo da Vinci.* Viking Penguin, New York, 2000 ($19.95).


FROM LEONARDO DA VINCI

Artist, anatomist, architect, mathematician, military engineer—few have been as protean as Leonardo. Sir Kenneth Clark called him "the most relentlessly curious man in history." To Nuland, "he is also the historical figure about whom we are most relentlessly curious." In this brief life, Nuland summarizes Leonardo's achievements skillfully. Being a physician (clinical professor of surgery at Yale University), he is particularly interested in Leonardo's pioneering anatomical dissections and drawings. But to him as to other biographers, Leonardo remains essentially elusive. As the English critic Walter Pater said, "he seemed to those about him as one listening to a voice, silent for other men."

THOMAS FINK AND YONG MAO'S *The 85 Ways to Tie a Tie: The Science and Aesthetics of Tie Knots.* Broadway Books, New York, 2000 ($14.95).


RONALD GRANT ARCHIVE

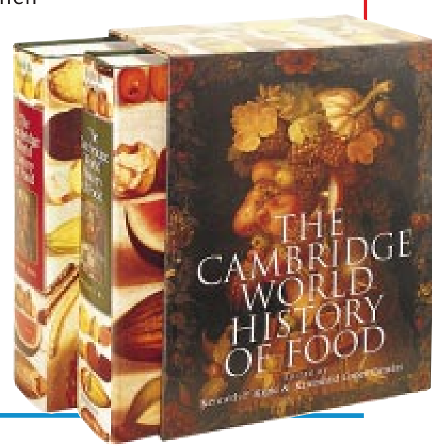
New ways of tying a necktie appear rarely. Some 50 years passed between the introduction of the Windsor knot and the arrival of the Pratt knot in 1989. "Rather than wait another half-century for the next knot," Fink and Mao write, "we considered a more formal approach." And so they present 85 tie-tying techniques, each one shown in a drawing with instructions on how to achieve the desired result. They also offer a brief history of neckwear and photographs of famous figures wearing ties, among them Fred Astaire in a four-in-hand, Frank Sinatra in a Windsor knot and the Duke of Windsor not wearing a Windsor.

But, being research physicists at the University of Cambridge, the authors are interested in more than sartorial versatility. They deal also with knot theory and topology. For the reader who wishes to probe tie-tying that deeply, they represent "knot sequences as random walks on a triangular lattice."

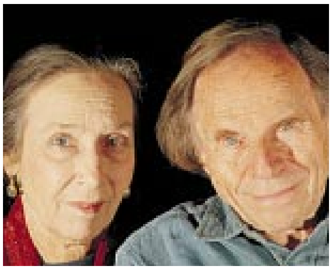
THE CAMBRIDGE WORLD HISTORY OF FOOD. *Edited by Kenneth F. Kiple and Kriemhild Coneè Ornelas.* Cambridge University Press, 2000 ($175).

Take chocolate, for example. Twenty-five entries detail the history of "the drink of the gods" from its use as an aphrodisiac to witchbroom disease on cacao plants. The two hefty volumes offer a cornucopia of scholarly information on lots more than our favorite food. Of particular interest is the exploration of the Paleolithic hunter-gatherer diet that opens the work. The editors then shift to domesticated plants and animals, turn next to beverages, and address vitamins, minerals and nutritional requirements, before setting out on a global tour of food and drink that includes the role food has played in the rise and fall of civilizations. They end with contemporary food-related policy issues.

Edited by historian Kenneth Kiple and his wife, Kriemhild Coneè Ornelas, with scholarly contributions from 224 experts from 15 countries, the volumes are not as sumptuous-looking inside as out, but they are nonetheless chock-full of fascinating, easy-to-find lore.



BETH PHILLIPS



The Needy Porcupine

Philip and Phylis Morrison explore the salty chemistry and nutrition of sodium and potassium

Nuggets glitter. Each of the close-bound atoms of any bit of the coinage metals pools an outer electron or two to form a sea of mobile electrons, the physical origin of metallic properties (see our December 2000 column). Here we contrast those rare and showy elements with two other metals, sodium and potassium, both more abundant and more important—yet seen in their pure state primarily in the chemical industry.

Today sodium is, like aluminum, an inexpensive metal. A fresh-cut silvery surface of sodium, soft as wax, covers itself at once with an ugly, rough rind, like some mineral cheese. Toss a small piece into water and watch it float as it dissolves, "dancing frenetically and developing hydrogen" (Primo Levi). Potassium, its heavier sister element in that family tree of elements we call the periodic table, could be described with the same words. But a pea-size dollop of potassium not only reacts vividly in water to release hydrogen but then ignites the hot outpouring gas!

Lustrous metals are not for the human organism. Modified atoms of sodium and potassium are both requisite for human life, but no tiny nugget will be found within your body. There they reside mostly in aqueous solution; a reacting atom of either one loses its outermost electron in water, to drift as a now charged atomic core, called an ion, amid the throng of water molecules, its positive charge balancing some far-wandering electron. Compounds such as sodium chloride (table salt) and its counterpart, potassium chloride, are familiar as stable, colorless crystals, precipitating, among many others, from evaporating saltwater. Typically relics of evaporation over geologic time, such natural deposits exist worldwide, wherever any body of water has been cut off from its sources.

For many, the nutritional intake of sodium runs 10-fold above need.

Sodium and potassium each make up between 2 and 3 percent by weight of average crustal rocks, weathering out of the rock mainly under the draw of a harsh reagent—liquid water. The ever cycling rains wash these ions down to well-mixed salt seas, sodium about 1 percent of seawater by weight, where it exceeds potassium more than 20-fold. Our sense of taste picks up salty ions in solution as distinctly as vision registers the luster of gold. For many of us, the nutritional intake of sodium runs 10-fold above need—the cultural legacy of savory food processing since earliest times. An arguable minimum is half of a gram a day for sodium but five or more times as much for potassium. We share the craving with land mammals from elephant to mouse.

In most of the wooded areas of this continent, from the Canadian Arctic tree line to Mexico, there dwells one unusual good-size rodent species, a slow, strong, patient gnawer. A 15-pound prickly male porcupine is safe from almost all predators of the woods, except for humans with guns and cars. Its celebrated quills form a final defense preceded by its threefold warning: first a visible pattern, then often loud teeth clacking, finally a goaty scent. Ignore all three, and you dare fierce and lasting contact with barbed quills able, once set, to ratchet their way inward. (Because the sharp quills often penetrate their tree-climbing owner itself after an accidental fall, adaptation has coated the quills with antibiotic, so that they rarely engender infection.)

Our North American porcupine, humble but certainly no pushover, lives under direst need of sodium. These vegetarians find an ample supply of staple calories from plants. Protein comes their way in the bursting buds of spring. Some fats they synthesize; some they find in seeds. Why are these modest creatures, amply fed on wild bush and tree, regarded as pests? Simply because they now gnaw and damage much human property near or in the woods. Whatever salty hands have touched, from ax handles to discarded wrappings, becomes the target of their needful gnawing. Nowadays the most common attractor for the porcupine is plywood in unattended outbuildings. The curing compound used in plywood is sodium nitrate, so porcupines chew doggedly at wooden walls for that scant, unseen prize. Control experiments have shown that they seek the sodium ion only, not potassium or other ions. Their sodium need opens a window onto the inner nature of animals and plants.

DUSAN PETRICIC

Two intrinsic systems set animal and plant life apart: the muscles that power locomotion, and the intricate nerve network that controls the organism, including the muscle fibers themselves. Sodium is an indispensable part of nerve and muscle function. But green plants have neither nerves nor muscles. Lacking these, most have little use for sodium, over the long or short term.

Plants must have sodium's sister atom, potassium. It is the dominant ion of the

Continued on page 91

French Leave

In his final column, **James Burke** discusses matters bucolic, adulterous, explosive, decorative, passionate and (fittingly) fugitive


DAVE PAGE

Some time ago, while rambling on about the virtues of phonetic spelling, I mentioned the fact that the very rare name pronounced in England "Fanshaw" is actually spelled "Featherstonhaugh." Yesterday I came across George William Featherstonhaugh, scientist and diplomat. English-born, married in 1808 the daughter of a former New York City mayor, settled in Duanesburg, N.Y. Went into railroads, then back to England to talk to rail maven George "Rocket" Stephenson. Returned Stateside, took up rocks, became the first U.S. government geologist. Was sent to survey bits of Arkansas, Wisconsin, Illinois, Georgia and the Carolinas. Finally came to rest in 1844 as British consul in Le Havre, France. And who says we never traveled before package tours.

G.W.'s stone-chipping proclivities were stimulated during the trip to Jolly Olde. While visiting his folks in Scarborough, Yorkshire, he had met the famous William Smith, humble-beginnings canal surveyor who first noticed that the same fossils turned up in the same strata, making it easier to identify the strata (which matters when you're cutting cuttings). In 1815, after noting the lay of the land up and down the entire country, Smith produced his prizewinner: "Delineation of the Strata of England and Wales." Replete with illustrations of 21 sedimentary beds in glorious Technicolor, it was the first proper geology map and earned him the sobriquet "Strata" Smith.

Careerwise, early on his way down (so to speak), Smith was employed at the Woburn estate of Francis, the duke of Bedford. He spoke geologically at His Grace's annual agricultural get-together with various landed aristos, where the other kind of good breeding was also discussed, since Duke Francis ran a model farm where he did a bit of sheep-rearing genetic manipulation before genetic manipulation. All written up by Arthur Young, a nifty dancer turned novelist turned agricultural writer and secretary of the first Board of Agriculture (of which the duke was a member). Young had an early go at farming but hit the bright lights of London in 1766 and then traveled nonstop for kind of the rest of his active life, only returning home from time to time to produce yet another "Travels in…" (His most famous is a rare and vivid firsthand account of the French Revolution as it affected life out in the until-recently-feudal sticks.)

In all this scribble-scribble, Young was encouraged by his lifelong pal Walter Harte, a now forgotten poet. Harte spent years writing a biography (of King Gustavus Adolphus of Sweden) only to have its style described in the *Dictionary of National Biography* as "execrable." Not much else to say, except he knew a clergyman named Joseph Warton. Another loser. Despite knowing Dr. Johnson, Garrick, Reynolds, Pope and any number of bigwigs (literally), Warton managed to sink without a trace. Apart, that is, from penning *The Enthusiast; or, The Lover of Nature,* said by some to have been the real literary precursor of the Romantic movement (another one!).

In 1751 Warton was taken on a tour of France by his patron the duke of Bolton so that if his ailing duchess died along the way, Warton could immediately marry the duke off to his other traveling companion (and doxy), the lovely Lavinia Fenton. By Aix-en-Provence the duchess hadn't croaked, so Warton went home. Whereupon she did. And after 23 years (and three children) as ducal mistress, Lavinia became Her Grace. Lavinia's affair with Bolton had started in 1728 when she was the Madonna of the day, playing Polly Peachum in the boffo *Beggar's Opera,* box-office smash of the entire 18th century: London run of 62 performances and then sellouts in theaters as far away as Malta.

Just as well for the play's author. Everything else John Gay wrote was instantly forgettable, and he spent most of his life whingeing about having been passed over for preferment and being permanently out of money. On one occasion, flushed with recent success and hanging out on the fringes of high society, he partook of the curative waters at Bath with the duchess of Marlborough and her pal, theatrical biggie and playwright William Congreve, not long before Congreve's carriage went over and the old boy died from his injuries.

> ***The geology map earned him the sobriquet "Strata" Smith.***

Less than a century later, Congreve's descendant Sir William was close to death in a different way: with his newly invented timed-airburst Congreve rockets. Fired to no avail at Fort McHenry during that little 1812 Anglo-American dustup, they had proved themselves earlier, in 1807, by practically razing the city of Copenhagen to the ground. So you win some, you lose some.

Around 1820 William became involved in an attempt to develop a method of printing two-color stamps, using compound plates to prevent forgery. His partner in this effort was one Bryan Donkin, engineer and inventor, who in 1812 had first put preserved food in cans and in 1804 had built the first continuous-process papermaking machine in England. It was cranked by hand, and a chain of small buckets lifted paper pulp out of a vat and dumped it onto a moving, shaking wire-mesh belt, where the


PATRICIA J. WYNNE

stuff drained, then was squeezed between rollers and dried to become (among other things) the first endless wallpaper. Which may have been why the machine's original (1798) inventor, Nicholas-Louis Robert, was a citizen of France, where wallpaper was the latest rave, because it gave the fleeting impression that you could afford the tapestries you couldn't afford.

Alas, Robert's license to print money never earned him a sou. His only lift in life came from knowing Jacques-Alexandre-César Charles, who ended up professor of "experimental physics" at the Paris Conservatory of Arts and Crafts. In December 1783, 10 days after the world-famous first manned flight by a Montgolfier hot-air balloon burning straw and paper fuel, Charles and Robert went five times longer and five times farther in their hydrogen-filled *Charlière* and pretty much set the design for balloons from then on.

But who remembers that? And who remembers that it was also Charles who got the gas-pressure-to-temperature-relationship law before Gay-Lussac reworked it and got the credit? But as a Frenchman, perhaps the worst of all for poor old Charles was that his young trophy wife, Julie, started a passionate affair with a poet she met while taking the waters at the Aix-les-Bains health resort in 1816 and then carried it on very publicly back in Paris.

The tall, handsome Alphonse de Lamartine soon became the darling of the salons and the Romantics' romantic. Making love, he said, calmed his nerves. Judging by the number of affairs he had, he must have ended catatonic. By 1833 Lamartine's writing had made him so well known, he was a paid-up member of the chattering classes both in lit crit and, in his new role as elected member of the Chamber of Deputies, politics. Ten years into this new career, he lurched to the Left, took up the workers' cause, and helped bring about the now ill-remembered 1848 revolution that got rid of Citizen-King Louis-Philippe and made Lamartine (ironically, given his propensities) French minister for foreign affairs in the new Republic.

Meanwhile the unfortunate Louis-Philippe and his wife slipped away to safety, smuggled across to England as Mr. and Mrs. Smith, "uncle and aunt" of the British consul at Le Havre: the unphonetic George William Featherstonhaugh.

And now it's time for me, too, to slip away. Adieu. SA

Wonders, *continued from page 89*

intracellular water of most plants (as it is in animals). Plant growth and what there is of movement depend on the inner water pressure that swells and stiffens plant cells—without it, plants wilt. A typical plant is about 0.5 percent potassium by weight, but sodium is often too low to report. Farmers have long known what plants require, and houseplant gardeners recognize the recipe on a fertilizer label that reads N4-P10-K6—nitrogen, phosphorus and potassium—all elements universal in life.

The electrical-pulse trains that travel down the nerves of animals are made by protein "valves." Specific molecular channels that penetrate the enclosing membrane are each able to open or to bar passage of a particular ion. Once transient charge flows are set up between sodium-rich exterior and potassium-rich interior, millisecond voltage pulses follow. Two distinct ions are essential. What passes down the length of the neuron is a quick but local current flow *across* the nerve wall, as the right valves open and close sequentially in response to the voltage change. (The energy is provided by the high-energy molecules that fuel most biochemical reactions.) The neural signal is not a passive electron flow pushed down a lossy wire. It is much more like a long string of tiny switchable batteries, set crosswise side by side down the long path. This remarkable process, whose signal speed can reach 100 meters a second and faster, has no real counterpart in the plant kingdom.

Potassium has a little secret. Its minor isotope of atomic weight 40 is weakly radioactive. A fair fraction of the ionizing radiation we receive from all sources—cosmic, local or man-made—is from the slow decay of essential internal potassium. Every minute a ripe tomato emits dozens of potassium gamma rays, and an average person about 25,000 of the rays. K^{40} has been decaying since the birth of the planet. On the young earth, potassium decays were up 10-fold. It may well be that the coming of multicellular life on earth—porcupines included—waited on the decline of potassium's intrinsic activity. Perhaps active potassium has always imposed some waiting period between the birth of a new sun out of recycled star debris and the rise of complex planetary life. Or are other soluble ions good enough to live by, out there? SA

DARRELL GULIN *Corbis*

DAN WAGNER

Sound Proof

Old speech habits are on the lam for a resident of Buckingham, notes **Steve Mirsky**

As Professor Henry Higgins, the fictional patrician phonetician, proved in the case of Eliza Doolittle, how one speaks can be as important as what one says. Therefore, recent research involving Queen Elizabeth II must have hit like a hurricane in Hartford, Hereford, Hampshire and the rest of the scepter'd isle: the queen no longer speaks the Queen's English. Well, not the Queen's English of half a century ago, anyway.

The changing nature of the queen's pronunciations was investigated by members of the Macquarie Center for Cognitive Science and the Speech Hearing and Language Research Center of Macquarie University. (Those institutions are in Australia, where some residents speak the Queensland English.) The researchers, who published the study in *Nature,* analyzed the vowel sounds made by the queen in Christmas messages from the 1950s and the 1980s. The authors note that they received permission from Buckingham Palace to perform the research, which proves that the Beatles were right and then wrong when they said, "Her Majesty's a pretty nice girl, but she doesn't have a lot to say."

Also scrutinized was the so-called standard southern British (SSB) accent, more likely to come from the mouths of the young and middle class. The researchers looked to 1980s recordings of female announcers on the BBC to compare the SSB to QE II. The inescapable conclusion: from the 1950s to the 1980s, the queen did indeed move her vowels. Although she still sounds distinct from the commoners on television and radio, the queen's accent by the 1980s was closer to regular folk than it had been three decades previous. Which proves that the Beatles were right and then right again when they continued, "Her Majesty's a pretty nice girl, but she changes from day to day."

The subtle move toward more common-denominator vocalizations may be the price of doing business in societies less and less dominated by adherence to traditional social castes. I am often reminded of the importance of similar speech patterns in engendering a sense of community. In my own Bronx neighborhood, for example, visitors can expect to be ritually greeted upon entering any of the local dining establishments with the welcoming words, "Youse wanna cuppuh cawfee?" The correct response to this query is, "Shaw, tanks." The incorrect response, "Why, yes, a splash of your most mellow Arabican would indeed be in order," can arouse suspicious glances that may in the fullness of time lead to beatings upon the capacious upside of one's head.

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My example, of course, involves both pronunciation and the separate issue of actual word usage. The choice of words is also an important indicator of one's relationship with the rest of society. Keith Greiner took this idea to heart recently when he broke down every single presidential inaugural address and counted the number of self-related words, such as *I, me, my* and *mine,* as well as inclusive words, like *we, us, our* and *ours*.

Greiner, who deals professionally with higher education data for an Iowa state agency, did the study to satisfy his personal curiosity and because the winters are very long in Iowa. He found that "since James Garfield's address in 1881, the percentage of words describing the inclusive 'we' relationship has grown dramatically." According to a Greiner graph, inclusive words account for about 2 percent of most speeches before Garfield but rise thereafter to an average of approximately 6 percent and hit a high of 10 percent for Ronald Reagan a century later.

Restricting the study to inaugural addresses successfully avoided potential confusion concerning presidential utterances that sound like *we*. These include the Francophone Thomas Jefferson's *"oui,"* the diminutive James Madison's self-deprecating self-description, "wee," and the rotund William Howard Taft's jubilant exclamation upon successfully extricating himself from the White House bathtub, "Weeeee."

So the queen sounds more like everyone else, and our presidents talk more like they *are* everyone else. Of course, the queen's speech no doubt changed naturally over time. Presidential communications alterations, on the other hand, may in part be conscious and manipulative, an attempt to appear in tune with the masses. Another wee thing to consider for us da people. SA