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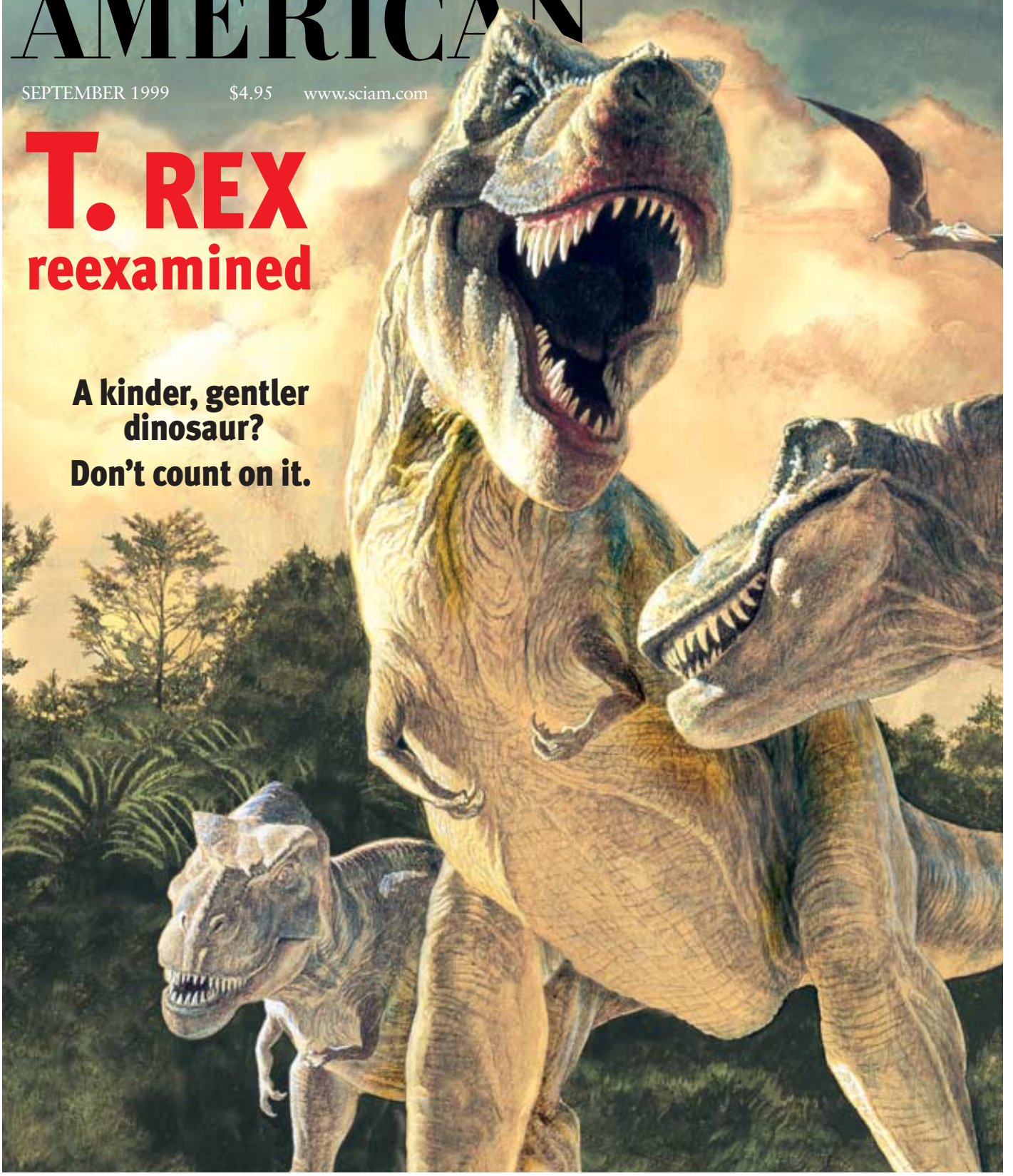
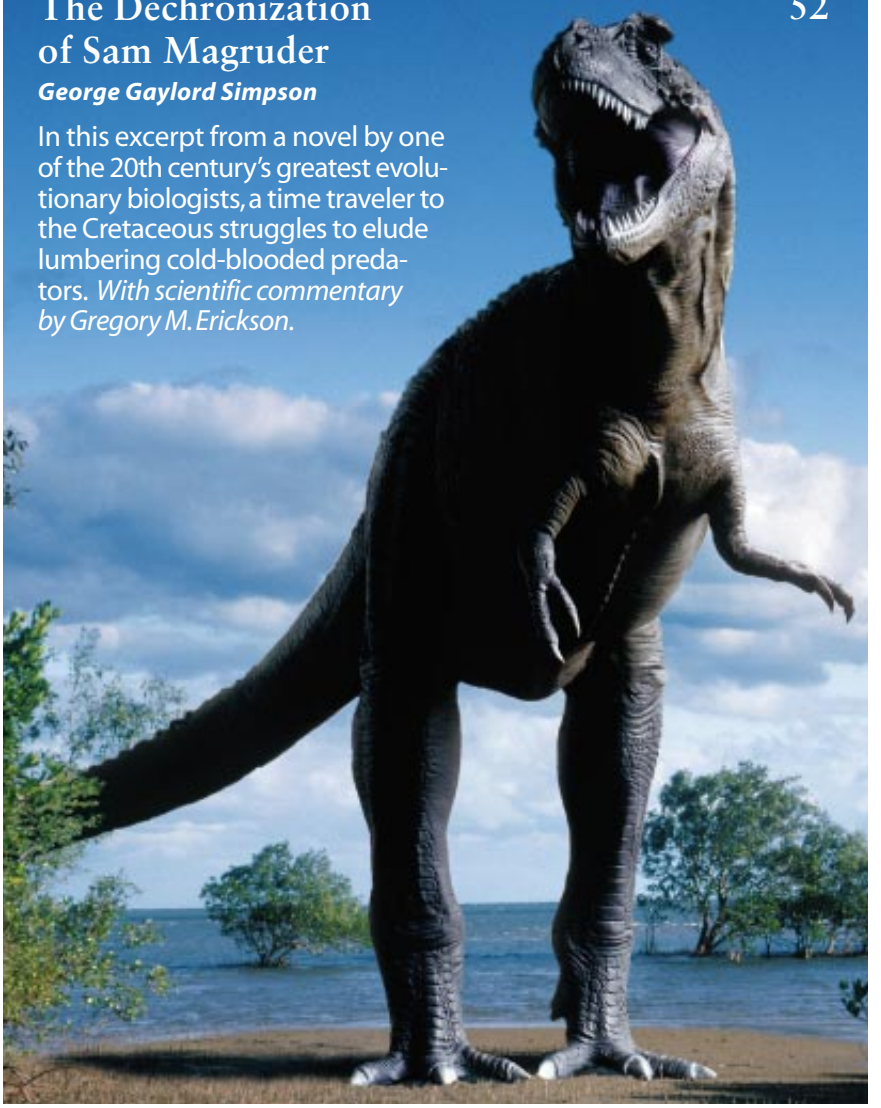


SCIENTIFIC AMERICAN

September 1999 Volume 281 Number 3

NEWS AND ANALYSIS

Uneasy sleep (page 24)



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Follow the Bouncing Planet

To the Greeks, those lights in the sky were *planetes,* "wanderers," that followed their own paths against the fixed stars and constellations of the firmament. Following Aristotle's lead, most Hellenic philosophers imagined the heavens as a nested set of rotating crystalline spheres centered on a round Earth. The sun, the moon and the other five known planets (Mercury, Venus, Mars, Jupiter, Saturn) spun overhead in their own separate spheres, while the stars sat embedded in the outermost sphere of all. That image of the crystalline spheres, spaced harmoniously apart, captured the essentially perfect and therefore unchanging nature that the universe was supposed to have.

The aggravating deviation from circular perfection, though, was that the planets insisted on moving apparently backward from time to time. When Ptolemy was distilling Hellenic cosmology into a single concept for his *Almagest* during the second century, rather than junk the flawed idea of circular orbits, he patched it by including a system of epicycles—circular wheels within the wheels—to modify the planets' orbits as needed (thus setting a precedent that would one day save the software industry).

DON DIXON

FROZEN BODIES at the solar system's edge attest to ancient orbital changes.

Ptolemy's patch wasn't simple, but it held for 1,400 years, until Copernicus and Galileo dragged Earth away from the center of the universe. It took Kepler and Newton to restore elegance to the system, by showing that the planets followed elliptical orbits that could be explained entirely through the force of that invisible mover, gravity. The heavens had regained their mathematically elegant, timeless perfection.

Then came the 20th century, ruining everything. Observation and calculation revealed that the dynamics of the whirling masses in solar systems are hugely complex and unstable in some configurations. Under the right circumstances, planets grabbing one another by the scruff of their gravitational necks can sling themselves into all new orbits. Our outer solar system bears the scars from just this kind of reorganization, as Renu Malhotra explains in "Migrating Planets," beginning on page 56.

Perhaps it reflects my own chaotic (read: messy) tastes, but I prefer the excitement and challenge of a universe in which planets ricochet off one another to the clockwork perfection of those crystalline spheres. It's the same inspiration I find in these lines by Christopher Marlowe:

> Nature that framed us of four elements,
> Warring within our breasts for regiment,
> Doth teach us all to have aspiring minds:
> Our souls, whose faculties can comprehend
> The wondrous Architecture of the world:
> And measure every wandering planet's course....

JOHN RENNIE, *Editor in Chief*
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LETTERS TO THE EDITORS

Our May issue prompted all sorts of interesting comments and questions from readers. We were particularly pleased that "Ada and the First Computer," by Eugene Eric Kim and Betty Alexandra Toole, inspired several of you to take a close look at Ada Lovelace's program for computing Bernoulli numbers. "What a delight to actually trace through Ada's code," writes Miguel Muñoz, a Los Angeles software developer. "To have so few flaws in an untested program this complex is remarkable." Muñoz and Peter M. Hobbins of Courtenay, B.C., discovered some additional bugs in her program (including line 4 of the source code shown on page 79, where the instruction should be ${}^2V_4 \div {}^2V_5$ instead of ${}^2V_5 \div {}^2V_4$), but both felt that these mistakes, along with the ones mentioned in the article, were the kind that would be spotted upon running the program on an engine. Before criticizing Ada's programming prowess, Hobbins notes, we must remember that "Ada and Charles Babbage had a working engine only in their minds." Additional reader responses follow.

ADA'S ERRORS

In their article "Ada and the First Computer," Eugene Eric Kim and Betty Alexandra Toole fail to distinguish between a printer's error in the original French article by Menabrea and Ada's translation of that error. (Several other mistakes in Ada's translation of the Menabrea article may be attributed to the English printer, and the A.L.L. is no doubt one such; Ada would not have miswritten her own initials.) Everyone knows how tricky it is to spot typos, but when you are translating something you have to pay some attention to its meaning. Hence, the responsibility for translating the statement that the cosine of n equals infinity, which she should have known was an absurdity, must be hers.

DOROTHY STEIN
Institute of Historical Research
University of London

Kim and Toole reply:

This error was certainly Ada's, but one cannot fairly ascribe it to mathematical incompetence. Anyone who has done translation, especially of technical documents, knows how arduous it can be, and Menabrea's article was more than 30 pages long. Additionally, both Charles Babbage and Charles Wheatstone reviewed Ada's translation, and neither caught the error.

COURTESY OF THE BRITISH MUSEUM

***ADA LOVELACE** extended the ideas of Charles Babbage and published the first computer program.*

GROWING NERVE CELLS

Gerd Kempermann and Fred H. Gage, in their otherwise excellent article "New Nerve Cells for the Adult Brain," have unfortunately perpetuated a misunderstanding regarding the effects of environment on brain growth. Like many authors before them, they referred to the "standard, rather spartan laboratory" conditions under which rats are normally housed as a "control" condition and to the large group cages with toys as "enriched." This leads to the misconception that environmental enrichment leads to supernormal brain growth. In fact, the environment that is "normal" for rats is the environment of evolutionary adaptation in which the brains of their ancestors evolved. This environment is far more complex even than the group playgrounds used in the laboratory (and, in fact, living in such an environment leads to even greater brain growth). What is demonstrated is not supernormal brain growth in enriched surroundings, but subnormal brain growth in the kind of impoverished environments in which laboratory rats are normally housed. This corrected perspective raises the unsettling notion that the literature on the psychology of learning based on rat data is almost universally derived from the behavior of neurally subnormal subjects!

THOMAS A. ALLAWAY
Algoma University College
Sault Ste. Marie, Ontario

Kempermann replies:

Our studies demonstrate that environmental stimulation has an effect on neurogenesis and cell survival. We do not intend to induce supernormal brain growth. Certainly under laboratory conditions that are deprived relative to feral conditions, the differences might be greater, but the point is that regulation is in fact possible. The scientific objective here is to understand basic biological principles, not to assess quantitatively how these principles affect higher cognitive functions.

DOCTORS' ORDER

In his profile of George D. Lundberg, former editor of the *Journal of the American Medical Association,* writer Tim Beardsley attempts to make a case for editorial freedom without raising the issue of whether a "crusading editor" is really the best way to ensure the integrity of the publication. Indeed, the content of *JAMA* on Lundberg's watch has been suspect to many of my peers precisely because it so clearly reflects a political agenda. AMA members see *JAMA* as the voice of their organization, and when that voice is too shrill and too discordant then perhaps a voice-change operation is just what the doctor ordered.

GREG E. BARRON
Laguna Hills, Calif.

XML: CHAOTIC CONTENT

With regard to Jon Bosak and Tim Bray's article "XML and the Second-Generation Web," all technology is a double-edged sword—and the same is true of Extensible Markup Language. On the one hand, XML is good for producing alternative presentations of information because it separates form from content. But it derives its power

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from enabling users to create many customized mini applications. So in this "let a thousand flowers bloom" scenario, one risks in principle a plethora of content that is hard to access because each instance is custom-built. To draw an analogy, people spent years making computer interfaces accessible; however, when the World Wide Web came along it turned every Web author into an interface designer, which chaotically resulted in each designer placing the controls on a page in some weird, specialized spot. Whereas in a standardized interface you know where to look for a given control, on a Web application you start from square zero each time. The double-edged potential behind XML comes from its ability to do precisely the same on the content front.

T. V. RAMAN
Adobe Systems

Editors' note: Raman was profiled in the September 1996 issue of Scientific American.

REMEMBERING KILLER WAVES

Frank I. González's "Tsunami!" is a fine article, and I read it with interest. I was a small child in Hilo when the 1946 wave hit and a teenager when the 1960 Chilean wave came. I nearly lost my life in that wave, which killed more than 60 Hiloans. There was ample warning that something would happen and an approximation of when but no hint of what the magnitude might be. I vividly remember being in civil defense headquarters in Hilo on the night of the 1960 tsunami, helping with the shortwave radios and being very relieved to hear that Christmas Island [Kiritimati] had seen only a very small rise in sea level. We believed (quite wrongly) that this meant that any wave would be minor. I suppose that a seismologist could have corrected us, but none was around. It's good that this appears to have changed.

DON MITCHELL
Buffalo, N.Y.

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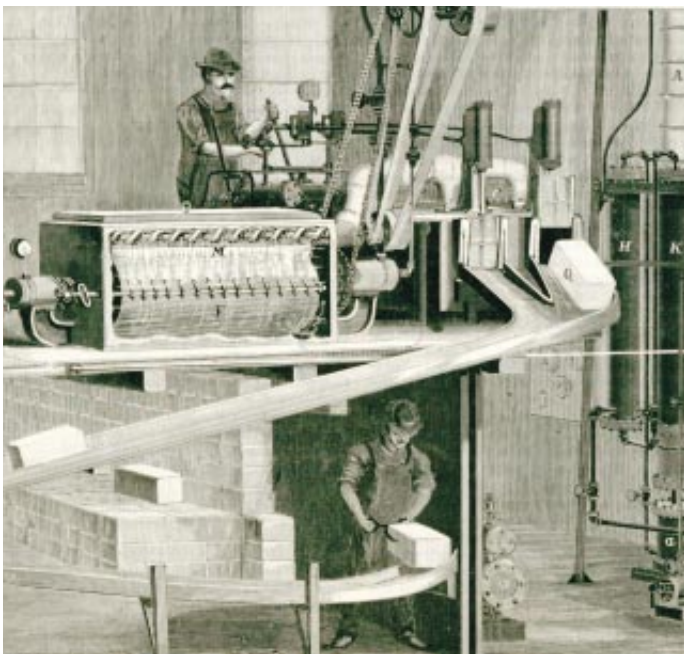
50, 100 AND 150 YEARS AGO

SCIENTIFIC AMERICAN

SEPTEMBER 1949

TELEVISION AND THE FAMILY—"In nearly two million U.S. homes, the flickering screen of the television set has paralyzed the family in its chairs. Obviously it is about time somebody began to measure the impact of this new social force. Preliminary data from a study sponsored by the Columbia Broadcasting System and Rutgers University has documented that television's most powerful impact is on children. Youngsters average more than two hours of watching each evening. The most surprising finding was the difference in the hold of television on different social groups: families with little education lose interest in television programs sooner than the better educated."

ENCEPHALITIS—"If our present hypotheses are correct, the encephalitic diseases of man and horses represent possibly the most complex disease cycle so far unraveled. The possible reservoir of the Western equine encephalomyelitis virus is mites, which pass it along to their young and to birds. The principal endemic cycle circulates the virus among birds and *Culex* mosquitoes. The possible epidemic cycle infects horses and men, who transmit the virus through the *Aëdes* mosquito."



The new Holden ice-making system

MAKING ICE—"By the courtesy of D. L. Holden, who has been connected with the manufacture of artificial ice for over thirty years, and may justly be called the father of that industry, we illustrate a remarkably interesting plant. The heart of this new system has a thin film of evaporating ammonia inside a cylinder (F), which causes water on the outside to freeze with great rapidity. As fast as ice forms, however, it is cut away by means of a set of knives arranged on a shaft. The slurry of ice shavings are carried away from the cylinder by a screw conveyor (M), and forced into the two hydraulic presses shown in the engraving, where they are squeezed into blocks of compact ice (Q)."

SEPTEMBER 1899

DEEP GOLD MINING—"It is beyond doubt that the auriferous beds of the Rand, in South Africa, will continue in depth far beyond a point where high temperature will render mining operations impossible. Where is this limit likely to be? Experiments have discovered a rise of 1° Fahrenheit for every 203 feet of vertical depth. If we assume that the maximum air temperature in which men and boys can do a shift's work is 100° F, we find that the limit of work by temperature is 12,000 feet vertical."

CARTHAGE—"Excavations by M. Gauckler in the ancient city of Carthage, underneath a Roman house dating to the time of Constantine, have revealed a pagan temple. In a remote corner of the hall there was found fastened against the wall a large slab of white marble bearing a dedication to Jupiter Ammon, identified with the sylvan god whom the barbarians adore. At the foot of this dedication was a white marble head of a votive bull carrying between its horns a crescent with an inscription dedicated to Saturn, and a score of granite baetyls [sacred meteoritic stones] and stone balls of a votive character."

SEPTEMBER 1849

SAVING WATER—"An American lady writing from Paris says that she has lately discovered the secret of the many beautiful and brilliant complexions seen in that city. It seems that water is considered by the French ladies as the great spoiler of the skin, so that unless some untoward circumstance really soils their faces, they exclude water almost entirely from their toilette tables, but content themselves with gentle rubbing with a dry, coarse towel."

BOSTON MEAN TIME—"Lieut. Davis, U.S. Navy, suggests, 'Hitherto we have used the English Meridian of Greenwich; all our astronomical calculations are fixed according to that, our nautical charts are adapted to it, and our chronometers are set to its time. The scientific importance of assuming an American Meridian is undoubted.' So long as we depend upon that from which we are separated by an ocean, our absolute longitudes remain indeterminate. There is no place on our coast, the longitude of which from Greenwich is so well ascertained as Boston. Yet there still exists an uncertainty in this longitude, of perhaps two seconds of time."

BLUEPRINT OF LIFE—"At the annual session of the American Scientific Association, held at old Harvard University, the celebrated Proff. Agassiz remarked, 'We find that young animals, of almost all classes, within the egg, differ widely from what they are in their full-grown condition. We find, too, that the young bat, or bird, or the young serpent, in certain periods of their growth, resemble one another so much that he would defy any one to tell one from the other—or distinguish between a bat and a snake.'"

NEWS AND ANALYSIS

IN FOCUS

THE FALLOUT FROM CASSINI

Controversy over the spacecraft's plutonium may threaten future missions to explore the solar system

COURTESY OF GLOBAL NETWORK AGAINST WEAPONS AND NUCLEAR POWER IN SPACE

***ANGRY PROTESTS** against the Cassini spacecraft's flyby of Earth have irked space agency officials, who insist there is no danger of an impact.*

At 3:28 A.M. Greenwich Mean Time on August 18, the two-story-tall Cassini spacecraft was expected to swoop past Earth, hurtling about 1,170 kilometers (725 miles) over the South Pacific at a blistering speed of 68,000 kilometers per hour (42,000 miles per hour). The flyby maneuver would use Earth's gravity like a slingshot, accelerating the spacecraft to its 2004 rendezvous with Saturn, where it will explore the planet's rings and its 18 known moons.

In the weeks before the flyby, however, critics of the Cassini mission warned of the potential for a nightmarish accident. The spacecraft contains three radioisotope thermoelectric generators (RTGs), which produce electricity from the heat emitted by the radioactive decay of plutonium 238 dioxide. RTGs have provided power for about two dozen spacecraft, including the Voyager and Galileo probes; the devices are particularly useful in the outer reaches of the solar system, where sunlight is too weak to generate much electricity. Critics have focused on Cassini because it holds a record amount of plutonium fuel: about 33 kilograms (72 pounds). More than 1,000 people demonstrated against the mission in Cape Canaveral, Fla., before the spacecraft's successful launch from there in October 1997. In June of this year anti-Cassini groups organized smaller demonstrations against the Earth flyby.

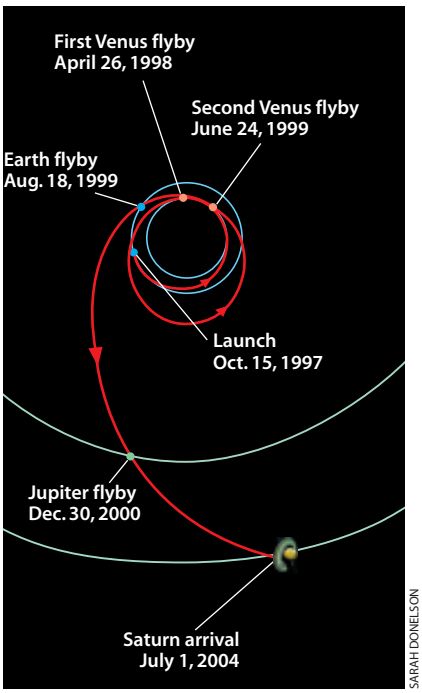
The protesters claimed that if the spacecraft hit Earth instead of swinging by it, much of the craft's plutonium fuel would be pulverized into fine particles that would spread throughout the atmosphere. The fuel pellets are enclosed in iridium capsules and two layers of graphite shielding, but the modules were not designed to withstand an ultrahigh-speed reentry. The harm that would be done by such a release is virtually impossible to predict—estimates vary from 120 fatal cancers worldwide to hundreds of thousands of deaths. Although far more plutonium has been released into the atmosphere by nuclear bomb tests, plutonium 238 is about 280 times more radioactive than plutonium 239, the material in bomb fallout. According to John Gofman, professor emeri-

tus of molecular and cell biology at the University of California at Berkeley, a single micron-size particle of plutonium 238, if inhaled, could cause lung cancer. "It's pretty hot stuff," Gofman says.

Fortunately, the chances of an impact on August 18 were calculated to be minuscule: less than one in a million, according to the National Aeronautics and Space Administration. Because Cassini is so heavy (more than 5,000 kilograms), it would take a mighty push—an explosive leak, for example, or a collision with a large meteor—to alter the spacecraft's trajectory significantly. As an extra precaution, the mission team at the Jet Propulsion Laboratory (JPL) in Pasadena, Calif., biased Cassini's trajectory so that it would miss Earth by at least 5,000 kilometers if the ground controllers lost contact with the craft.

Even some of Cassini's opponents acknowledged that the flyby would probably be uneventful. Only 60 people showed up at the Cape Canaveral protest in June. "People are still concerned, but it's really out of our hands," explains Bruce Gagnon, who organized the demonstration. Michio Kaku, a physicist at the City University of New York who has been the most prominent Cassini critic in the scientific community, says NASA should not draw the wrong lesson from the anticipated success of the flyby. "Sooner or later," Kaku maintains, "the odds will catch up with us."

Over the next 10 years NASA is planning three more missions that are expected to use plutonium fuel for electric power: Europa Orbiter, which will travel to Jupiter's fourth-largest satellite; Pluto-Kuiper Express, which will whiz past the farthest planet; and Solar Probe, which will go into an elongated orbit to study the sun. John McNamee, project manager for the missions at JPL, says that all three spacecraft will journey too far from the sun to rely on solar power. The probes would have to carry oversize solar panels to generate enough electricity for their needs. Besides adding weight to the craft, the large panels would be difficult to deploy and control. "Solar power just isn't technically feasible for these missions," McNamee remarks.



***GRAVITY-ASSIST FLYBYS** are needed to speed Cassini to Saturn (planets' orbits not drawn to scale).*

Unlike Cassini, the three planned missions will not fly by Earth, but McNamee says this is not because of any concerns that the probes might hit our planet. The future spacecraft will be several times lighter than Cassini, so they will not need as many gravity-assist flybys to reach their destinations. For the same reason, the probes will not need giant rockets to blast them into space. Cassini was launched by a powerful Titan 4 booster—the reliability of which has been questioned after some recent spectacular failures. The future missions will most likely be launched by the space shuttle or by updated Delta or Atlas rockets, McNamee says.

This prospect frightens Kaku. With a spacecraft carrying plutonium, the launch is by far the most dangerous moment. "If Cassini had blown up at launch, it would've been the end of the space program," he says. "We're putting a lot of hope on a firecracker." According to NASA, however, even a catastrophic launch accident would not release any plutonium fuel. The U.S. Department of Energy (DOE), which builds the RTGs, has subjected them to extensive tests that simulated the conditions of a rocket explosion. The testers fired .30- and .50-caliber bullets at RTG components to determine if they could be pierced by shrapnel. They also slammed rocket sleds against the devices, exposed them to propellant fires and detonated explosives to mimic blast waves.

Most of the tests did not damage the plutonium-fuel capsules, but some of the more severe impacts created fissures that would have released small amounts of fuel. NASA officials assert that such intense impacts would be unlikely during a launch accident. Kaku, though, looked at the same test results and came to the opposite conclusion. "The worst case," he says, "is if it explodes high in the atmosphere and the winds blow the plutonium around. Whole areas of Florida would have to be quarantined. And you could kiss Disney World good-bye." Aerospace engineers dispute this claim: Jerry Grey, a mechanical and aerospace engineer at Princeton University, says RTGs proved their survivability in 1968, when a military satellite carrying two generators was destroyed in a launch explosion in California. The RTGs landed in the Santa Barbara Channel and were retrieved intact from the seabed. "Nothing has a zero hazard," Grey notes. "But the hazard from RTGs is so small it should not bar their use."

In the debate over RTGs, however, perceptions are sometimes more important than facts. NASA officials admit that the Cassini controversy may threaten the chances of any future space mission that would carry radioisotopes. "I think it may be a problem," concedes Robert Mitchell, Cassini's program manager. "The amount of effort needed to get missions like this approved will increase."

Meanwhile the DOE is developing a more efficient generator for spacecraft called the Advanced Radioisotope Power System (ARPS). If successful, ARPS would require 50 percent less plutonium fuel than a comparable RTG does. ARPS would also be about 25 percent lighter, no small consideration for a spacecraft component. NASA is paying the DOE $75 million to develop the generators, and JPL's McNamee says flight units could be ready for the planned 2003 launch of Europa Orbiter. The spacecraft would then need to carry as little as five kilograms of plutonium fuel.

But this effort has not satisfied the Cassini protesters. "It doesn't matter to us, because it takes so little plutonium to create havoc," Gagnon argues. Kaku would prefer that NASA spend its money developing better solar power technologies for its spacecraft. "NASA is saying that solar is difficult and nuclear is easier," he states. "I'm saying that solar is difficult but not impossible." Kaku acknowledged that solar power is currently not a viable option for a probe to Pluto, but technical advances may eventually make such a mission possible. "The technology is not there yet," Kaku says. "But that's okay. Pluto is not going to go away." —*Mark Alpert*

CONSERVATION

CONGO CITY

Gorillas and the rain forest come to the Bronx

DENNIS DeMELLO *Wildlife Conservation Society*

***ZOO VISITORS** remain indoors behind glass, which also permits the gorillas to peer in. Other rain-forest denizens include mandrills, red river hogs and okapis.*

It can be so difficult to tell the difference between real and fake at the new Congo Gorilla Forest exhibit at the Bronx Zoo in New York City that even the mandrills get confused. In a recent foray in her new digs, a mandrill mother approached the glass that separates her from zoo-goers. She suddenly assumed a defensive posture and backed off, pulling her baby with her. A lovely bronze sculpture of a rock python—with apparently just the right-looking twist to its neck—on the visitors' side had spooked her. "It was one of the greatest moments that I've had in this exhibit," says project director Lee C. Ehmke. "It is pretty amazing that these zoo-bred mandrills, fourth or fifth generation, are somehow hardwired for snakes."

That kind of realism, and reaction, is exactly what the designers of the just-opened $43-million, 6.5-acre exhibit aimed for. And although the monkey's response was unexpected—the bronzes by Priscilla Denaci Deichmann were to be accurate but purely decorative—it illustrates an attention to detail that makes the Congo Gorilla Forest really resemble a mysterious, exhilarating walk through an African rain forest, without the bug bites. To create this exhibit, which is inhabited by 75 different species, the Bronx Zoo team used the techniques of immersion design: the fabrication of natural-looking landscapes and flora and fauna that many zoos started pursuing in the

1980s. But, according to experts in the field, they raised the bar.

"What Congo does in my opinion is take immersion design further and do it finer," says Jon C. Coe of CLRdesign in Philadelphia. "The level of detail is very high throughout." Coe was one of the designers of Woodland Park in Seattle, the gorilla exhibit that in the late 1970s pioneered landscape immersion by making a not-so-real habitat so realistic that Dian Fossey approved.

In Congo many tricks create the impression of meandering, natural trails: mushrooms are lit by fiber optics hidden in the fallen tree that serves as a passageway for visitors; the climbing liana vines are reinforced with metal; the stately *Uapaca* trees are made of epoxy; and some roots are crafted from pipe cleaners. The Goliath frog hiding in one of the 11 waterfalls, as well as a green mamba snake and a Goliath beetle hidden elsewhere, will never move of its own accord. And the huge rock outcropping that obscures the main exhibit building is made of concrete laced with an irrigation system that is encouraging a tangle of ferns to take hold.

The idea is to steep visitors in an equatorial ecosystem, to have them happen on various creatures and unusual vantage points, to appeal to their emotions and sense of discovery. But Congo not only achieves immersion, "it breaks ground in a couple of other areas that are

J. HEDDEN

RE-CREATING THE CONGO—by painting realistic details on fake trees, for instance—took seven years of painstaking attention to detail.

important," Coe remarks. "It backs up the emotional side with information."

One example of this marriage of emotional pull and educational push can be found when visitors wander into the Treasures of the Rain Forest gallery. In a cavelike area they see a thermal image of themselves on a screen. The hottest parts of their bodies burn white and bright yellow as they approach. At first it is simply entrancing to see where one's body is hot—and then comes the sudden realization that this is a hungry python's view of you, thanks to the heat-sensitive pits in its mouth. "What we are doing here is showing people how a python can sense prey," explains Walter G. Deichmann, Congo's creative director.

Deichmann, Ehmke and other designers and scientists from the Wildlife Conservation Society—which runs the Bronx Zoo—worked to ensure that the animals would be as engaged as the visitors. By building hidden feeding stations into the mandrill and red river hogs display and into the gorilla habitat and by changing the dispensing schedule, they encourage foraging behavior. (To prevent foraging from going too far, however, they also electrified some of the vegetation so that it, too, can lead a happy, healthy life.) Searching for food makes the animals a lot less bored and can bring them close to the bulletproof, reinforced glass that surrounds the visitors—who provide another source of entertainment for the gorillas. A food-dispensing termite mound, for example, straddles the glass separating people from the apes.

And just down the window from the termite mound, Deichmann has incorporated a heating-cooling system into a large (fake) tree in another effort to draw the gorillas toward their viewers. On a recent July day when New York City temperatures climbed into the high 90s, several of the older gorillas clustered in the air-conditioned hollow tree. "They are pretty smart," observes Colleen McCann, the zoo's primatologist. "They found a nice, comfortable spot." Meanwhile their kids were off playing in the shade of (real) trees.

—Marguerite Holloway

HEALTH

SILICONE SAFE

A major report finds that silicone breast implants don't lead to cancer

Women who have silicone breast implants are no more likely than the rest of the population to develop cancer, immunological diseases or neurological disorders, a committee of the Institute of Medicine (IOM) reported on June 21. Moreover, mothers with implants may safely breast-feed their infants, as there is no evidence of toxicity in the milk. The IOM committee drew its conclusions after holding public hearings (during which women with implants told of their experiences) and reviewing scientific literature on silicone breast implants (first made in 1962) and silicone.

The analysis—funded by the U.S. Department of Health and Human Services and the National Institute of Arthritis and Musculoskeletal and Skin Diseases—is the latest in a series to have found such results. Similar announcements were made last year by scientists who were appointed by judges overseeing implant liability litigation in the U.S. and by researchers in Britain reviewing implant safety for the British Department of Health.

Still, the IOM committee points out, breast implants are not without risks. The tissue around the implants may contract, causing pain and disfigurement and leading to infection by skin bacteria that normally reside in the lactiferous ducts of a healthy breast. Also, implants have a finite life span, and rupture rates of gel implants and the deflation frequencies of current saline models have not been determined. Problems lead to additional surgery to replace or remove them.

Not everyone is convinced by the IOM report. Some believe that a study based on other studies—called a meta-analysis—is inherently flawed because of assumptions made about the quality of previous research. In any case, implant manufacturers have already agreed to a total settlement estimated at $4 billion with plaintiffs who claimed physical harm; now-bankrupt Dow Corning will be paying the most, some $3.2 billion.

—Christina Reed

SIU Photo Researchers, Inc.

BREAST IMPLANTS may not be toxic, but they still carry risks, such as rupture.

BIOINFORMATICS

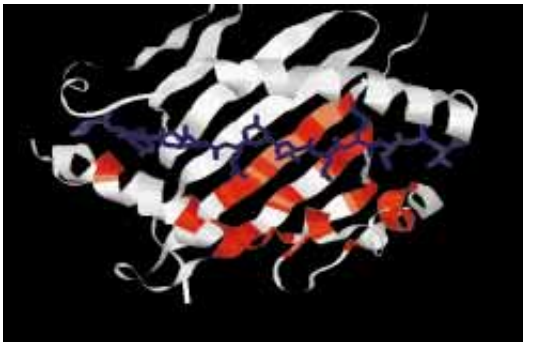
CALCULATING IMMUNITY

Computers may be able to determine the molecular interactions in an immune response

The immune system can vanquish bacteria, viruses and cancer cells with an accuracy that puts drugs to shame—*if* it recognizes them as enemy aliens. But although researchers have learned a good deal about how the body's defensive army is organized, they cannot usually predict exactly how the atomic-level interactions between invaders and defenders will play out and thus which alien proteins will stimulate a response. If the engagement of pathogens' proteins with immune cells could be modeled in detail on computers, laboratory-synthesized molecules could rev up the immune system and induce it to attack recalcitrant tumors and fight incipient infections for which no vaccine now exists.

Today's computers and programs actually have all that it takes to model molecules; the problem is that there are far too many possibilities to sift through them all. The immune system produces thousands of different proteins whose job it is to look out for infiltrators, in any of billions of different combinations. Infiltrators carry a similarly colossal number of molecular identifiers. So the number of ways the two might combine is unimaginably huge. Computers easily get bogged down in problems with vast numbers of possibilities.

Hence the interest surrounding a new study that concludes that predicting novel immune-antigen interactions is in fact doable with a reasonable—though still large—number of experiments. Juergen Hammer and his colleagues at Hoffman-La Roche in Nutley, N.J., and Milan, Italy, as well as at the University of Saarland in Germany, have spent the past seven years engaged in an exhaustive analysis of which antigens do and which do not interact strongly with one of the immune system's key generals, a protein called HLA-DR that exists in hundreds of variant forms. The investigators have determined that the problem can be broken down into smaller bites that can be tackled experimentally. The solutions to the individual bite-size problems can then be combined in a straightforward way.



COURTESY OF HOFFMAN-LA ROCHE

FRAGMENT** of a germ's protein* **(blue)** ***triggers an immune response when bound by an HLA molecule **(red and white).**

Immune proteins of the type Hammer and his colleagues studied bind to pathogens' proteins as the first step toward triggering a defensive response. Antigens, which generally consist of chains of 13 to 20 amino acids, might attach themselves on the surfaces of immune cells in many different positions. Each amino acid in the antigen is one of 20 naturally occurring types, each type having unique chemical characteristics.

Researchers have known for a while that the relevant immune proteins bind antigens in a handful of separate "pockets," each of which attaches to one amino acid in the antigen. Pockets with different structures bind to different amino acids. Hammer's group has showed that binding in similarly shaped pockets always follows the same rules. One type of pocket might, for example, bind the amino acid tryptophan strongly but serine not at all; another type might bind both moderately well. Furthermore, whatever binds in one pocket does not interfere with binding in adjacent pockets. And an antigen that binds well to key pockets separately will bind well overall.

Hammer's team had to produce 1,000 different synthetic antigens for the 10,000 different chemical binding tests they needed to generate a statistical model of the HLA-DR binding problem. Hammer created special software to combine and expand the experimental results into a mathematical form. The outcome represents "the majority of human HLA-DR peptide binding specificity," the authors claim.

Hammer then used the program to analyze sets of hundreds of novel antigens to check whether he could predict which were likely to bind to various HLA-DR types. The prognostications matched experimental results well. The authors note that such software should become increasingly useful as other biotechnologies, such as "DNA chips," start to yield large amounts of data about proteins in all manner of organisms. When Hammer's software was let loose on protein sequences corresponding to genes active in colon cancer, it predicted amino acid sequences that could stimulate immune system attacks on that disease.

Immunologist Thomas Kieber-Emmons of the University of Pennsylvania says it remains to be seen how well Hammer's technique, published in *Nature Biotechnology*, will fare in the real world: sometimes cells fail to bind antigens as expected. But he thinks it is an approach that others will probably try to emulate.

Hammer's program tackles only one key immune molecule, and there are no guarantees that the simplifying shortcuts he found in HLA-DR will hold in other parts. But it looks as though the problem of calculating complex immune system interactions may be getting easier.

—Tim Beardsley in Washington, D.C.

IN BRIEF

La Niña Continues

The National Oceanic and Atmospheric Administration predicts that the current La Niña will persist into 2000. La Niña is characterized by colder-than-normal areas in the Pacific Ocean, which affect atmospheric flow. For the U.S., that means a dry winter in the Northeast and the South and a rainy one in the Pacific Northwest. *—Philip Yam*

But I Own a Porsche …

In what could change the bar scene, investigators say that attraction depends on the menstrual cycle. When conception chances were highest, women seeking a short-term relationship preferred the "masculinized" look of a squarer jaw and wider face, which may indicate good health. During other phases, women favored more feminized faces, attributing to them more positive personality traits. "Selection might have favored human females who pursued a mixed mating strategy" under certain conditions, the authors write in the June 24 *Nature*. *—P.Y.*

More "In Brief" on page 24

AVIATION

STRIKE ZONE

A little ecology and technology could keep birds away from airplanes

Airplanes and birds just can't get along. Every year pilots in the U.S. report more than 5,000 bird strikes, which cause at least $400 million in damage to commercial and military aircraft. Although any airborne encounter is going to be harder on the bird (just ask romance-novel cover boy Fabio, who encountered one while riding a roller coaster), the damage the animals can inflict on aircraft control surfaces or engines can lead to disaster. In 1975 a DC-10 taking off from New York City's John F. Kennedy airport ran into a flock of seagulls and lost one of its three engines; the airliner slid off the runway and burned, although everyone on board escaped unharmed. Four years ago the crew of a U.S. Air Force AWACS plane wasn't so lucky. The Boeing 707 lost two of its four engines after striking a flock of geese during takeoff; the crash killed all 24 people on board.

Despite having experimented with everything from electromagnetics to ultrasonic devices to scarecrows, the Federal Aviation Administration (FAA) has yet to endorse one single sensational solution that will keep birds out of the path of an oncoming aircraft. The best bet right now is understanding bird behavior, although an intriguing old pilots' tale—that radar can scatter birds—may carry enough truth to ultimately offer a viable technical solution to a deadly problem.

Before the 1970s, bird strikes were rare, partly because bird populations were at an all-time low. But conservation efforts—including banning such pesticides as DDT and broadening the Migratory Bird Treaty Act in 1972—have paid off big: the Canada goose population, for instance, about 600,000 in the mid-1980s, exploded to two million birds in a decade. With humans taking over the birds' old habitats, flocks of protected species have made a home out of the wide-open spaces of international airports, which tend to be built along migratory flight paths on once undesirable, now federally restored and protected wetlands. "Birds don't seek a kindred spirit there," explains Ed Cleary, staff wildlife biologist for the FAA. "They see habitat that is attractive to them."

At first, airports' efforts to control birds had a whimsical, Seussian quality: staffs tried automatic noisemakers, such as gas cannons and ultrasonic devices, and posted allegedly frightening predator effigies. But the flocks remained. "There's no magic black box out there," Cleary says. "What we have got to do at any airport is determine why the animals are there and take measures to eliminate what is attracting them."

So in 1991 the FAA brought in the U.S. Department of Agriculture's Wildlife Services Program, the branch of the government assigned to deal with wildlife-human conflicts. "We found that a lot of technological approaches have to be used intelligently and judiciously—and sparingly," says program head Richard A. Dolbeer. What works, they have found through tests at the Wildlife Service's research station near Sandusky, Ohio, is a multipronged assault designed to make the airport unattractive to birds. Measures include minimizing open water near runway ends, closing nearby garbage dumps and removing other food sources such as insects (through pesticides), setting off random explosions from fireworks and gas cannons, and even reintroducing predators, such as trained falcons and dogs, and allowing professional biologists armed with shotguns and permits to bag a limited number of the federally protected avians. The approach seems to work: New York's JFK, which in 1988 reported more bird strikes than any other U.S. airport—300—has reduced that number by 75 percent.

To eliminate the risk entirely, some researchers have not given up hope for the magic black box to shoo birds away. Jim Genova of the Washington, D.C.–based Defense Research Associates is working on a project based on research begun in the 1960s by biophysicist A. H. Frey. Following up on reports that people could hear radar, Frey found that his graduate students could accurately "hear" information coming out of microwave transmitters. (The students also reported headaches afterward.) Theorizing that the microwaves caused pulses of heat in the brain, which in turn expanded and contracted the cochlea, Genova set out to try sending a microwave alarm to birds.

At the Sandusky facility in 1997, he and his colleagues mounted a microwave transmitter on a truck and sent it barreling toward a cage of wild birds. When the transmitter was switched on, the birds were startled and did their best to fly out of the vehicle's path more quickly than when the transmitter was off. Genova says that tweaking the pulses sent out by a common aircraft transmitter called a DME (for distance-measuring equipment), he can turn a ubiquitous aircraft instrument into an warning siren for wildlife.

Not everyone is as enthusiastic as Genova. "The jury is still out," says the FAA's Cleary. "We are considering trying to put it to rest one way or the other." Genova plans next spring to mount a modified DME in a small plane and head toward a flock of birds to see if it works. If it doesn't, the pilot may well have a bigger headache to contend with than the microwave variety. —*Phil Scott*

PHIL SCOTT, a freelance writer in New York City, described commercial launch failures in the July issue.

PETER GRIDLEY FPG

***TAKEOFFS AND LANDINGS** are the most likely times for bird strikes.*

In Brief, *continued from page 21*

Alzheimer's Vaccine?

Researchers at Elan Pharmaceuticals in South San Francisco suggest in the July 8 *Nature* that a vaccine against Alzheimer's disease may be possible. The mice in the study were genetically modified to come down with an Alzheimer's-like condition—complete with altered beta-amyloid, a protein that causes the buildup of sticky insoluble deposits called plaque in the brains of Alzheimer's patients. Then, using beta-amyloid itself to stimulate an immune response, the team prevented plaque formation in six-week-old mice and reduced plaque in older mice. Elan plans to begin safety trials, but whether such a vaccine might help is uncertain. The plaque could be a symptom and not a cause of Alzheimer's. *—Christina Reed*

Sleeping Like a Baby

Among new parents, knowledge of the "Back to Sleep" campaign is as common as dirty diapers. Now John M. Graham, director of the craniofacial clinic at Cedars-Sinai Medical Center in Los Angeles, notes a drawback to placing sleeping infants on their backs to reduce the risk of sudden infant death syndrome: the constant pressure on the soft skull can deform the head and shorten muscles on one side of the neck. The incidence of misshapen heads has increased fivefold over the past five years. Neck stretching, head-turning exercises or corrective helmets can remedy the problem. *—Sasha Nemecek*

JENNIE WOODCOCK *Reflections Photolibrary/Corbis*

Head bending

Rabbit, Run

For the first time, a government panel of scientists has endorsed a nonanimal method for testing the safety of new chemicals. The Interagency Coordinating Committee on the Validation of Alternative Methods (supported by 14 federal agencies) stated that the test, marketed as Corrositex, can either fully replace or significantly reduce some kinds of animal testing. Corrositex incorporates artificial skin to evaluate harmful substances. Regulatory agencies, such as the Consumer Products Safety Commission, rely on the findings of such panels to set federal requirements for safety testing; decisions on including the test are expected from regulatory agencies by the end of the year. *—S. N.*

More "In Brief" on page 26

ANTI GRAVITY

Strife after Death

Freud said that sometimes a cigar is just a cigar. By the same logic, sometimes a snake is just a snake. Which is good, because I've been thinking a lot about snakes lately. Unprovoked, such contemplation might make me consider analysis of a Freudian nature, but these thoughts have clear inspiration—namely, the *New England Journal of Medicine* (*NEJM*) and the U.S. House of Representatives.

NEJM recently carried a letter with the striking title, "Envenomations by Rattlesnakes Thought to Be Dead." The authors, Jeffrey R. Suchard and Frank LoVecchio of the Good Samaritan Regional Medical Center in Phoenix, described five cases of men—only men do dumb stuff like this, apparently—who got the surprise of their life from snakes that had just shuffled off their own mortal coils. Make no mistake, these snakes were as dead as Julius Caesar. "They retain some primitive reflex actions for a short while after being killed," Suchard explains.

"Patient 1 bludgeoned a rattlesnake on the head with wood," the authors write in *NEJM*. Evidently he was smacking the snake's head with his own head. Patient 1 was bitten on the finger when he picked up the dead snake.

"Patient 2 shot a rattlesnake, striking the head several times, and observed no movement for three minutes." Patient 2 lifted the snake, got a dose of venom in his finger and became the subject of observation himself, at the hospital.

"Patient 3 shot and then decapitated a rattlesnake." And then picked it up. Patient 3 was a thorough guy. Now he's a thorough guy whose friends call him Lefty. Actually, he didn't lose a whole hand, just a finger. When Patient 3 picked up the dead head, the venom-loaded fangs caused enough tissue damage to make amputation necessary.

"Patient 4 was envenomated on his left ring finger and right index finger by a decapitated rattlesnake head that had been motionless for five minutes." Patient 4 thus contributed to medical science by establishing a minimum waiting period for safely picking up a severed rattlesnake head: more than five minutes. Actually, "decapitated snake heads are dangerous for between 20 and 60 minutes after removal from the body of the snake," Suchard notes. "If that's not dead, I don't know what is."

"Patient 5 was envenomated on the left index finger by a rattlesnake he had presumed to be dead from multiple gunshot wounds, including one to the head." Patient 5 apparently never heard of Rasputin.

The authors note that alcohol may often impair a man's judgment enough to make snake-handling seem like a righteous idea and that "education to prevent snakebites should include warnings against handling recently killed snakes." In the interests of science education and public safety, SCIENTIFIC AMERICAN therefore warns: Don't handle recently killed snakes.

Rattlers, of course, are more than just snakes. They are symbols of wildness and power, qualities that inspired American colonists to put them on some of the first American flags, along with the written advice "Don't Tread on Me." Of course, the U.S. long ago replaced the rattler with stars and stripes. But the spirit of the old symbol and motto still lurks behind the newer flag, like a rattler under a slab.

So it came as a shock when the House of Representatives recently overwhelmingly approved a Constitutional amendment outlawing "desecration" of the flag. (Congress failed to address whether desecration of the flag includes wrapping oneself in it.) Such legislation is counterproductive, treading as it does on the free-speech guarantees of the First Amendment. It is also unnecessary. A seemingly destroyed rattler is still dangerous; a country that tolerates the occasional destruction of its symbols, including images directly descended from the rattlesnake, is still powerful. *—Steve Mirsky*

MICHAEL CRAWFORD

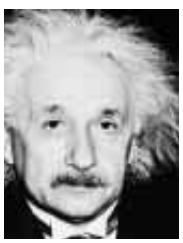
In Brief, *continued from page 24*

More New Elements

In June, Lawrence Berkeley National Laboratory announced the creation of the heaviest elements yet, elements 118 (118 protons, 175 neutrons) and 116 (116 protons, 173 neutrons). Krypton and lead were smashed together and occasionally fused to create element 118, which decayed in 0.0001 second to 116 and then to 106 (seaborgium). This "cold fusion" was not thought capable of producing such heavyweights until recent calculations suggested it. The new members of the periodic table follow the discovery of element 114 by the Joint Institute for Nuclear Research in Dubna, Russia, which in the July 16 *Nature* reports confirmation of its earlier find. —*P.Y.*

Why Einstein Was Einstein

The June 19 *Lancet* partially explains why Albert Einstein was brilliant. After receiving samples and data from pathologist Thomas Harvey, who pickled Einstein's brain hours after his death in 1955, Sandra F. Witelson and her colleagues at McMaster University discovered that the physicist's brain was 15 percent wider in both hemispheres, thanks to one centimeter more growth in the inferior parietal lobes—a region implicated in visual interpretations, mathematical thought and imagery of movements. The growth may have compensated for Einstein's missing parietal operculum—a bend in the cerebrum that normally covers the so-called Sylvian fissure. —*C.R.*



CORBIS/BETTMANN

Good parietal lobes

Digital Divide

The U.S. Department of Commerce has issued its third report on Internet access (www.ntia.doc.gov), which notes that white and Asian households are more likely to have access than black and Hispanic ones are. Economic factors are key: 60.3 percent of households making $75,000 or more use the Internet, but only 19.1 percent of those making between $25,000 and $35,000 do. Overall, 40 percent of American homes have a computer, and one quarter log on. The danger is that those with the least access will be left behind economically. A July 13 United Nations report echoes that idea. It finds that only 3 percent in Russia, 0.2 percent in Arab states and 0.04 percent in southern Asia are Net-ready and suggests a penny tax on long e-mails to raise $70 billion to wire the wireless. —*P.Y.*

COSMOLOGY

SKEWING THE COSMIC BELL CURVE

Nonrandom features could sink inflation

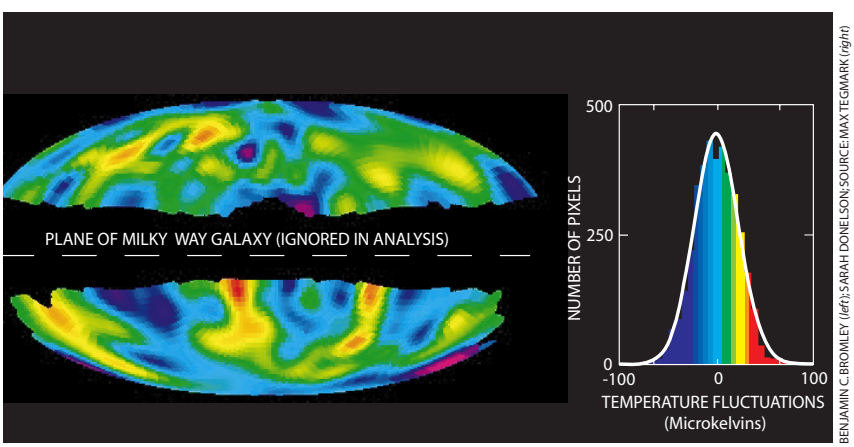
Sometimes it seems that the only thing expanding faster than the universe is cosmologists' bewilderment. Several teams have now reopened what most had thought was a closed case: the random distribution of matter in the nascent universe. Maybe, the researchers say, it is not as random as normally assumed. If confirmed, their findings could rule out inflation, the prevailing model of the early universe—indeed, the only model that has survived decades of winnowing—and set cosmology back 20 years.

Inflation neatly explains the delicate balance of order and randomness in the cosmos: an extra-rapid expansion smoothed out any flagrant unevenness while creating new irregularity, just enough to seed astronomical structures such as galaxy clusters but not so much as to make the cosmos into a bleak web of black holes. The clumping shows up in the snapshot of the infant universe provided by the cosmic microwave background radiation. The radiation has an average temperature of 2.7 kelvins, with deviations of 30 or so microkelvins in different parts of the sky representing slight variations in the density of matter.

Ever since these deviations—or anisotropies—were first seen by the National Aeronautics and Space Administration's Cosmic Background Explorer (COBE) satellite, measurement of their strength at different scales has become cosmologists' most incisive tool. In undertaking their analyses, however, researchers generally take for granted one of the strongest predictions of inflation: that the density values cluster around the average according to a Gaussian distribution—the familiar bell curve. Inflation is driven by a quantum field that generates a kind of antigravity, bloating space. This field fades away, but to have the desired effect, it must do so slowly. That gives the field plenty of time to try to reach the same value at each point in space. Yet exact equality is impossible in quantum mechanics—it would violate the Heisenberg uncertainty principle—and the best the field can do is settle into a Gaussian distribution, which minimizes the overall energy. Such a pattern describes the spatial variations (the precursor of the density undulations) on every length scale. It is, in a sense, the most random that random can be.

By one count, 28 studies over the past five years have corroborated that prediction. But there's always someone who spoils the curve. In the past year, non-Gaussianity has emerged in studies of the COBE data by four teams, led respectively by Pedro G. Ferreira of CERN; Jesús Pando, then at Strasbourg Observatory; Dmitri Novikov of the University of Kansas; and Robert G. Crittenden of the Canadian Institute for Theoretical Astrophysics.

In principle, their conclusions are consistent with the earlier null results because they look for different types of deviations from the bell curve. Nevertheless, most cosmologists are doubtful. The new findings, they worry, could be a case of data-mining: patterns will eventually



BENJAMIN C. BROMLEY (*left*); SARAH DONELSON; SOURCE: MAX TEGMARK (*right*)

RANDOM DENSITY FLUCTUATIONS in the early universe (left) *might not exactly follow a bell curve* (right), *as inflation predicts.*

arise in any data set out of pure chance. "If you look too hard for something, you may end up finding it," says Benjamin C. Bromley of the University of Utah, one of the leading skeptics. The risk is especially acute in this case, because mathematical analysis can subtly distort the statistical properties of data. Moreover, COBE data are notoriously noisy, and the purported effect looks remarkably like an instrumental glitch: it appears only in one small area of the sky and on an angular scale close to the limit of the satellite's resolution.

And yet the inklings of non-Gaussianity won't go away. For several years, observers have been measuring the anisotropies at finer resolutions than COBE did, using balloon-borne and ground-based telescopes—most recently, the Mobile Anisotropy Telescope. Perplexingly, no two instruments seem to agree. Enrique Gaztañaga, Pablo Fosalba and Emilio Elizalde of the Institute of Space Studies of Catalonia in Barcelona conclude that either the experimental errors are twice their stated values—or the anisotropies are non-Gaussian. A skewed or widened bell curve would accentuate differences among regions of the sky and hence among the observations. Gaztañaga says that the discrepancies have, if anything, worsened with time.

Other studies have glimpsed non-Gaussianity in the distribution of galaxies and intergalactic gas clouds. Unfortunately, an inborn skew is hard to tease apart from the effect of gravity, which slowly makes matter less Gaussian. The technique least susceptible to this pitfall involves gargantuan galaxy clusters, as cited by James Robinson and his col-

BY THE NUMBERS

U.S. Immigration

From the founding of the republic to the mid-1920s, U.S. immigration was largely unrestricted, but shortly thereafter Congress passed legislation severely limiting entry from all regions except northwestern Europe. Beginning in 1965 and continuing thereafter, it passed a series of more liberal laws, including the Immigration and Reform Act of 1986, under which 2.7 million illegal aliens, mostly from Mexico, were given legal immigrant status. The new laws not only promoted diversity but also opened the door to the longest and largest wave of immigration ever—27 million since 1965, including illegal entries. Until now, the two largest waves had been from 1899 through 1914, which reached 13.6 million, and from 1880 through 1898, which reached 8.6 million. Not all immigrants stay: in recent years, emigration has been about 220,000 annually.

In 1996, a more or less typical year, there were 916,000 legal immigrants plus an estimated 275,000 who came illegally. Favorite immigrant destinations were California, where one third went, and the New York metropolitan area, which drew about one in six. As a group, immigrants are less skilled and younger than the average American. Of the legal immigrants, 65 percent entered under family reunification programs and 13 percent under employment-based preference programs; 14 percent were refugees or asylum seekers. From 1990 through 1998, an average of 460,000 immigrants a year became citizens.

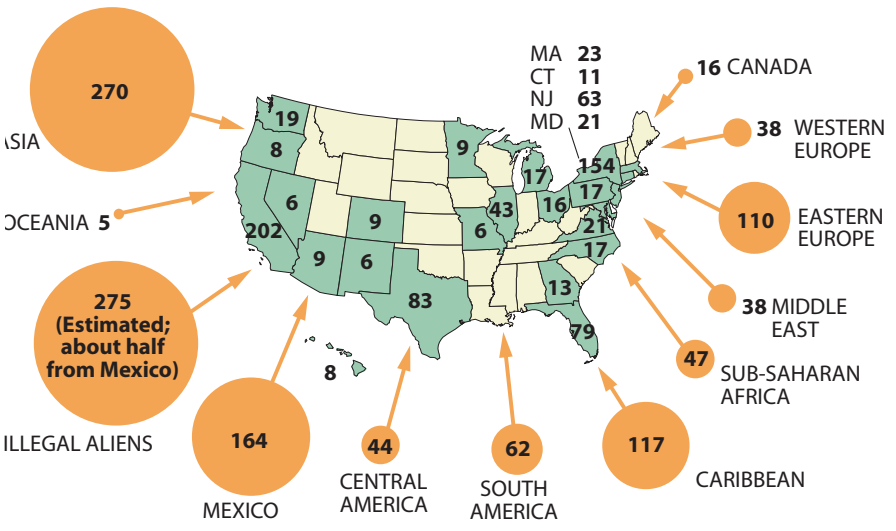
There is sharp disagreement over immigration policy. Some, like Virginia Abernethy of Vanderbilt University, say that high immigration threatens American labor and the environment; Roy Beck, Washington editor of *Social Contract,* says it contributes to "demographic Balkanization." But the late Julian Simon of the University of Maryland believed that immigration is beneficial, because an increase in population raises the number of creative minds and hence the pace of innovation. And then there are those who, like historian Arthur M. Schlesinger, Jr., feel that "any curtailment of immigration offends something in the American soul."

On at least two points virtually everyone agrees. The first is that the U.S. population will grow enormously, absent a drastic reduction in immigration. A big drop in immigration does not seem imminent in view of pressures from many ethnic groups, which generally support a heterogeneous society, and from employers who depend on low-wage labor. The U.S. Census Bureau's latest projection, which assumes a continuation of recent immigration and emigration levels over the next half a century, puts the U.S. population at 394 million in 2050. Of the 122 million increase between now and then, 80 million would be added because of immigration. The pros-

leagues at the University of California at Berkeley, by Jeffrey A. Willick of Stanford University and by Katsuji Koyama and his colleagues at Kyoto University.

Observations suggest that such clusters are as common now as they were when the universe was about half its present age. That means the universe must be less dense than cosmologists once thought; new clusters have been unable to form because matter has become too diluted. The three teams suspect that some non-Gaussianity is also needed, because a wider variation in the primordial density would have allowed massive clusters to develop earlier on. But skeptics argue that cluster mass estimates and theories of structure formation are not precise enough to know for sure.

As usual, cosmologists need more data. NASA's Microwave Anisotropy Probe, scheduled for launch late next year, should settle the matter. The new Chandra x-ray satellite may also help, by studying galaxy clusters. And what if the universe really is non-Gaussian? The leading alternative to inflation as of five years ago, in which astronomical structures were seeded by kinks in the fabric of space and time, predicted non-Gaussianity but also, alas, far too few clusters. Theorists have proposed various modifications to inflation—adding a second quantum field, say—yet they admit to a certain fatigue in always being asked to stretch the theory to account for uncertain observations. "I really think theorists should have backbone," says theorist Michael Turner of the University of Chicago. Until the claim of non-Gaussianity seems less random, cosmologists plan to stay resolute. —*George Musser*



SOURCE: U.S. Immigration and Naturalization Service. Numerals indicate number of immigrants in thousands. Map shows states with at least 5,000 legal immigrants in 1996. Circles show immigrants by country of birth.

RODGER DOYLE

pects beyond 2050 depend on a variety of factors, among them population growth in developing countries, incomes in developing countries relative to those in the U.S., the availability of alternative host countries and the cost of transportation to the U.S. Of these, only population can be predicted with even a moderate degree of confidence.

The second point of agreement is that the U.S. will become increasingly more diverse. In 1980 the U.S. was 80 percent Anglo—that is, non-Hispanic white. It is now 72 percent Anglo, and by 2050, according to Census Bureau projections, it will be 53 percent. California and New Mexico are now slightly less than half Anglo, and by 2015 Texas will also be a minority Anglo state. There is much apprehension that continued immigration of Mexican nationals will lead to dominance of the Spanish language in the Southwest. Such fears seem to be overblown, for several studies show that most second-generation Mexican-Americans speak fluent English.

—*Rodger Doyle (rdoyle2@aol.com)*

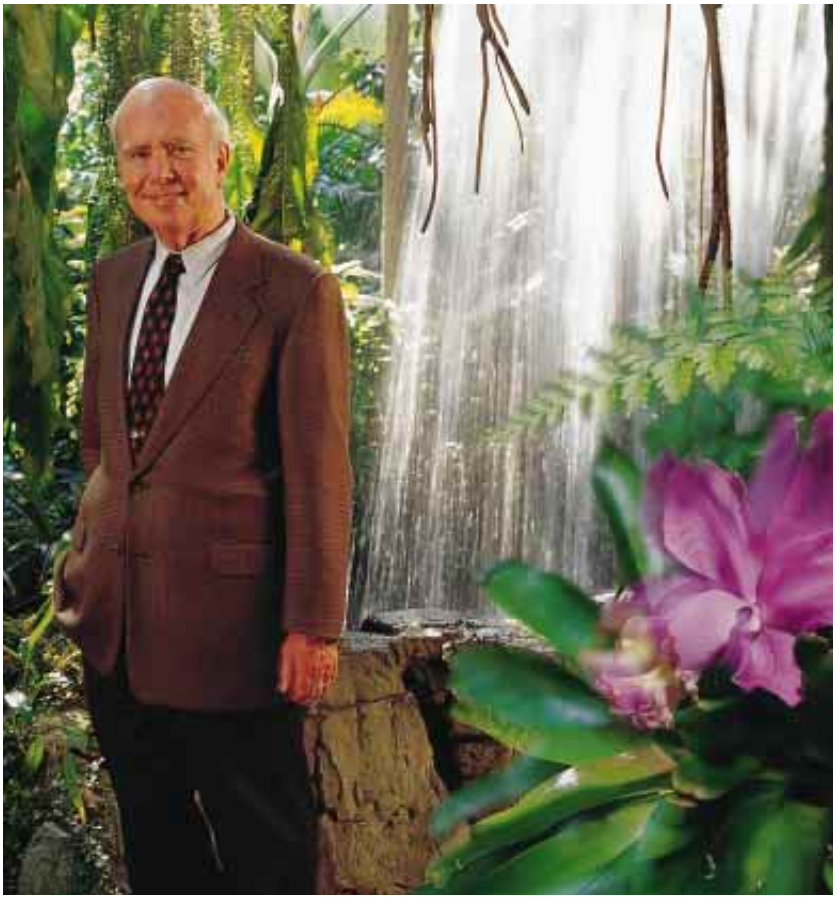
PROFILE

Defender of the Plant Kingdom

Botanist Peter H. Raven wants the world to save its plant species. All of them.

Peter H. Raven, a man used to looking at the big picture, has a big idea. The 63-year-old scientific diplomat and director of the Missouri Botanical Garden in St. Louis was set in August to call on the world's plant scientists, gathered at an international congress, to save the whole plant kingdom from extinction. Raven, for the past two decades a leading advocate for the preservation of biodiversity, predicts that without drastic action, two thirds of the world's 300,000 plant species will be lost during the next century as their habitats are destroyed. Yet he believes that an international commitment to bring vulnerable species into cultivation in botanical gardens, or into seed banks, could avert the catastrophe. "If you are going to give a single valuable present to the people 100 years from now, then saving all the plants might be a very good way of doing it," he says.

Such a grandiose scheme might sound like an idle fantasy. But Raven is a member of 22 academies of science around the globe and has an impressive history of organizing major projects. (His institution provides the headquarters for a network that is already trying to preserve U.S. plants.) He has just stepped down from a 12-year term as home secretary of the National Academy of Sciences, and he chairs the report review committee of the National Research Council, the operating arm of the academies of science, engineering and medicine. In that role he has overseen formal reviews of some 2,200 studies, many on controversial subjects. Raven is "a very good scientific politician and a good negotiator," says Bruce M. Alberts, president of the science academy.



JAMES VISSER *Gamma Liaison*

***GREEN WARRIOR:** Peter H. Raven's polite tenacity has persuaded many scientists and members of the public to work to preserve ecosystems.*

Raven also has a remarkable ability to raise money. In his 30 years as director of the Missouri Botanical Garden, he has transformed it from an academic backwater to one of the leading plant research centers in the world. The 79-acre garden today employs 62 Ph.D.-level botanists, many of them based in other countries, and in collaboration with overseas institutions runs collection programs in numerous regions of botanical interest. The institution has added several new buildings, and a variety of stunning new decorative gardens have made it a renowned tourist attraction.

Raven was for a time on a board that administered George Soros's philanthropy in the former Soviet Union, a position that helped him to raise $1.3 million to restore the decaying headquarters of the Komarov Institute in St. Petersburg, which houses the major botanical collections of the former Soviet Union. He also persuaded St. Louis–based agrochemical giant Monsanto to donate $3 million toward a new herbarium and research center for his own institution, a connection presumably not harmed by the fact that his wife, Katherine E. Fish, is Monsanto's director of public policy. Raven talked to SCIENTIFIC AMERICAN in his elegant office at the Missouri Botanical Garden shortly before the opening of the 16th International Botanical Congress in August. Unlike many scientists, he favors an impeccable business suit and tie. His manner is restrained, although he does not shrink from expressing firm opinions.

His interest in the natural world started early: Raven was eight years old when he joined the student section of the California Academy of Sciences. Within a few years he was collecting plants "fairly seriously." Biology was not offered at his high school in the early 1950s, so the academy provided a social structure and a learning opportunity. In 1950 he was asked to go on a Sierra Club Base Camp outing to the Sierra Nevada. He shared a ride with G. Ledyard Stebbins of the University of California at Davis—who is, according to Raven, the leading plant evolutionary biologist of the century—

and became a regular on the expeditions for the next six years.

After earning degrees at the University of California at Berkeley and at Los Angeles, he was recruited by Stanford University in 1962. He was soon making waves: he moved into an office next door to that of Paul R. Ehrlich, who was studying the diets of butterfly larvae. Together they coined the term "co-evolution" to describe the influence that mutually dependent species such as butterflies and plants can exert on each other. The word "crystallized the whole area in a special way," Raven recounts.

During the 1960s Raven's ideas about population, consumption, technology and the environment began to take shape as he came to realize that human stresses on the biosphere were "a whole new factor" in evolution. Raven first became aware of mass extinction in the tropics as an ongoing calamity in 1967, while working as a temporary field course instructor in Costa Rica.

He maintained that interest at the Missouri Botanical Garden from 1972 onward, wielding his academic influence to support research on tropical ecology and plants. Until the early 1980s he was active in plant classification and evolution, especially in connection with the family Onagraceae, which includes fireweed and the evening primrose. But since then he has been "almost exclusively" involved with promoting sustainability and conservation, systematizing knowledge about plants worldwide: he was among the organizers of the conference in Washington, D.C., in 1986 that put the term "biodiversity" into the scientific lexicon. He also devotes "a fair amount of time" to being co-chair of a joint project with the Science Press of Beijing to publish a 50-volume, English-language flora of China.

Raven makes no apologies for playing the dual roles of scientist and activist: he believes people should express their opinions "as broadly as possible." Facts trip off his tongue: world population has increased from 2.5 billion in 1950, when he first explored the Sierra Nevada, to six billion today, he notes, and the world has over that period lost 20 percent of its agricultural land and 25 percent of its topsoil; extinction rates are now about 1,000 times their historic levels and rising. About half the people in the world are malnourished, while the U.S. consumes resources at rates 30 to 40 times that of people in some parts of the world.

Raven points out the irony that although many pontificators project the 21st century to be the century of biology, the soundest predictions foresee a quarter of all species on the earth going extinct in the first 25 years of the new century. "We're acting in a way that is scientifically very irresponsible, and we need to speak out about that," he asserts. He takes issue with blind confidence that human ingenuity will solve the world's problems: unless human populations stabilize and achieve acceptable levels of consumption, he warns, "even the best science and technology can't save us." But he says large corporations can be influential in bringing about constructive change.

GAY BUMGARNER *Tony Stone Images*

CO-EVOLUTION
of mutually dependent species—such as this great spangled fritillary butterfly and coneflower—was an early interest of Raven's.

Raven is firmly in the camp that believes biotechnology can contribute to solving the world's problems by producing better crops. He has lobbied for the U.S. to ratify the 1992 Convention on Biodiversity, which was intended to protect endangered animals and plants, but is disturbed that it has become embroiled in a protracted examination of the safety of genetically modified organisms. The diversion, he says, has for the most part "nothing to do with biodiversity." He says he understands that many people are fearful about some possible products of biotechnology, such as so-called terminator seeds that could be planted only once, to protect the developers' intellectual property. But objectors are probably reflecting underlying concern about who will control agriculture in the next century, Raven suggests. Likewise, recent public anxiety about the effects of a common bioengineered pesticide, *Bt,* on monarch butterflies reflects a misunderstanding. Monarchs and many other insects are killed by the billions by conventional chemical sprays, he observes, so to suppose that *Bt* is a big new problem is "absurd"; nothing suggests that monarchs consume significant amounts in the wild. These worries, Raven believes, represent deeper apprehensions about nature.

Raven has been in a position to do something about fears about terminator seeds and what are termed TGURTs, seeds that have special properties that are activated by applying proprietary chemicals. He has encouraged the National Research Council to formulate a comprehensive study of intellectual property in relation to crops. One of his frequent opponents in biotechnology debates, Rebecca J. Goldburg of the Environmental Defense Fund, suggests that Raven's connections with Monsanto amount to a conflict of interest. But longtime friend Ehrlich counters that he has faith in Raven's integrity. "It's not where you get the money from," he states, "it's how you spend it."

Although Raven next year will vacate his role as chair of the National Research Council's report review committee, he continues to be a member of the President's Committee of Advisors on Science and Technology, where as chair he helped produce an influential report urging the administration to expand studies of ecosystems and create incentives to preserve them. And he recently became chair of the research and exploration committee of the National Geographic Society. The society "has been searching for ways to express itself in conservation and sustainability," he explains, a direction that puts it in line with his own professional passion of the past 20 years. The society gives away several million dollars each year in grants, publishes its magazine in six languages and operates a TV channel that broadcasts in 55 countries, so Raven will be well positioned to raise public awareness about global issues. He might even manage to save some of the 200,000 plants that could otherwise disappear.

—Tim Beardsley in St. Louis

DEFENSE TECHNOLOGY

IN PLANE SIGHT

Unmanned aerial vehicles prove their potential over Kosovo

While U.S. and allied fighters and bombers were being hailed for their performance during NATO's Operation Allied Force earlier this year, another, less celebrated type of aircraft was quietly providing a glimpse of the future of warfare. These remote-controlled, pilotless aircraft were used over Kosovo in greater numbers and for more hours than in previous conflicts, and although many were lost, their performance may have solidified their place in the U.S. military arsenal.

COURTESY OF JOINT TACTICAL UNMANNED AERIAL VEHICLES

HUNTER UAVs, which have a nine-meter (29-foot) wingspan and are seven meters long, provided remote surveillance over Kosovo.

As a concept, the use of "unmanned aerial vehicles" for intelligence gathering has made sense for a lot of years and a lot of reasons. UAVs, as the Pentagon calls them, are operated not unlike the hobbyist's remote-controlled airplanes; soldiers on the ground man computer stations with controls that fly the aircraft. Onboard "prying eyes"—cameras, radar, infrared and other sensors—pass intelligence information—target locations, troop movements, battle damage assessments—to the ground station.

UAVs offer many of the capabilities that fixed-wing aircraft can provide, but they are less expensive, they can fly for many more hours, and they don't put pilots at risk. Information superiority is the number-one goal of the modern military, and UAVs are rapidly becoming key pieces of the U.S. military puzzle. Allied Force commanders proved more willing than ever to deploy UAVs over even the most heavily defended spots, and they did not overly concern themselves with the loss of an aircraft or two.

Ultimately, as Allied Force showed, UAVs are expendable. During three months of operations over Kosovo, at least 15 U.S. unmanned aircraft were lost to Serbian attacks or accidents, and many more allied UAVs were also destroyed. Meanwhile only two manned aircraft, one an F-117A stealth bomber, were shot down. The downing of the F-117A was a major story and a huge embarrassment for the Pentagon, but losses of unmanned aircraft were hardly mentioned. That's the way it's supposed to be, says retired Maj. Gen. Kenneth R. Israel, a longtime UAV supporter and former director of the Defense Airborne Reconnaissance Office. Unmanned aircraft, he believes, provide "an opportunity to have information superiority without the consequences of having high casualty rates." In other words, he adds, "People don't mind losing UAVs."

Indeed, during a single day this past May three UAVs were shot down by Serbian forces over the same spot, and yet the little-publicized mission was considered a success. The target of the mission remains classified; military officials who requested anonymity said the UAVs were sent out to photograph evidence of "ethnic cleansing and grave sites," as one official put it. "The target was considered so important they sent them in knowing they might be lost," he said.

Despite the losses, Israel feels UAVs "acquitted themselves very well" over Kosovo. "I think the people who were very critical of UAVs should stand back and do a reassessment" of that opinion, he says of the Pentagon officials and policymakers opposed to the current UAV programs.

But the Pentagon's record for unmanned aircraft development is considered spotty at best. Cost overruns and technical problems have plagued some programs, and military leaders have not advanced the development of unmanned systems as quickly or as eagerly as supporters thought they should. Because of these and other factors, including a cultural bias toward high-tech, high-priced manned systems, U.S. forces in Europe had only a handful of simple UAVs at their disposal at the beginning of the air war.

They made the most of them. Army Hunter UAVs, Air Force Predators and Navy Pioneers logged thousands of hours over Kosovo to rave reviews. The Hunters were flying against considerable odds; the army canceled the program in 1996, preferring to wait for a more advanced system that has proved difficult to obtain. Accordingly, the few Hunters left over were pressed into service and proved themselves so reliable and useful that the army is looking for ways to upgrade and sustain its meager fleet.

The Predator, meanwhile, is both a success story and a major question mark. Considered the first successful product of a Pentagon rapid-development initiative [see "Smart Shopping," "Technology and Business," March 1996], the Predator program has had its share of delays and technical glitches and is not yet ready for full-blown production.

Nevertheless, supporters say, UAVs are on the rise. Faster, higher-flying UAVs, such as the air force's Global Hawk, are expected to bring wholly new capabilities to the U.S. military, and even more ambitious plans are on the drawing board. Future unmanned aircraft may be used as so-called surrogate satellites, dispatched during crises to fly in the upper reaches of the earth's atmosphere for days at a time. And UAVs one day could be "weaponized," allowing them to launch missiles and drop bombs for less money and less risk than manned aircraft.

The Pentagon, of couse, isn't likely to give up its costly manned aircraft programs anytime soon to pursue a fleet of pilotless planes. Supporters do think, however, that unmanned systems of all kinds—aircraft, ground vehicles and even submarines—may best serve the interests of a U.S. tax paying public that overwhelmingly supports two elusive ideals: a more cost-efficient Pentagon and virtually casualty-free warfare.

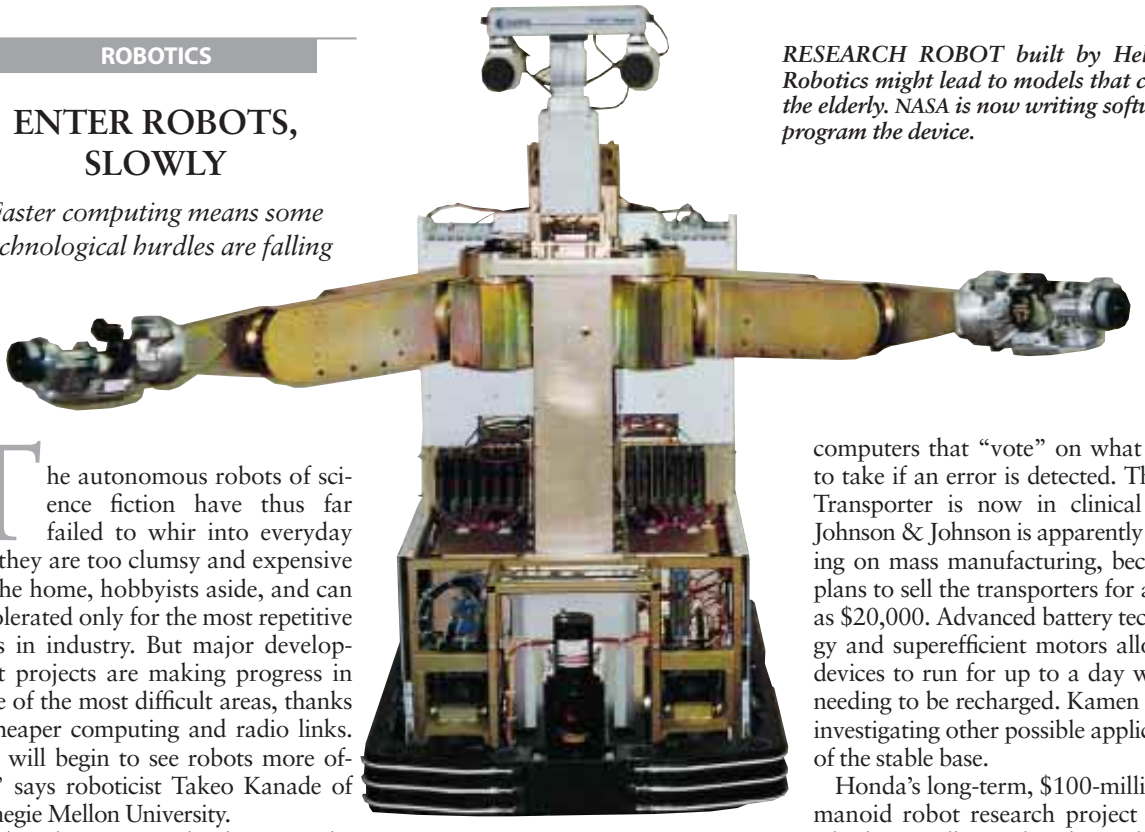
—Daniel G. Dupont

DANIEL G. DUPONT is the editor of Inside the Pentagon *in Washington, D.C. He wrote about Pentagon antisatellite weapons in the June issue.*

ROBOTICS

ENTER ROBOTS, SLOWLY

Faster computing means some technological hurdles are falling



RESEARCH ROBOT built by HelpMate Robotics might lead to models that care for the elderly. NASA is now writing software to program the device.

COURTESY OF HELPMATE ROBOTICS

The autonomous robots of science fiction have thus far failed to whir into everyday life: they are too clumsy and expensive for the home, hobbyists aside, and can be tolerated only for the most repetitive tasks in industry. But major development projects are making progress in some of the most difficult areas, thanks to cheaper computing and radio links. "We will begin to see robots more often," says roboticist Takeo Kanade of Carnegie Mellon University.

Although "smart" technology can take numerous forms, almost all mobile robots to date use wheels, a choice that has confined them to a single floor of a building. But Johnson & Johnson, in partnership with inventor Dean Kamen, has recently announced a gyro-balanced wheelchair that can rear up on two wheels, traverse uneven terrain and climb stairs, while keeping its occupant perfectly stable. Kamen says the biggest challenge in the five-year project was ensuring the safety of a user even during a collision or a component failure: the system employs three Pentium-class computers that "vote" on what action to take if an error is detected. The Ibot Transporter is now in clinical trials. Johnson & Johnson is apparently counting on mass manufacturing, because it plans to sell the transporters for as little as $20,000. Advanced battery technology and superefficient motors allow the devices to run for up to a day without needing to be recharged. Kamen is now investigating other possible applications of the stable base.

Honda's long-term, $100-million humanoid robot research project rejects wheels: its walking robots have a humanlike gait and can turn in place and climb stairs. Yuji Haikawa, a senior engineer on the project, says the current focus is on integrating a vision system into the machines; no practical applications have yet been selected. The current version, the P3, has only about 25 minutes of battery life and does little except walk; moreover, the design employs far too many motors to be reliable, according to roboticist Hans Moravec of Carnegie Mellon. But Moravec says Honda's investment may pay off, because the company will have acquired unique expertise in high-performance mechanical and control systems that could become profit centers as the cost of computing decreases.

Moravec believes that gains in computing power in the next three years will make it possible for computers to maintain detailed, possibly three-dimensional maps of their surroundings and so achieve acceptable reliability while behaving more flexibly than today's devices do. (His definition of acceptable reliability is six months between navigational disasters.) Moravec is planning to build a basketball-size device, equipped

ED QUINN *SABA*

IBOT TRANSPORTER from Johnson & Johnson transports inventor Dean Kamen down a flight of stairs in a demonstration.

with 24 attached cameras, that can plug into and control forklift trucks and similar vehicles used in factories.

Simpler wheeled robots made by HelpMate Robotics in Danbury, Conn., do trundle around the corridors of some hospitals, carrying drugs or documents and even operating elevators. They use sensors to avoid obstacles and navigate by means of beacons and an internal map. Other robots serve as security guards in commercial buildings, detecting disturbances and alerting humans when necessary. But these machines, based on 1980s-era computing technology, need to be installed by specialists and must follow fixed routes: sales have been slow. HelpMate has recently built a more capable research robot that has arms, voice recognition and stereo vision. The device is being evaluated by the National Aeronautics and Space Administration, which is writing software for it. Joseph F. Engelberger, HelpMate's president and chairman, says the company aims to raise capital to develop a version to serve as a companion and helper for the elderly.

Mobot in Pittsburgh already has a couple of machines that employ fast Pentium processors and serve as greeters and guides for visitors to the city's Carnegie Museum of Natural History. These machines lack functional arms but employ primarily vision-based navigation, rather than an electronic map, to find their way around. According to Mobot's David White, that makes them less expensive and easier to install than HelpMate-style machines, although a company expert is still needed for a day, and at $90,000 the machines are beyond consumer budgets. They will track people's faces by the end of the year and will converse within two years, White promises.

Those impatient to be the first on their block with a useful domestic robot might consider a lawn mower from Friendly Machines in Even Yehuda, Israel, which can mow a lawn in parallel stripes, avoiding obstacles, and uses a buried wire to detect the edges. And Gecko Systems in Round Rock, Tex., is allowing technically savvy users to try out its experimental robot vacuum cleaner. The $2,500 device is controlled by wireless link from a program running on a PC and uses an advanced algorithm to maneuver around objects, according to Gecko's Martin Spencer. Robbie the Robot it isn't, but it's a start.

—*Tim Beardsley in Washington, D.C.*

HORTICULTURE

NOT MAKING SCENTS

Thanks to commercial hybridization, flowers seem to be losing their fragrance

That which we call a rose by any other name would smell as sweet—in Shakespeare's time, that may well have been the case. The rose in its natural state was prized for the fragrant aroma that emanated from its blossoms, but today's modern versions would hardly tickle any Elizabethan's nose. For reasons that are still not clearly understood, floral scent is the number-one casualty of crossbreeding, and many other new varieties of once famously fragrant blossoms have, like the rose, lost their aroma.

Horticulturists introduce about 1,000 new hybrid plants every year, and hybrids now account for about 70 percent of the shrubs currently on the market (and the number is higher for flowers). The goal is to produce flowers with larger and more numerous blossoms, brighter and increased variation of color, resistance to disease, and a long shelf life. Although the loss of floral scent has been recognized for years as a major problem in floriculture, it has been accepted as an inevitable trade-off for improved market value.

If genetic engineering can remove floral scent, then it stands to reason that a similar process may be able to bring it back. Although research has been conducted to analyze the composition of floral scents, very little is known about the genes that produce them. Natalia Dudareva of the department of horticulture and landscape architecture at Purdue University is one of the few scientists studying this aspect of plant biology. The facility at Purdue, which Dudareva set up in 1997, and one at the University of Michigan are the only two laboratories in the world devoted to the study of floral scent at the biomolecular level.

Initially, Dudareva and her colleagues began their work not as a quest to determine why floral fragrance was vanishing but as a mission to learn about it on the molecular level. "We wanted to find out what can affect [scent], what is missing in nonscented flowers, and if it's possible to isolate the genes that

produce volatile compounds," she says.

When volatile compounds combine in varying proportions, they produce a unique smell that is distinct to all plants of the same type. In wild plants, these chemicals attract pollinators and repel and kill pests; they can also serve as an alarm to other plants when an individual is threatened by viral attack or other danger. But for commercially grown flowers, the consequences of scent loss have been less dramatic, because they have largely been removed from the wild.

Restoring the aroma to commercial blossoms won't be easy. About 700 different volatile compounds have been characterized from floral scent, but research is still in its formative stages. "We don't know how [the compounds] synthesized," Dudareva concedes. "Or if we know how they're synthesized, we don't know how they're regulated and what we have to do to put the scent back." Replacing scent is a complex undertaking: knowing how plants produce volatile compounds and what genes govern redolence is just one step in the process. It goes beyond a single reaction or a single gene put back into place, Dudareva explains; scent-making involves entire biochemical pathways.

DEBORAH DAVIS *Photonica*

COMMERCIAL BLOSSOMS, which are bred mostly for size, color, resistance to disease, and long shelf life, seem to be losing their redolence as a result.

In response to the growing concern about disappearing fragrances, the first conference on floral scent will be held this month in Oxford, England. It may be a while before researchers can restore the sweet smell of a rose without compromising its other commercially important features. But it seems only natural to demand that a blossom have scent. "Certainly when I go to nurseries and see how people choose flowers," Dudareva says, "they still go and put their nose in, even though the flower has no smell. I think this is automatic—we want to smell flowers." *—Roxanne Nelson*

ROXANNE NELSON is a freelance writer based in Seattle.

CYBER VIEW

When Publishing Could Mean Perishing

Not many like to think about a chemical disaster like the one in 1984 in Bhopal, India, in which 2,000 people were killed and another 200,000 injured after the accidental leakage of 40 tons of methyl isocyanate from a Union Carbide factory. Even fewer in the U.S. want to think about a similar tragedy happening here. But in 1990 Congress decided the threat was real enough to require an estimated 66,000 industrial sites working with extremely hazardous substances to disclose worst-case accident scenarios. It was all part of risk-management plans that are supposed to cover everything from potential hazards to emergency responses. The intention—reaffirmed as recently as 1997, when the Environmental Protection Agency (EPA) reported similar plans—was to make a searchable database of these risk-management plans available over the Internet.

Some people, however, are concerned that allowing full access to the data to anyone who wanted them, anywhere in the world, might make it easier for would-be terrorists to attack those facilities. Early this year the Center for Democracy and Technology, along with other advocacy groups, raised the alarm after hearing that proposals to limit access to this information were being considered by the House Commerce Committee. In a publicly released letter to the committee's chairman, Representative Thomas J. Bliley of Virginia, the CDT's executive director, Jerry Berman, argued forcefully that the Freedom of Information Act mandates that the information must be supplied in the format requested if it is easily reproducible in that form. Therefore, because the worst-case scenario data will be submitted in electronic form, it must be made available electronically. But on May 13, Bliley introduced House bill HR 1790, the Chemical Safety Information and Site Security Act of 1999. In summary, it says the data would be given mostly on paper to local government officials and to the public under controlled reading conditions, such as in a reference library.

In one sense, there is nothing new about a conflict between the right to know and the reluctance to publish. Proponents of publication point out that the information is likely to be readily available whether or not the database appears on the Internet, because many local newspapers have made it their business to learn about hazards surrounding chemical plants. Moreover, terrorism is rare; ordinary industrial accidents are far more likely to happen, as ranking Commerce Committee Democrat John D. Dingell of Michigan pointed out in a statement this past February. According to the EPA's own 1997 report, between 1987 and 1996 there were more than 600,000 accidental releases of toxic chemicals in the U.S. that together killed 2,565 people and caused 22,949 injuries. Having information about chemical plants, therefore, could help communities protect themselves better, as could knowing what kinds of accidents have happened around other, similar plants.


DAVID SUTER

At a panel at this year's Computers, Freedom, and Privacy conference, however, representatives of the EPA, the House Commerce Committee, the Chemical Manufacturers Association, the National Security Council and e-Consulting Services in Washington, D.C., vehemently backed the idea of restrictions. They took the position adopted by the Federal Bureau of Investigation and argued that putting the information on the Internet is a security risk and that it is not uncommon for rules to specify how public information may be released and used. Jody R. Westby, e-Consulting's president, claimed that computer systems in these chemical plants are vulnerable. Hack in through the computers from a safe distance, and it might be possible to blow up the community. But Rick Blum, OMB Watch's representative to the panel (which also included Freedom of Information advocates from Wired News and Community Right-to-Know), countered: "Even if putting this information out were to double the risk of terrorism, the risk is near zero. And the last time I checked, two times zero is still zero."

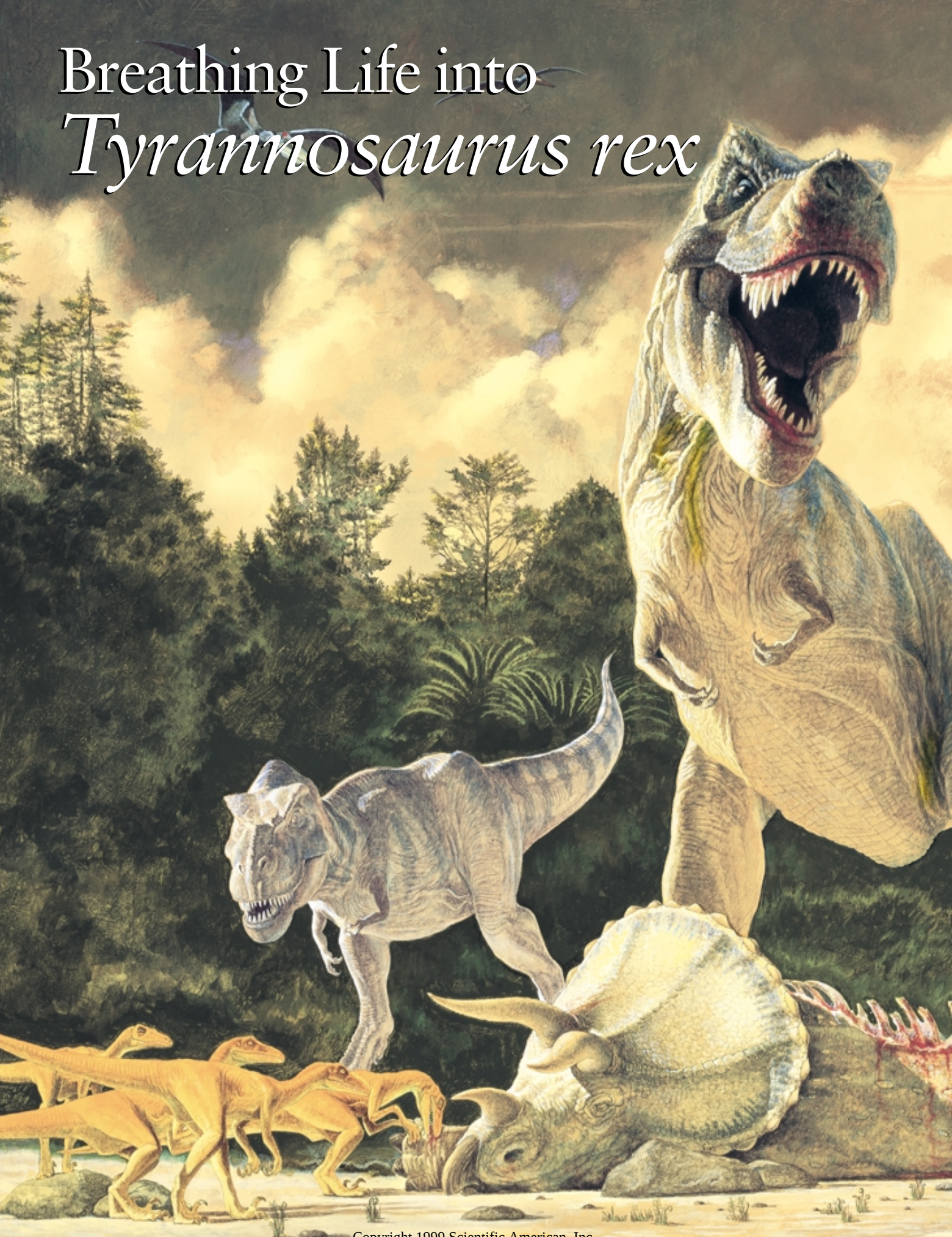
More to the point, perhaps, is the psychology of the Net, so to speak. Activist John Gilmore's oft-quoted remark that "the Net perceives censorship as damage and routes around it" still applies: suppress information in one place, and it will pop up in another. While the government debates what to do with the chemical database information—which finished trickling in from chemical facilities on June 21—private citizens have begun taking action. Community Right-to-Know, in the person of activist Paul Orum, has been quietly compiling and making available via the World Wide Web information about chemical plants collected from public sources. The site analyzes the areas around 10 Du Pont chemical plants, claiming that over seven million people in surrounding areas may be vulnerable to worst-case accidents. It argues that the chemical industry should not be lobbying Congress to help keep its activities secret but should seek to reduce the hazards it poses to nearby communities.

It's hard to argue with that point of view, just as it seems obvious that information in the public domain should be made freely available to the public. Or, as Berman put it in his letter to Bliley, "Any proposal to limit the forms or formats in which [worst-case scenario] information would be available to the public would set a terrible precedent."

The issue of public versus limited availability is going to come up time and again as we try to get used to the Internet and its capacity to make anything posted on it instantly accessible worldwide. The notion that the information can be controlled by gatekeepers if it is available solely on paper or has to be read in a library is dubious at best, at least in this particular case. As soon as you start to argue along those lines, you realize you're arguing that the Internet makes no difference—and that we know is not true. —*Wendy M. Grossman*

WENDY M. GROSSMAN, a freelance writer based in London, described on-line learning in the July issue.

Breathing Life into *Tyrannosaurus rex*



By analyzing previously overlooked fossils and by taking a second look at some old finds, paleontologists are providing the first glimpses of the actual behavior of the tyrannosaurs

by Gregory M. Erickson

Dinosaurs ceased to walk the earth 65 million years ago, yet they still live among us. Velociraptors star in movies, and *Triceratops* clutter toddlers' bedrooms. Of these charismatic animals, however, one species has always ruled our fantasies. Children, Steven Spielberg and professional paleontologists agree that the superstar of the dinosaurs was and is *Tyrannosaurus rex*.

Harvard University paleontologist Stephen Jay Gould has said that every species designation represents a theory about that animal. The very name *Tyrannosaurus rex*—"tyrant lizard king"—evokes a powerful image of this species. John R. Horner of Montana State University and science writer Don Lessem wrote in their book *The Complete* T. Rex, "We're lucky to have the opportunity to know *T. rex,* study it, imagine it, and let it scare us. Most of all, we're lucky *T. rex* is dead." And paleontologist Robert T. Bakker of the Glenrock Paleontological Museum in Wyoming described *T. rex* as a "10,000-pound [4,500-kilogram] roadrunner from hell," a tribute to its obvious size and power.

In Spielberg's *Jurassic Park,* which boasted the most accurate popular depiction of dinosaurs ever, *T. rex* was, as usual, presented as a killing machine whose sole purpose was aggressive, bloodthirsty attacks on helpless prey. *T. rex*'s popular persona, however, is as much a function of artistic license as of concrete scientific evidence. A century of study

KAZUHIKO SANO

***TYRANNOSAURUS REX* defends its meal, a *Triceratops,* from other hungry *T. rex*. Troodontids, the small velociraptors at the bottom left, wait for scraps left by the tyrannosaurs, while pterosaurs circle overhead on this typical day some 65 million years ago. Trees and flowering plants complete the landscape; grasses have yet to evolve.**

and the existence of 22 fairly complete *T. rex* specimens have generated substantial information about its anatomy. But inferring behavior from anatomy alone is perilous, and the true nature of *T. rex* continues to be largely shrouded in mystery. Whether it was even primarily a predator or a scavenger is still the subject of debate.

Over the past decade, a new breed of scientists has begun to unravel some of *T. rex*'s better-kept secrets. These paleobiologists try to put a creature's remains in a living context—they attempt to animate the silent and still skeleton of the museum display. *T. rex* is thus changing before our eyes as paleobiologists use fossil clues, some new and some previously overlooked, to develop fresh ideas about the nature of these magnificent animals.

Rather than draw conclusions about behavior solely based on anatomy, paleobiologists demand proof of actual activities. Skeletal assemblages of multiple individuals shine a light on the interactions among *T. rex* and between them and other species. In addition, so-called trace fossils reveal activities through physical evidence, such as bite marks in bones and wear patterns in teeth. Also of great value as trace fossils are coprolites, fossilized feces. (Remains of a herbivore, such as *Triceratops* or *Edmontosaurus,* in *T. rex* coprolites certainly provide "smoking gun" proof of species interactions!)

One assumption that paleobiologists are willing to make is that closely related species may have behaved in similar ways. *T. rex* data are therefore being corroborated by comparisons with those of earlier members of the family Tyrannosauridae, including their cousins *Albertosaurus*, *Gorgosaurus* and *Daspletosaurus,* collectively known as albertosaurs.

Solo or Social?

Tyrannosaurs are usually depicted as solitary, as was certainly the case in *Jurassic Park*. (An alternative excuse for that film's loner is that the movie's genetic wizards wisely created only one.) Mounting evidence, however, points to gregarious *T. rex* behavior, at least for part of the animals' lives. Two *T. rex* excavations in the Hell Creek Formation of eastern Montana are most compelling.

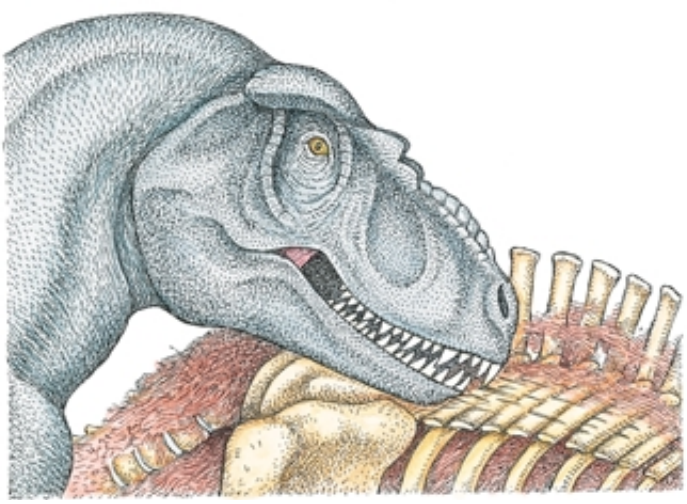
In 1966 Los Angeles County Museum researchers attempting to exhume a Hell Creek adult were elated to find another, smaller individual resting atop the *T. rex* they had originally sought. This second fossil was identified at first as a more petite species of tyrannosaur. My examination of the histological evidence—the microstructure of the bones—now suggests that the second animal was actually a subadult *T. rex*. [*see illustration on page 48*]. A similar discovery was made during the excavation of "Sue," the largest and most complete fossil *T. rex* ever found. Sue is perhaps as famous for her $8.36-million auction price following ownership haggling as for her paleontological status [see "No Bones about It," News and Analysis, Scientific American, December 1997]. Remains of a second adult, a juvenile and an infant *T. rex* were later found in Sue's quarry. Researchers who have worked the Hell Creek Formation, myself included, generally agree that long odds argue against multiple, loner *T. rex* finding their way to the same burial. The more parsimonious explanation is that the animals were part of a group.

An even more spectacular find from 1910 further suggests gregarious behavior among the Tyrannosauridae. Researchers from the American Museum of Natural History in New York City working in Alberta, Canada, found a bone bed—a deposit with fossils of many individuals—holding at least nine of *T. rex*'s close relatives, albertosaurs.

Philip J. Currie and his team from the Royal Tyrrell Museum of Paleontology in Alberta recently relocated the 1910 find and are conducting the first detailed study of the assemblage. Such aggregations of carnivorous animals can occur when one after another gets caught in a trap, such as a mud hole or soft sediment at a river's edge, in which a prey animal that has attracted them is already ensnared. Under those circumstances, however, the collection of fossils should also contain those of the hunted herbivore. The lack of such herbivore remains among the albertosaurs (and among the four–*T. rex* assemblage that included Sue) indicates that the herd most likely associated with one another naturally and perished together from drought, disease or drowning.

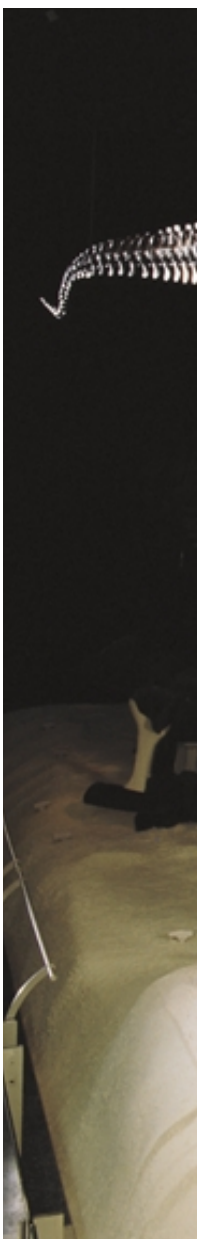
From examination of the remains collected so far, Currie estimates that the animals ranged from four to almost nine meters (13 to 29 feet) in length. This variation in size hints at a group composed of juveniles and adults. One individual is considerably larger and more robust than the others. Although it might have been a different species of albertosaur, a mixed bunch seems unlikely. I believe that if *T. rex* relatives did indeed have a social structure, this largest individual may have been the patriarch or matriarch of the herd.

Tyrannosaurs in herds, with complex interrelationships, are in many ways an entirely new species to contemplate. But science has not morphed them into a benign and tender collection of Cretaceous Care Bears:



PATRICIA C. WYNNE

NIPPING STRATEGY (*above*) enabled *T. rex* to remove strips of flesh in tight spots, such as between vertebrae, using only the front teeth.



some of the very testimony for *T. rex* group interaction is partially healed bite marks that reveal nasty interpersonal skills. A paper just published by Currie and Darren Tanke, also at the Royal Tyrrell Museum, highlights this evidence. Tanke is a leading authority on paleopathology—the study of ancient injuries and disease. He has detected a unique pattern of bite marks among theropods, the group of carnivorous dinosaurs that encompasses *T. rex* and other tyrannosaurs. These bite marks consist of gouges and punctures on the sides of the snout, on the sides and bottom of the jaws, and occasionally on the top and back of the skull.

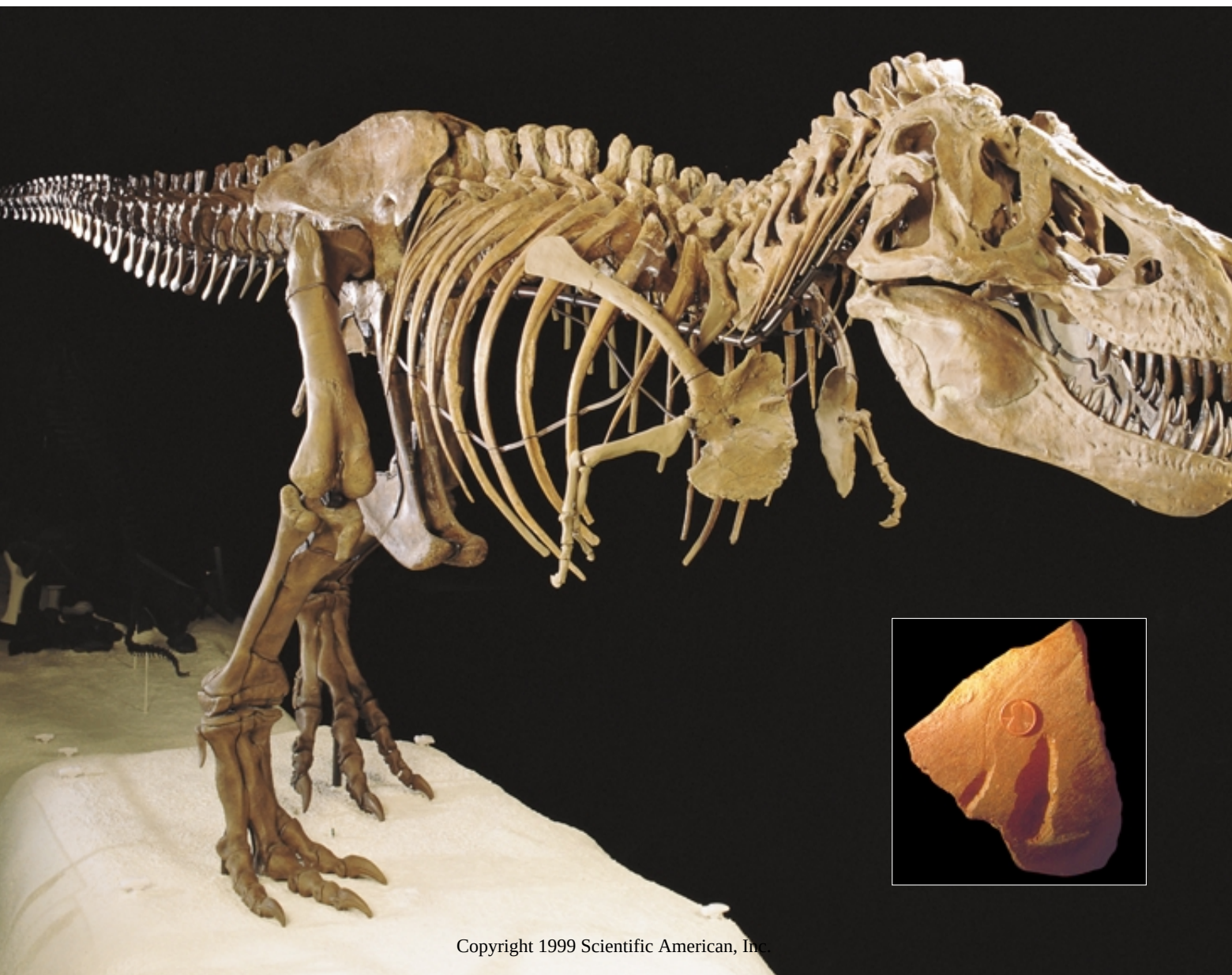
Interpreting these wounds, Tanke and Currie reconstructed how these dinosaurs fought. They believe that the animals faced off but primarily gnawed at one another with one side of their complement of massive teeth rather than snapping from the front. The workers also surmise that the jaw-gripping behavior accounts for peculiar bite marks found on the sides of tyrannosaur teeth. The bite patterns imply that the combatants maintained their heads at the same level throughout a confrontation. Based on the magnitude of some of the fossil wounds, *T. rex* clearly showed little reserve and sometimes inflicted severe damage to its conspecific foe. One tyrannosaur studied by Tanke and Currie sports a souvenir tooth, embedded in its own jaw, perhaps left by a fellow combatant.

The usual subjects—food, mates and territory—may have prompted the vigorous disagreements among tyrannosaurs. Whatever the motivation behind the fighting, the fossil record demonstrates that the behavior was repeated throughout a tyrannosaur's life. Injuries among younger individuals seem to have been more common, possibly because a juvenile was subject to attack by members of his own age group as well as by large adults. (Nevertheless, the fossil record may also be slightly misleading and simply contain more evidence of injuries in young *T. rex*. Nonlethal injuries to adults would have eventually healed, destroying the evidence. Juveniles were more likely to die from adult-inflicted injuries, and they carried those wounds to the grave.)

Bites and Bits

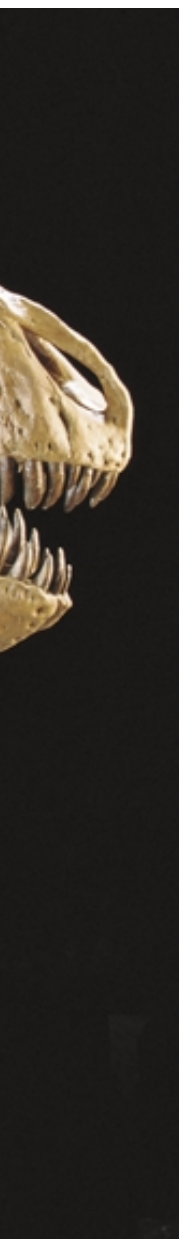
Imagine the large canine teeth of a baboon or lion. Now imagine a mouthful of much larger canine-type teeth, the size of railroad spikes and with serrated edges. Kevin Padian of the University of California at Berkeley has summed up the appearance of the huge daggers that were *T. rex* teeth: "lethal bananas."

LOUIS PSIHOYOS *Matrix*; GREGORY M. ERICKSON (*inset*)



Despite the obvious potential of such weapons, the general opinion among paleontologists had been that dinosaur bite marks were rare. The few published reports before 1990 consisted of brief comments buried in articles describing more sweeping new finds, and the clues in the marred remains concerning behavior escaped contemplation.

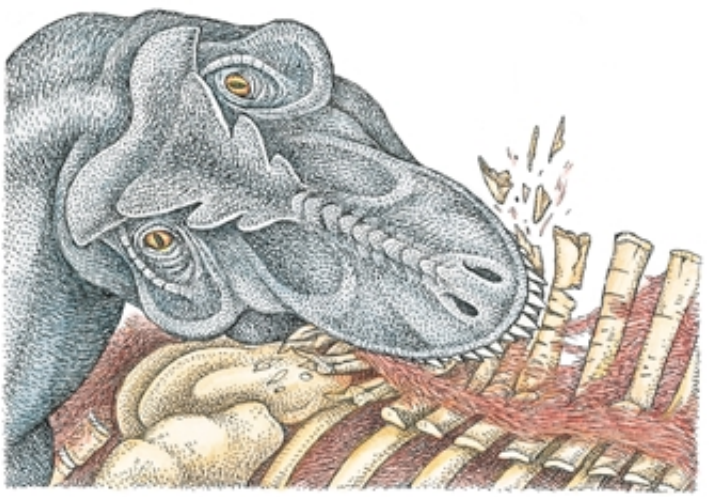
Nevertheless, some researchers speculated about the teeth. As early as 1973, Ralph E. Molnar of the Queensland Museum in Australia began musing about the strength of the teeth, based on their shape. Later, James O. Farlow of Indiana University–Purdue University Fort Wayne and Daniel L. Brinkman of Yale University performed elaborate morphological studies of tyrannosaur dentition, which made them confident that the "lethal bananas" were robust, thanks to their rounded cross-sectional configuration, and would endure bone-shattering impacts during feeding.



In 1992 I was able to provide material support for such speculation. Kenneth H. Olson, a Lutheran pastor and superb amateur fossil collector for the Museum of the Rockies in Bozeman, Mont., came to me with several specimens. One was a one-meter-wide, 1.5-meter-long partial pelvis from an adult *Triceratops*. The other was a toe bone from an adult *Edmontosaurus* (duck-billed dinosaur). I examined Olson's specimens and found that both bones were riddled with gouges and punctures up to 12 centimeters long and several centimeters deep. The *Triceratops* pelvis had nearly 80 such indentations. I documented the size and shape of the marks and used orthodontic dental putty to make casts of some of the deeper holes. The teeth that had made the holes were spaced some 10 centimeters apart. They left punctures with eye-shaped cross sections. They clearly included carinas, elevated cutting edges, on their anterior and posterior faces. And those edges were serrated. The totality of the evidence pointed to these indentations being the first definitive bite marks from a *T. rex*.

This finding had considerable behavioral implications. It confirmed for the first time the assumption that *T. rex* fed on its two most common contemporaries, *Triceratops* and *Edmontosaurus*. Furthermore, the bite patterns opened a window into *T. rex*'s actual feeding techniques, which apparently involved two distinct biting behaviors. *T. rex* usually used the "puncture and pull" strategy, in which biting deeply with enormous force was followed by drawing the teeth through the penetrated flesh and bone, which typically produced long gashes. In this way, a *T. rex* appears to have detached the pelvis found by Olson from the rest of the *Triceratops* torso. *T. rex* also employed a nipping approach in which the front (incisiform) teeth grasped and stripped the flesh in tight spots between vertebrae, where only the muzzle of the beast could fit. This method left vertically aligned, parallel furrows in the bone.

Many of the bites on the *Triceratops* pelvis were spaced only a few centimeters apart, as if the *T. rex* had methodically worked his way across the hunk of meat as we would nibble an ear of corn. With each bite, *T. rex* appears also to have removed a small section of bone. We presumed that the missing bone had been consumed, confirmation for which shortly came, and from an unusual source.



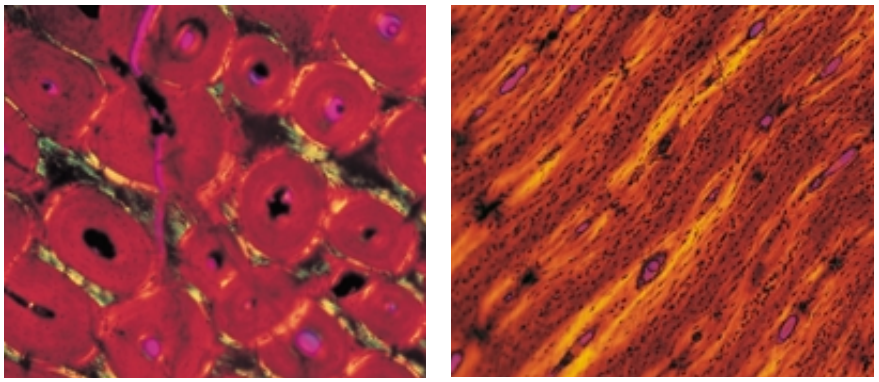
PATRICIA C. WYNNE

MASSIVE FORCE generated by *T. rex* in the "puncture and pull" biting technique (*above*) was sufficient to have created the huge furrows on the surface of the section of a fossil *Triceratops* pelvis shown in the inset at the left. The enormous body of the *T. rex* (*skeleton at left*) and its powerful neck musculature enabled the "pull" in "puncture and pull."

In 1997 Karen Chin of the U.S. Geological Survey received a peculiar, tapered mass that had been unearthed by a crew from the Royal Saskatchewan Museum. The object, which weighed 7.1 kilograms and measured 44 by 16 by 13 centimeters, proved to be a *T. rex* coprolite [*see illustration on page 48*]. The specimen, the first ever confirmed from a theropod and more than twice as large as any previously reported meat-eater's coprolite, was chock-full of pulverized bone. Once again making use of histological methods, Chin and I determined that the shattered bone came from a young herbivorous dinosaur. *T. rex* did indeed ingest parts of the bones of its food sources and, furthermore, partially digested these items with strong enzymes or stomach acids.

Following the lead of Farlow and Molnar, Olson and I have argued vehemently that *T. rex* probably left multitudinous bite marks, despite the paucity of known specimens. Absence of evidence is not evidence of absence, and we believe two factors account for this toothy gap in the fossil record. First, researchers have never systematically searched for bite marks. Even more important, collectors have had a natural bias against finds that might display bite marks. Historically, museums desire complete skeletons rather than single, isolated parts. But whole skeletons tend to be the remains of animals that died from causes other than predation and were rapidly buried before being dismembered by scavengers. The shredded bits of bodies eschewed by museums, such as the *Triceratops* pelvis, are precisely those specimens most likely to carry the evidence of feeding.

Indeed, Aase Roland Jacobsen of the Royal Tyrrell Museum recently surveyed isolated partial skeletal remains and compared them with nearly complete skeletons in Alberta. She found that 3.5 times as many of the individual bones (14 percent) bore theropod bite marks as did the less disrupted remains (4 percent). Paleobiologists therefore view the majority of the world's natural history museums as deserts



GREGORY M. ERICKSON

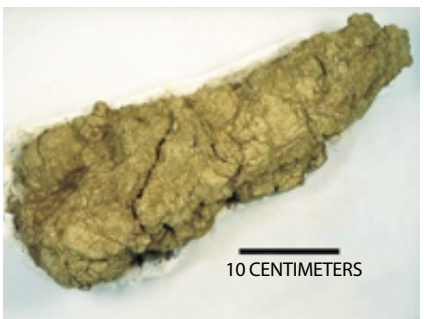
BONE MICROSTRUCTURE reveals the maturity of the animal under study. Older individuals have bone consisting of Haversian canals (*large circles, left*), bone tubules that have replaced naturally occurring microfractures in the more randomly oriented bone of juveniles (*right*). Microscopic examination of bone has shown that individuals thought to be members of smaller species are in fact juvenile *T. rex*.

of behavioral evidence when compared with fossils still lying in the field waiting to be discovered and interpreted.

Hawk or Vulture?

Some features of tyrannosaur biology, such as coloration, vocalizations or mating displays, may remain mysteries. But their feeding behavior is accessible through the fossil record. The collection of more trace fossils may finally settle a great debate in paleontology—the 80-year controversy over whether *T. rex* was a predator or a scavenger.

When *T. rex* was first found a century ago, scientists immediately labeled it a predator. But sharp claws and powerful jaws do not necessarily a predator make. For example, most bears are omnivorous and kill only a small proportion of their food. In 1917 Canadian paleontologist Lawrence Lambe examined a partial albertosaur skull and ascertained that tyrannosaurs fed on soft, rotting carrion. He came to this conclusion after noticing that the teeth were relatively free of wear. (Future research would show that 40 percent of shed tyrannosaur teeth are severely worn and broken, damage that occurs in a mere two to three years, based on my estimates of their rates of tooth replacement.) Lambe thus established the minority view that the beasts were in fact giant terrestrial "vultures." The ensuing arguments in the predator-versus-scavenger dispute have centered on the anatomy and physical capabilities of *T. rex*, leading to a tiresome game of point-counterpoint.



KAREN CHIN

KING-SIZE COPROLITE, 44 centimeters long, is the largest of its kind from a carnivorous animal, more than twice the size of any previously reported. Its size, age, contents and geographic context rule out anything other than a tyrannosaur, and most likely a *T. rex*, as its producer.

Scavenger advocates adopted the "weak tooth theory," which maintained that *T. rex*'s elongate teeth would have failed in predatory struggles or in bone impacts. They also contended that its diminutive arms precluded lethal attacks and that *T. rex* would have been too slow to run down prey.

Predator supporters answered with biomechanical data. They cited my own bite-force studies that demonstrate that *T. rex* teeth were actually quite robust. (I personally will remain uncommitted in this argument until the discovery of direct physical proof.) They also note that Kenneth Carpenter of the Denver Museum of Natural History and Matthew Smith, then at the Museum of the Rockies, estimate that the "puny" arms of a *T. rex* could curl nearly 180 kilograms. And they point to the work of Per Christiansen of the University of Copenhagen, who believes, based on limb proportion, that *T. rex* may have been able to sprint at 47 kilometers per hour. Such speed would be faster than that of any of *T. rex*'s contemporaries, although endurance and agility, which are difficult to quantify, are equally important in such considerations. (For one prominent paleontologist's impressions of *T. rex*'s predatory abilities, see "The Dechronization of Sam Magruder," by George Gaylord Simpson, on page 52].

Even these biomechanical studies fail to resolve the predator-scavenger debate—and they never will. The critical determinant of *T. rex*'s ecological niche is discovering how and to what degree it utilized the animals living and dying in its environment, rather than establishing its presumed adeptness for killing. Both sides concede that predaceous animals, such as lions and spotted hyenas, will scavenge and that classic scavengers, such as vultures, will sometimes kill. And mounting physical evidence leads to the conclusion that tyrannosaurs both hunted and scavenged.

Within *T. rex*'s former range exist bone beds consisting of hundreds and sometimes thousands of edmontosaurs that died from floods, droughts and causes other than predation. Bite marks and shed tooth crowns in these edmontosaur assemblages attest to scavenging behavior by *T. rex*. Jacobsen has found comparable evidence for albertosaur scavenging. Carpenter, on the other hand, has provided solid proof of predaceous behavior, in the form of an unsuccessful attack by a *T. rex* on an adult *Edmontosaurus*. The intended prey escaped with several broken tailbones that later healed. The only animal with the stature, proper dentition and biting force to account for this injury is *T. rex*.

Quantification of such discoveries can help determine the degree to which *T. rex* undertook each method of obtaining food, and paleontologists can avoid future arguments by adopting standard definitions of predator and scavenger. Such a convention is necessary, as a wide range of views pervades vertebrate paleontology as to what exactly makes for each kind of feeder. For example, some extremists contend that if a carnivorous animal consumes any carrion at all, it should be called a scavenger. But such a constrained definition negates a meaningful ecological distinction, as it would include nearly all the world's carnivorous birds and mammals.

In a definition more consistent with most paleontologists' common-sense categorization, a predatory species would be one in which most individuals acquire most of their meals from animals they or

their peers killed. Most individuals in a scavenging species, on the other hand, would not be responsible for the deaths of most of their food.

Trace fossils could open the door to a systematic approach to the predator-scavenger controversy, and the resolution could come from testing hypotheses about entire patterns of tyrannosaur feeding preferences. For instance, Jacobsen has pointed out that evidence of a preference for less dangerous or easily caught animals supports a predator niche. Conversely, scavengers would be expected to consume all species equally.

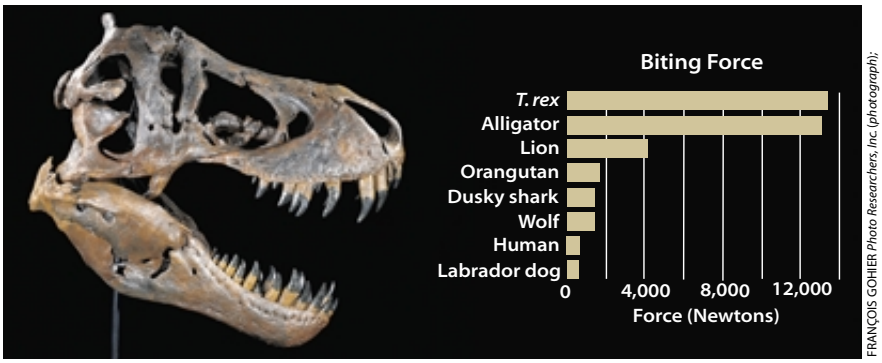
Within this logical framework, Jacobsen has compelling data supporting predation. She surveyed thousands of dinosaur bones from Alberta and learned that unarmored hadrosaurs are twice as likely to bear tyrannosaur bite marks as are the more dangerous horned ceratopsians. Tanke, who participated in the collection of these bones, relates that no bite marks have been found on the heavily armored, tanklike ankylosaurs.

Jacobsen cautions, though, that other factors confuse this set of findings. Most of the hadrosaur bones are from isolated individuals, but most ceratopsians in her study are from bone beds. Again, these beds contain more whole animals that have been fossilized unscathed, creating the kind of tooth-mark bias discussed earlier. A survey of isolated ceratopsians would be enlightening. And analysis of more bite marks that reveal failed predatory attempts, such as those reported by Carpenter, could also reveal preferences, or the lack thereof, for less dangerous prey.

Jacobsen's finding that cannibalism among tyrannosaurs was rare—only 2 percent of albertosaur bones had albertosaur bite marks, whereas 14 percent of herbivore bones did—might also support predatory preferences instead of a scavenging niche for *T. rex,* particularly if these animals were in fact gregarious. Assuming that they had no aversion to consuming flesh of their own kind, it would be expected that at least as many *T. rex* bones would exhibit signs of *T. rex* dining as do herbivore bones. A scavenging *T. rex* would have had to stumble on herbivore remains, but if *T. rex* traveled in herds, freshly dead conspecifics would seem to have been a guaranteed meal.

Coprolites may also provide valuable evidence about whether *T. rex* had any finicky eating habits. Because histological examination of bone found in coprolites can give the approximate stage of life of the consumed animal, Chin and I have suggested that coprolites may reveal a *T. rex* preference for feeding on vulnerable members of herds, such as the very young. Such a bias would point to predation, whereas a more impartial feeding pattern, matching the normal patterns of attrition, would indicate scavenging. Meaningful questions may lead to meaningful answers.

Over this century, paleontologists have recovered enough physical remains of *Tyrannosaurus rex* to give the world an excellent idea of what these monsters looked like. The attempt to discover what *T. rex* actually *was* like relies on those fossils that carry precious clues about the daily activities of dinosaurs. Paleontologists now appreciate the need for reanalysis of finds that were formerly ignored and have recognized the biases in collection practices, which have clouded perceptions of dinosaurs. The intentional pursuit of behavioral data should accelerate discoveries of dinosaur paleobiology. And new technologies may tease information out of fossils that we currently deem of little value. The *T. rex,* still alive in the imagination, continues to evolve. SA



FRANÇOIS GOHIER *Photo Researchers, Inc. (photograph);* SARAH DONELSON *(graph)*

BITE-FORCE GRAPH shows that *T. rex* is the undisputed champion. The author, working with bioengineer Dennis R. Carter of Stanford University, simulated the production of feeding bite marks, which are typically less than full strength, using a cast of a *T. rex* tooth on cow pelvises. They made a conservative estimate of approximately 13,000 newtons (about 2,900 pounds) for one side of the mouth.

The Author

GREGORY M. ERICKSON has studied dinosaurs since his first expedition to the Hell Creek Formation badlands of eastern Montana in 1986. He received his master's degree under Jack Horner in 1992 at Montana State University and a doctorate with Marvalee Wake in 1997 from the University of California, Berkeley. Erickson is currently conducting postdoctoral research at Stanford and Brown universities aimed at understanding the form, function, development and evolution of the vertebrate skeleton. *Tyrannosaurus rex* has been one of his favorite study animals in this pursuit. He has won the Romer Prize from the Society of Vertebrate Paleontology, the Stoye Award from the American Society of Ichthyologists and Herpetologists, and the Davis Award from the Society for Integrative and Comparative Biology. He will shortly become a faculty member in the department of biological science at Florida State University.

Further Reading

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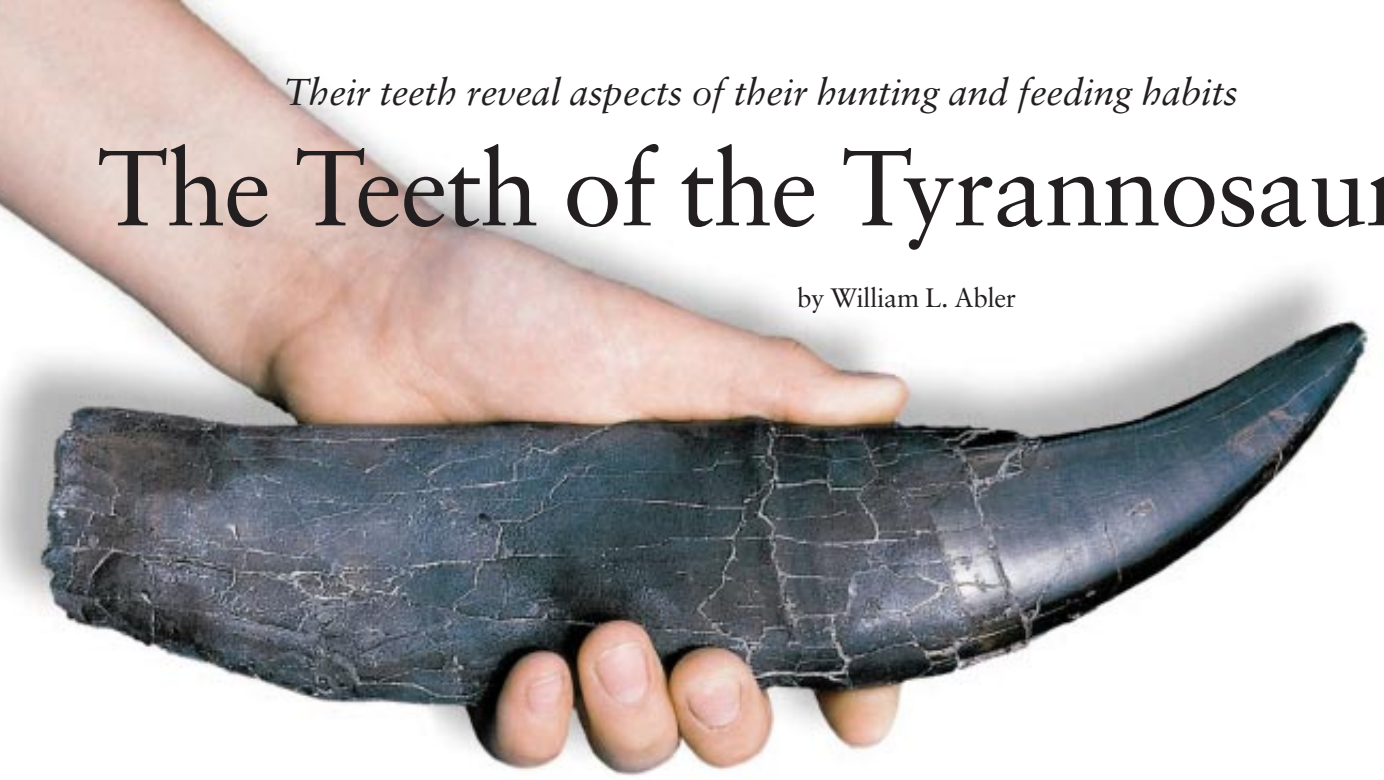
Their teeth reveal aspects of their hunting and feeding habits

The Teeth of the Tyrannosaurs

by William L. Abler



FRANÇOIS GOHIER *Photo Researchers, Inc.*

MASSIVE TOOTH of a tyrannosaur: only about 25 percent of the tooth (*smooth section at right*) would have been visible above the gum line.

Understanding the teeth is essential for reconstructing the hunting and feeding habits of the tyrannosaurs. The tyrannosaur tooth is more or less a cone, slightly curved and slightly flattened, so that the cross section is an ellipse. Both the narrow anterior and posterior surfaces bear rows of serrations. Their presence has led many observers to assume that the teeth cut meat the way a serrated steak knife does. My colleagues and I, however, were unable to find any definitive study of the mechanisms by which knives, smooth or serrated, actually cut. Thus, the comparison between tyrannosaur teeth and knives had meaning only as an impetus for research, which I decided to undertake.

Trusting in the logic of evolution, I began with the assumption that tyrannosaur teeth were well adapted for their biological functions. Although investigation of the teeth themselves might appear to be the best way of uncovering their characteristics, such direct study is limited; the teeth cannot really be used for controlled experiments. For example, doubling the height of a fossil tooth's serrations to monitor changes in cutting properties is impossible. So I decided to study steel blades whose serrations or sharpness I could alter and then compare these findings with the cutting action of actual tyrannosaur teeth.

The cutting edges of knives can be either smooth or serrated. A smooth knife blade is defined by the angle between the two faces and by the radius of the cutting edge: the smaller the radius, the sharper the edge. Serrated blades, on the other hand, are characterized by the height of the serrations and the distance between them.

To investigate the properties of knives with various edges and serrations, I created a series of smooth-bladed knives with varying interfacial angles. I standardized the edge radius for comparable sharpness; when a cutting edge was no longer visible at 25 magnifications, I stopped sharpening the blade. I also produced a series of serrated edges.

To measure the cutting properties of the blades, I mounted them on a butcher's saw operated by cords and pulleys, which moved the blades across a series of similarly sized pieces of meat that had been placed on a cutting board. Using weights stacked in baskets at the ends of the cords, I measured the downward force and drawing force required to cut each piece of meat to the same depth. My simple approach gave consistent and provocative results, including this important and perhaps unsurprising one: smooth and serrated blades cut in two entirely different fashions.

The serrated blade appears to cut meat by a "grip and rip" mechanism. Each serration penetrates to a distance equal to its own length, isolating a small section of meat between itself and the adjacent serration. As the blade moves, each serration rips that isolated section. The blade then falls a distance equal to the height of the serration, and the process repeats. The blade thus converts a pulling force into a cutting force.

A smooth blade, however, concentrates downward force at the tiny cutting edge. The smaller this edge, the greater the force. In effect, the edge crushes the meat until it splits, and pulling or pushing the blade reduces friction between the blade surface and the meat.

After these discoveries, I mounted actual serrated teeth in the experimental apparatus, with some unexpected results. The serrated tooth of a fossil shark (*Carcharodon megalodon*) indeed works exactly like a serrated knife blade does. Yet the serrated edge of even the sharpest tyrannosaur tooth cuts meat more like a smooth knife blade, and a dull one at that. Clearly, all serrations are not alike. Nevertheless, serrations are a major and dramatic feature of tyrannosaur teeth. I therefore began to wonder whether these serrations served a function other than cutting.

The serrations on a shark tooth have a pyramidal shape. Tyrannosaur serrations are more cubelike. Two features of great interest are the gap between serrations, called a cella, and the thin slot to

which the cella narrows, called a diaphysis. Seeking possible functions of the cellae and diaphyses, I put tyrannosaur teeth directly to the test and used them to cut fresh meat. To my knowledge, this was the first time tyrannosaur teeth have ripped flesh in some 65 million years.

I then examined the teeth under the microscope, which revealed striking characteristics. (Although I was able to inspect a few *Tyrannosaurus rex* teeth, my cutting experiments were done with teeth of fossil albertosaurs, which are true tyrannosaurs and close relatives of *T. rex*.) The cellae appear to make excellent traps for grease and other food debris. They also provide access to the deeper diaphyses, which grip and hold filaments of the victim's tendon. Tyrannosaur teeth thus would have harbored bits of meat and grease for extended periods. Such food particles are receptacles for septic bacteria—even a nip from a tyrannosaur, therefore, might have been a source of a fatal infection.

Another aspect of tyrannosaur teeth encourages contemplation. Neighboring serrations do not meet at the exterior of the tooth. They remain separate inside it down to a depth nearly equal to the exterior height of the serration. Where they finally do meet, the junction, called the ampulla, is flask-shaped rather than V-shaped. This ampulla seems to have protected the tooth from cracking when force was applied. Whereas the narrow opening of the diaphysis indeed put high pressure on trapped filaments of tendon, the rounded ampulla distributed pressure uniformly around its surface. The ampulla thus eliminated any point of concentrated force where a crack might begin.

Apparently, enormously strong tyrannosaurs did not require razorlike teeth but instead made other demands on their dentition. The teeth functioned less like knives than like pegs, which gripped the food while the *T. rex* pulled it to pieces. (This so-called puncture-and-pull technique is also discussed in "Breathing Life into *Tyrannosaurus rex*," on page 42.) And the ampullae protected the teeth during this process.

An additional feature of its dental anatomy leads to the conclusion that *T. rex* did not chew its food. The teeth have no occlusal, or articulating, surfaces and rarely touched one another. After it removed a large chunk of carcass, the tyrannosaur probably swallowed that piece whole.

Work from an unexpected quarter also provides potential help in reconstructing the hunting and feeding habits of tyrannosaurs. Herpetologist Walter Auffenberg of the University of Florida spent more than 15 months in Indonesia studying the largest lizard in the world, the Komodo dragon [see "The Komodo Dragon," by Claudio Ciofi; SCIENTIFIC AMERICAN, March]. (Paleontologist James O. Farlow of Indiana University–Purdue University Fort Wayne has suggested that the Komodo dragon may serve as a living model for the behavior of the tyrannosaurs.) The dragon's teeth are remarkably similar in structure to those of tyrannosaurs, and the creature is well known to inflict a dangerously septic bite—an animal that escapes an attack with just a flesh wound is often living on borrowed time. An infectious bite for tyrannosaurs would lend credence to the argument that the beasts were predators rather than scavengers. As with Komodo dragons, the victim of what appeared to be an unsuccessful attack might have received a fatal infection. The dead or dying prey would then be easy pickings to a tyrannosaur, whether the original attacker or merely a fortunate conspecific.

If the armamentarium of tyrannosaurs did include septic oral flora, we can postulate other characteristics of its anatomy. To help maintain a moist environment for its single-celled guests, tyrannosaurs probably had lips that closed tightly, as well as thick, spongy gums that covered the teeth. When tyrannosaurs ate, pressure between teeth and gums might have cut the latter, causing them to bleed. The blood in turn may have been a source of nourishment for the septic dental bacteria. In this scenario, the horrific appearance of the feeding tyrannosaur is further exaggerated—their mouths would have run red with their own bloodstained saliva while they dined. SA

EXPERIMENTAL DEVICE (*above*) for measuring cutting forces of various blades: weights attached to cords at the sides and center cause the blade to make a standard cut of 10 millimeters in a meat sample (*represented here by green rubber*). Below is a close-up of filaments of tendon, trapped between serrations on a tyrannosaur tooth.

PHOTOGRAPHS COURTESY OF WILLIAM L. ABLER

The Author

WILLIAM L. ABLER received a doctorate in linguistics from the University of Pennsylvania in 1971. Following a postdoctoral appointment in neuropsychology at Stanford University, he joined the faculty of linguistics at the Illinois Institute of Technology. His interests in human origins and evolution eventually led him to contemplate animal models for human evolution and on to the study of dinosaurs, particularly their brains. The appeal of dinosaurs led him to his current position in the Department of Geology at the Field Museum, Chicago.

Further Reading

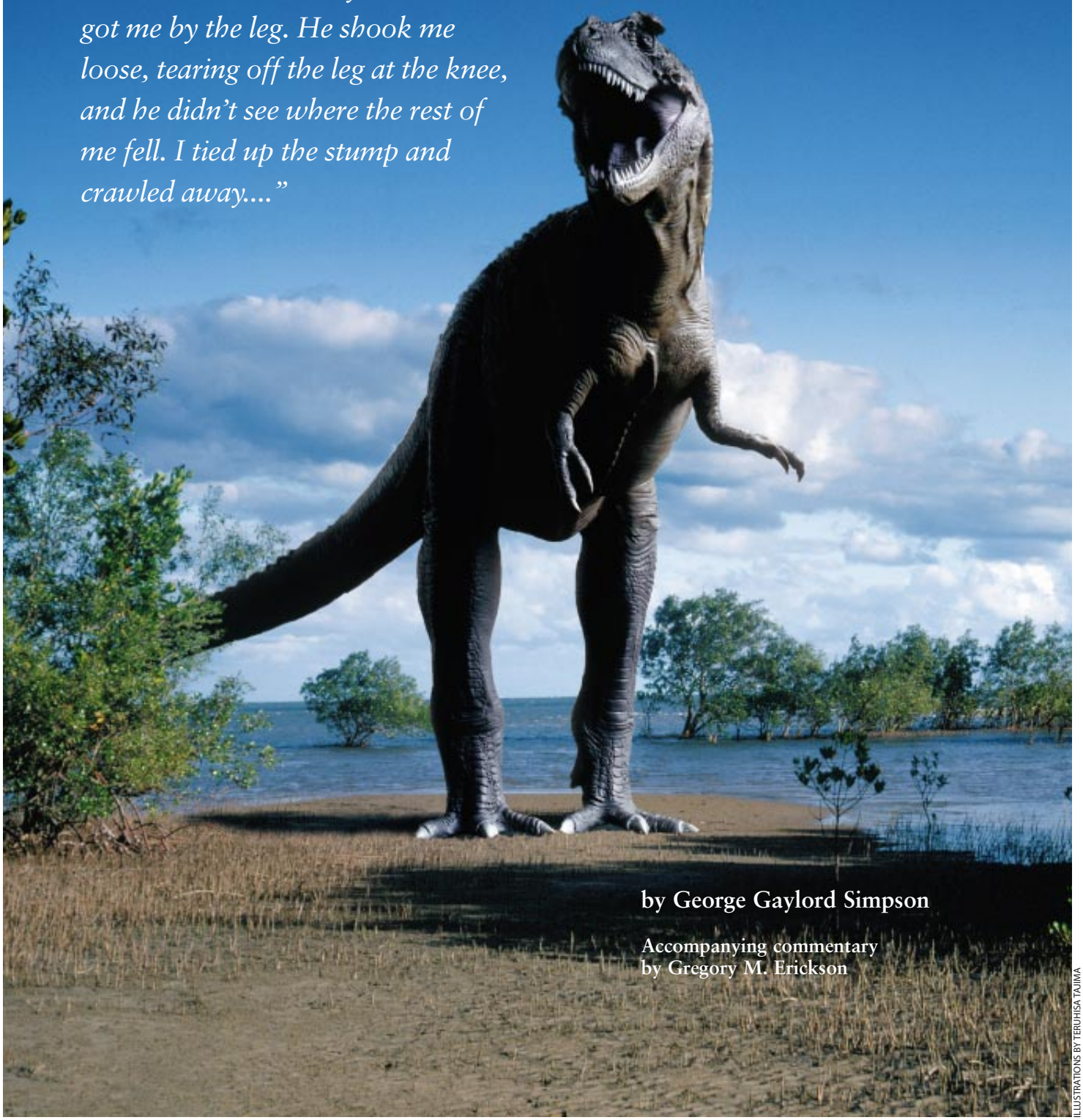
THE SERRATED TEETH OF TYRANNOSAURID DINOSAURS, AND BITING STRUCTURES IN OTHER ANIMALS. William Abler in *Paleobiology,* Vol. 18, No. 2, pages 161–183; 1992.

TOOTH SERRATIONS IN CARNIVOROUS DINOSAURS. William Abler in *Encyclopedia of Dinosaurs.* Edited by Philip J. Currie and Kevin Padian. Academic Press, 1997.

BOOK EXCERPT

The Dechronization of Sam Magruder

"The brute—it was a tyrannosaur—got me by the leg. He shook me loose, tearing off the leg at the knee, and he didn't see where the rest of me fell. I tied up the stump and crawled away...."



by George Gaylord Simpson

Accompanying commentary by Gregory M. Erickson

ILLUSTRATIONS BY TERUHISA TAJIMA

Perhaps the most common advice given to aspiring novelists is, "Write what you know." George Gaylord Simpson, regarded by many as the 20th century's greatest vertebrate paleontologist, took that suggestion to heart when he tried his hand at science fiction. Published posthumously in 1996, his short novel, The Dechronization of Sam Magruder (*St. Martin's Griffin*), *tells the story of a "time-scientist" who starts one day in the year 2162 and winds up face-to-face with a subject Simpson unquestionably knew: dinosaurs, particularly* Tyrannosaurus rex. *Magruder is also a writer. He leaves his memoirs as scratches on sandstone slabs for posterity, buried and later fortuitously discovered.* —The Editors

My name is Samuel TM12SC48 Magruder AChA3*. Good old Sam Magruder. Odd that I should want to put down my names and titles first, or to put them down at all. Names are to distinguish us from other men, and I am the only man who exists or ever has existed. Titles are supposedly to label our capacities, really to try to impress our associates. The qualifications of AChA3* have not much bearing on my present life, and my associates here are definitely not impressed. But there it is: I cling to being Sam Magruder. I want to reassure myself that I *am* I, that this is the same being who is to be born 80 million years from now and registered as Samuel TM12SC48 Magruder. Yet *that* person does not really exist in any time dimension or universe. He is only *going to* exist.

After describing how his experiments unwittingly allowed him to slip back in time, Magruder recounts his arrival in the past....

I landed up to my waist in mucky water. I was naked as a newborn baby. The time-slip did not work on my clothes or anything around me. It would not have mattered much, anyway, since all I had in my pockets were keys and some money, not exactly useful in the Cretaceous. The clothes themselves would have been useful at first, but would not have lasted long.

I let out an involuntary yell of surprise. There was a tremendous splashing and thrashing about on the other side of some reeds. I started wading over, partly to investigate and partly because I could not think of anything else to do and felt silly just standing there. The bottom was sticky black ooze. In places I sank in so I was afraid I would be bogged down, so I swam until I came to the reeds. I groped with my bare feet and found a little relatively solid footing. I parted the screen of vegetation; the saw-toothed edges lacerated my hands.

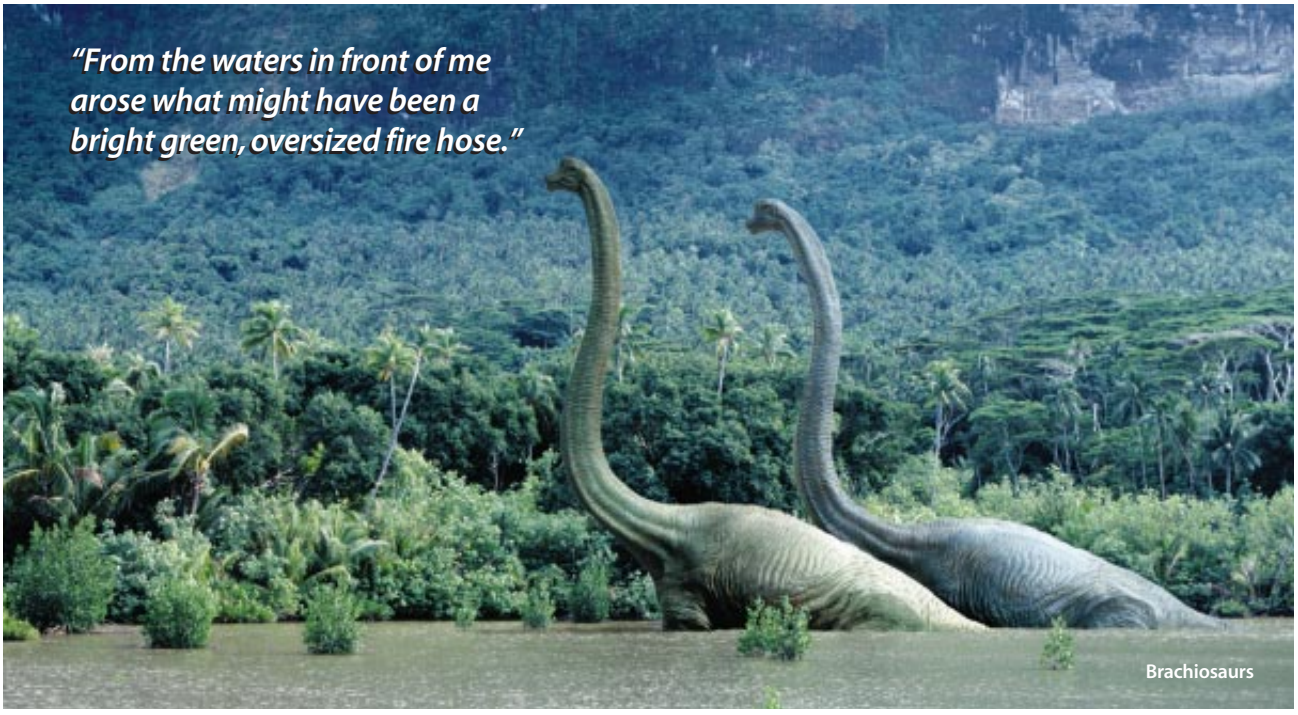
From the waters in front of me arose what might have been a bright green, oversized fire hose. Perhaps two feet in diameter where it emerged from the water, it tapered to about half that in the fifteen feet of its exposed length. It ended, not in a nozzle as I almost expected, but in a head of sorts. The head was wedge-shaped in profile, and a crimson eye glared near the top. Behind and below the eye was a smaller, black earhole. The mouth, open in what looked like a vapid grin, was rimmed with white, pencil-like teeth.

I did not immediately identify this apparition. I should have, because my training in chronology included a stiff course in paleontology, but I was laboring under two inevitable disabilities. In the first place, I had not yet located myself even roughly in time. A swamp could occur at any time since rain began. I knew, by now, that I had slipped into what had been the past for me, into time before 29 February 2162, but how far back? It could have been no more than a few months or it could have been into the dim and lifeless mysteries of the Archaeozoic Era. I had to expect anything whatever, and I had no frame of reference for any more explicit expectation.

The second difficulty in recognition arose from the limitations of paleontological restoration. The colors of prehistoric animals are unknown. Playing it safe, artists have not dared to use the **emerald-green hue** of the creature I now saw before me. They show the eyes as brown or black, not the startling crimson of the reality before me. My mental image from student days was all the wrong colors. Would you immediately recognize a bright red, stripeless tiger or a purple-spotted squirrel?

Perhaps some future biotechnology will allow us to determine dinosaur coloration. For now, however, Simpson remains correct, and the colors remain a mystery.

The critter and I stared at each other for what seemed like a long time. It never did identify me, but I finally got it placed. It was a dinosaur. Among the numerous kinds of dinosaurs, large



Brachiosaurs

and small, it was one of the sauropods. No others, even in that race of giants, reached quite the size implied by the emergent neck of this monstrosity. No others had such long, hoselike necks, such small heads in relation to their overall hugeness, or such discrepant pencil stubs for teeth.

I was not at all frightened. I am no braver than I have to be, but the sight was so interesting that I did not think of danger. Then I remembered that the sauropods were, are (in my peculiar circumstances I am never quite sure what tense to use)—that they are vegetarians. Doubtless my new acquaintance would lash back if I annoyed it, but at least it did not view me as a potential snack. I gave an experimental shout, and sure enough it startled and went splashing off, waving its neck in alarm.

The encounter was stabilizing for me. You have no idea how disorienting it is not to know, even approximately, *when* you are living. I had already worked up considerable anxiety as to the time into which I had slipped, and this creature gave me a fairly good estimate. At least I thought that it did, although I have since decided that I was a few scores of millions of years off the mark. Here was **one of the large sauropod dinosaurs**, possibly a *Diplodocus*. Their heyday was in the late Jurassic, perhaps 140 million years before 2162. So that, more or less, is where, or rather when, I decided I was. Later I saw so many species that I knew to be much later in age that I had to revise my estimate. This is certainly the late Cretaceous, not the late Jurassic, and only about 80, rather than 150, million years before the time from which I slipped. Evidently the sauropods survived much longer than I remember from my professional school days, or perhaps the paleontologists of 2162 have slipped up on this point.

Diplodocus *lived earlier than* T. rex, *but Simpson is right about the potential of sauropods and* T. rex *interacting. Titanosaurs, a type of sauropod, did live in the southern range of* T. rex *in the southwestern U.S.*

Magruder has survived his first night but is about to encounter his first T. rex. . . .

It was a bright day, and by noon I had a crowning misery. I was severely sunburned. I blistered all over, and I must have developed a high fever. When I returned to my senses, the insect bites and the sunburn persuaded me that for a pale, thin-skinned, furless mammal, clothing might be as necessary for survival as food.

I did return to my senses. I was shocked back into them sometime during the course of the afternoon by my first sight of a tyrannosaur and by another close shave I had at the shore of the lagoon. Looking back, the haze of my memory clears with me standing in the magnolia grove, watching something move between me and the lake. It was a reptile, a dinosaur fifteen feet high as it poised on its ponderous hind legs, thirty feet long from its obscene snout to the end of its great, tapered tail. This was no inoffensive hulk of a herbivorous sauropod. It was a carnivore, and it saw meat. Its small, two-toed hands were held up beneath its tremendous jaw in a way that might have seemed ludicrously ladylike if the intention had

not been so obviously grim. Its teeth were six-inch daggers and gleamed white as it swung its ponderous head to face me. In a sort of hypnotic horror, I thought inconsequentially, "But your teeth should be dark brown!" I had often seen the tyrannosaur skull in the Universal Natural History Museum, and its teeth were deeply colored. I had never stopped to think that the discoloration was the result of mineralization and that in the living animal the teeth would be white, as they are.

My impulse was the same as yours would have been; I wanted to turn and run. Fortunately for me, the pumping adrenaline in my bloodstream threw my tortured muscles into spasm. I was literally rooted to the spot. I could not have run during that moment if my life had depended on it, as, indeed, I was sure it did. **The awful monster launched its charge,** and still I stood impotently. Only as it loomed directly over me, its whistling bellow resounding in my ears like the trumpet of doom, did I recover volition enough to leap to one side. Unable to throw so much momentum into a swerve, the tyrannosaur thundered by, knocking down the small trees as if they were herbs, and finally skidding to a stop twenty yards beyond me.

T. rex *running speed was of great debate when Simpson wrote* Sam Magruder. *Over the years, estimates have ranged wildly, from about eight to 70 kilometers (five to 45 miles) per hour. Per Christiansen's investigations now suggest a top speed of perhaps 47 kph, significantly better than the best human sprinters.*

My weakness had led me unwillingly into the one tactic by which a man may safely face a tyrannosaur. To run would be to die, for who could outrun that tremendous animal machine? But by the grace of physical law, man's two hundred pounds can dodge agilely while the tyrannosaur's five tons must continue straight on or only slowly change its course. Before a charging tyrannosaur, you have only to step aside and let the mountain of flesh go by. I cannot conquer a thrill of horror whenever one of these obscenities comes in view, but since that first charge they have been less dangerous to me than flies. I need not even worry about them while I sleep. Like that of all dinosaurs, **their sluggish reptilian metabolism** requires external warmth to stoke their fires. They are quiescent in the cool night air and do not stir dangerously until the morning sun has limbered them....

Based on bone histology and other anatomical criteria, most researchers now believe that dinosaurs were intermediate between "cold-blooded" lizards and crocodiles and "warm-blooded" birds and mammals. Even advocates of a cold-blooded T. rex *would agree that it would not have cooled substantially in a Cretaceous environment overnight, thanks to its huge size.*

After that first charge, I correctly expected a return, but I had already grasped the secret of defense. In command of myself now, I stood until the futile mountain of demoniac flesh was upon me, then dodged and watched it crash onward toward the lagoon. When it finally stopped, I was hidden among the few trees still standing. It looked about aimlessly. Obviously its **tiny reptilian brain** had lost all memory of what the excitement was about. It wandered about for a few minutes, then loped off around the shore and out of sight. I rejoiced in being *Homo sapiens* and marked up one score for our side.

Sorry, Sam, but T. rex *probably would have sniffed you out, finishing your saga right here. Studies of tyrannosaur olfactory lobe size from skulls are revealing that* T. rex *had a very good sense of smell.* —G.M.E.

After decades of existence among the dinosaurs, Magruder leaves his final message from the past, with the hope of an eventual reader....

I lost count there a little at first, but I must be over sixty years old now, counting together my two severed lives. Even without my accident, that's a ripe old age in the Cretaceous. I haven't much time left or much strength left to finish these slabs and to bury them where they'll have a chance, however slight, of being preserved—and found.

I have written mostly at *Pentaceratops* Valley, but that is not the place for the slabs. The valley is being eroded, and anything buried there must be washed out and ground to pieces in the millions of years to come. The swamp is the place. There each flood buries things deeper. The earth groans and buckles under the load—and preserves it. I am there now, near where I first saw the Cretaceous. The slabs are here. I brought the others down last year, and this year a final one, blank, for my last words. As soon as this is finished, I'll bury them deeply in the ooze.

The accident—well, it had to happen sooner or later. I suppose I've slowed down, and perhaps I've become a little careless. I've dodged so many dinosaurs. I dodged one too many and was careless once too often. The brute—it was a tyrannosaur—got me by the leg. Fortunately, you might say, he shook me loose, tearing off the leg at the knee, and he didn't see where the rest of me fell. I tied up the stump and crawled away, but I'm done. That was yesterday and I can't last much more than another day at best.

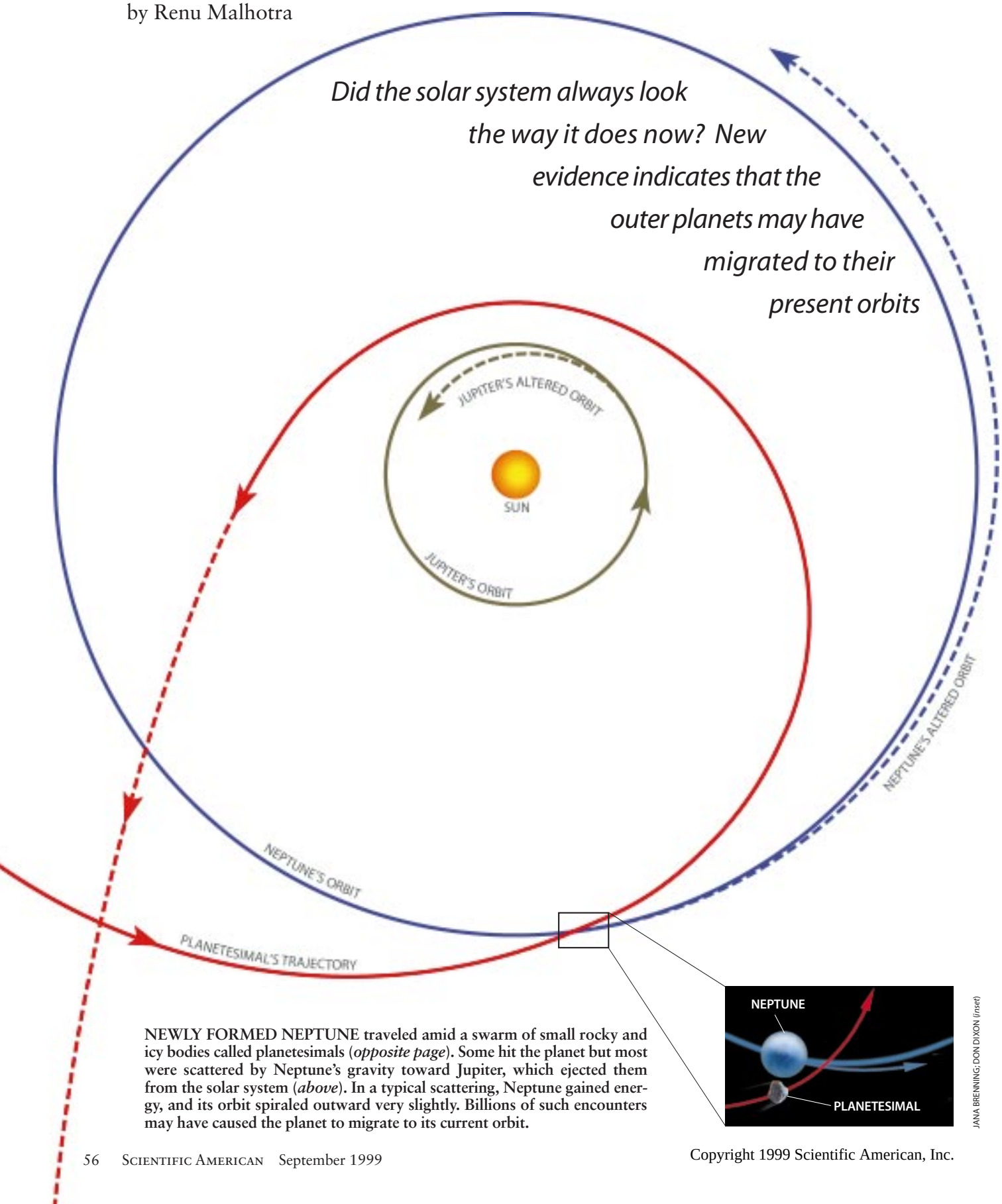
There; the first seven slabs are safe, as safe as I can manage.

There isn't much more to say. I've had no joy, but a little satisfaction, from this long ordeal. I have often wondered why I kept going. That, at least, I have learned and I know it now at the end. There could be no hope and no reward. I always recognized that bitter truth. But I am a man, and a man is responsible for himself. SA

Migrating Planets

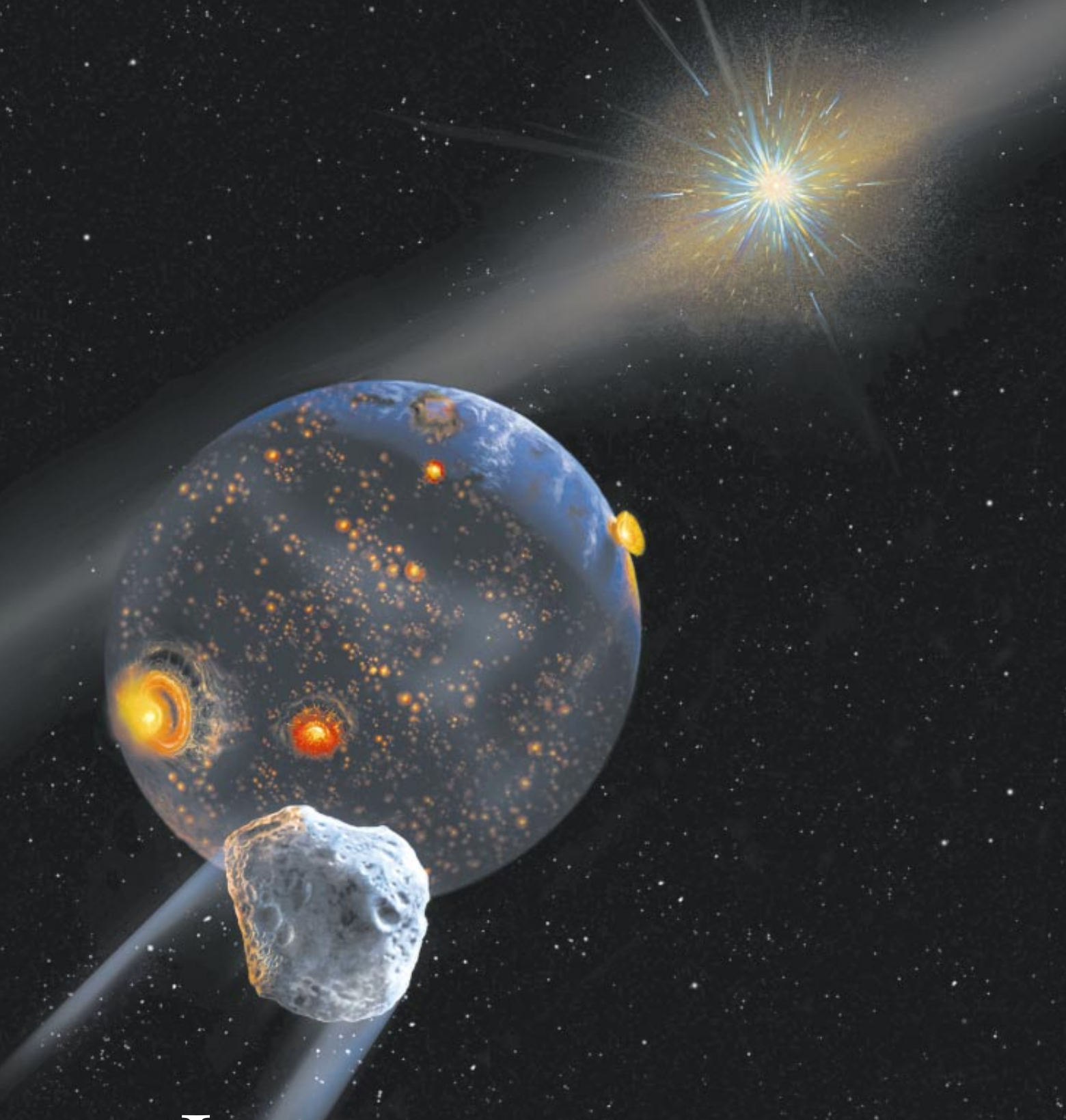
by Renu Malhotra

Did the solar system always look the way it does now? New evidence indicates that the outer planets may have migrated to their present orbits



JANA BRENNING; DON DIXON (*inset*)

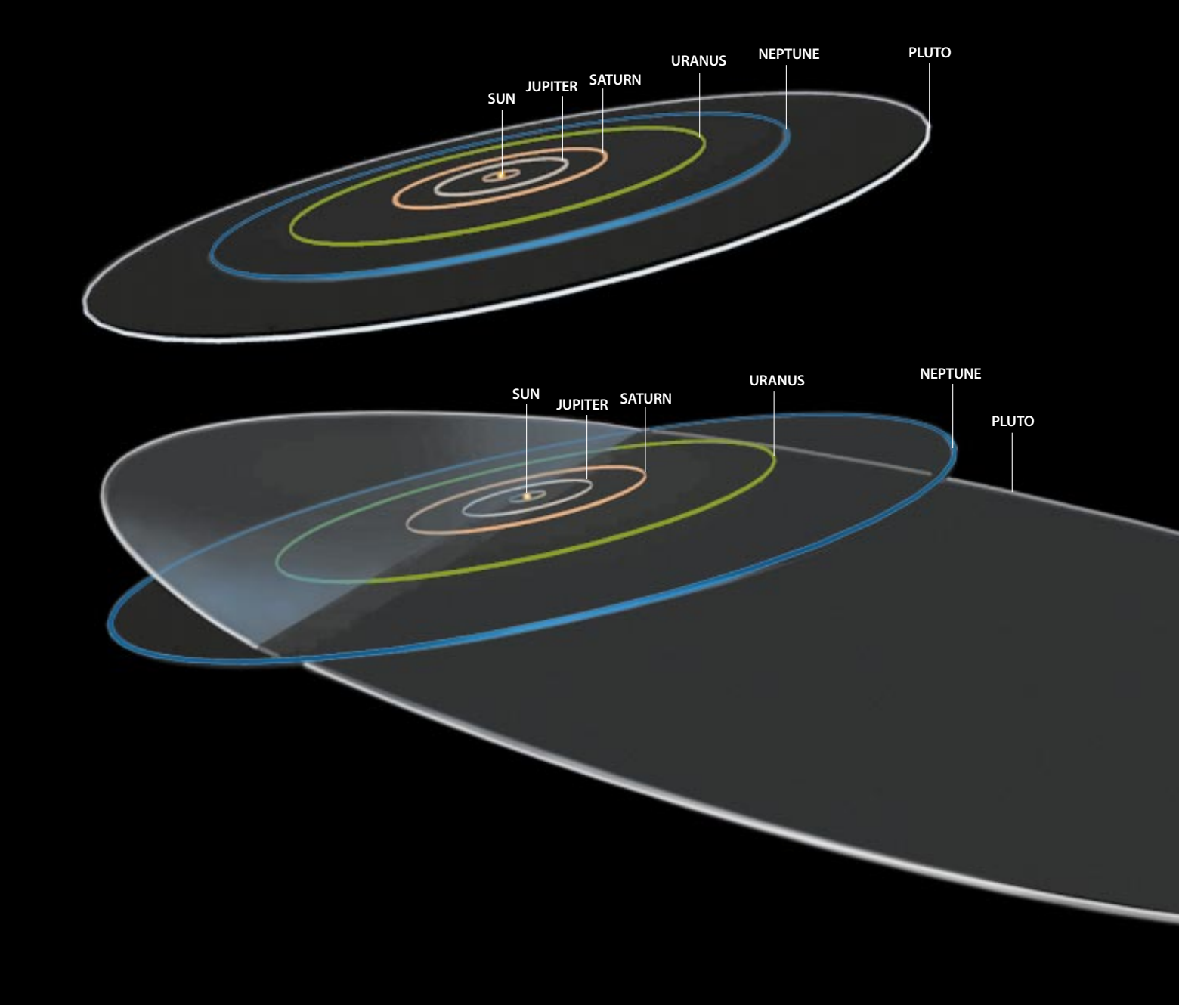
NEWLY FORMED NEPTUNE traveled amid a swarm of small rocky and icy bodies called planetesimals (*opposite page*). Some hit the planet but most were scattered by Neptune's gravity toward Jupiter, which ejected them from the solar system (*above*). In a typical scattering, Neptune gained energy, and its orbit spiraled outward very slightly. Billions of such encounters may have caused the planet to migrate to its current orbit.



DON DIXON

In the familiar visual renditions of the solar system, each planet moves around the sun in its own well-defined orbit, maintaining a respectful distance from its neighbors. The planets have maintained this celestial merry-go-round since astronomers began recording their motions, and mathematical models show that this very stable orbital configuration has existed for almost the entire 4.5-billion-year history of the solar system. It is tempting, then, to assume that the planets were "born" in the orbits that we now observe.

Certainly it is the simplest hypothesis. Modern-day astronomers have generally presumed that the observed distances of the planets from the sun indicate their birthplaces in the solar nebula, the primordial disk of dust and gas that gave rise to the solar system. The orbital radii of the planets have been used to infer the mass distribution within the solar nebula. With this

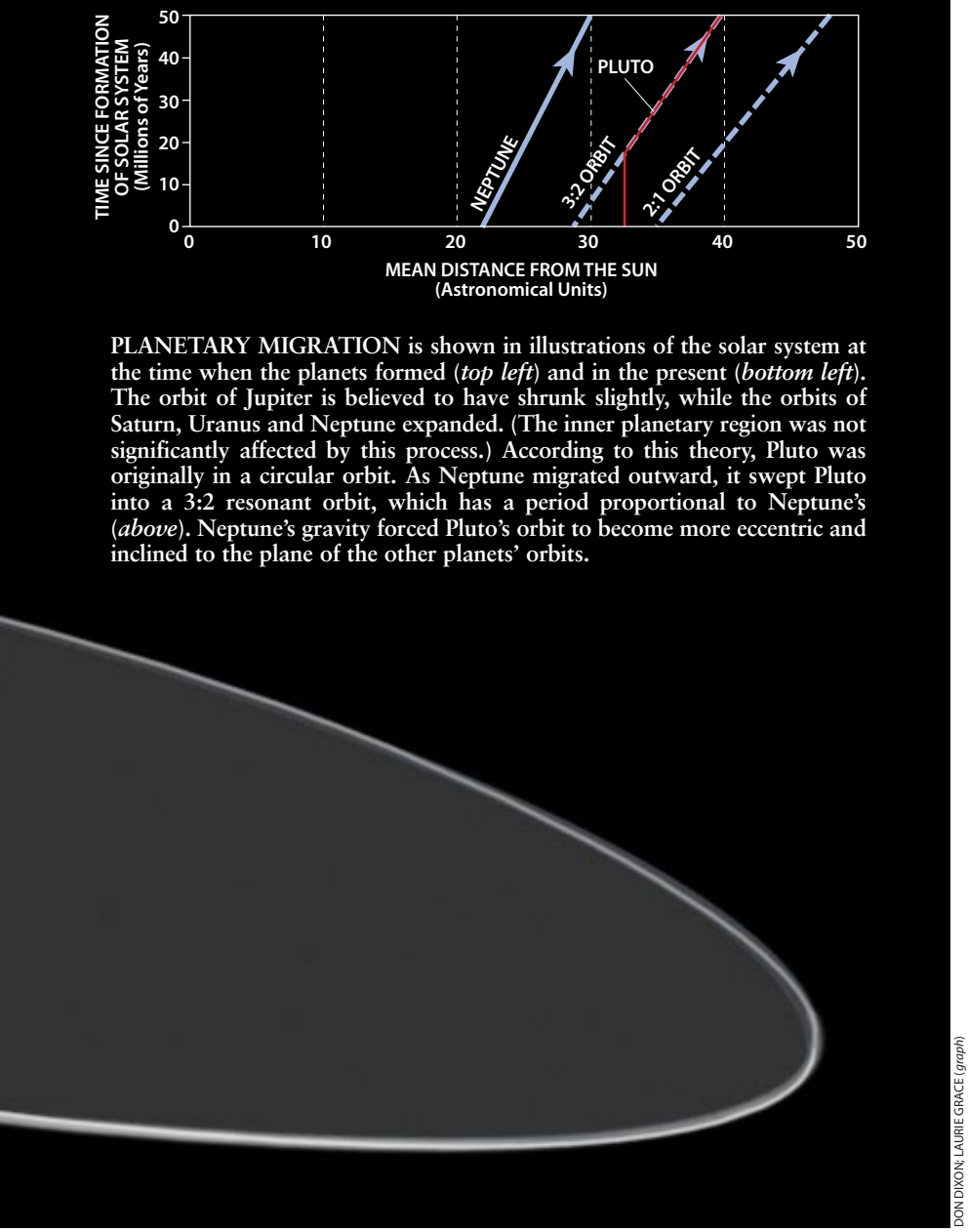


basic information, theorists have derived constraints on the nature and timescales of planetary formation. Consequently, much of our understanding of the early history of the solar system is based on the assumption that the planets formed in their current orbits.

It is widely accepted, however, that many of the smaller bodies in the solar system—asteroids, comets and the planets' moons—have altered their orbits over the past 4.5 billion years, some more dramatically than others. The demise of Comet Shoemaker-Levy 9 when it collided with Jupiter in 1994 was striking evidence of the dynamic nature of some objects in the solar system. Still smaller objects—micron- and millimeter-size interplanetary particles shaken loose from comets and asteroids—undergo a more gradual orbital evolution, gently spiraling in toward the sun and raining down on the planets in their path.

Furthermore, the orbits of many planetary satellites have changed significantly since their formation. For example, Earth's moon is believed to have formed within 30,000 kilometers (18,600 miles) of Earth—but it now orbits at a distance of 384,000 kilometers. The moon has receded by nearly 100,000 kilometers in just the past billion years because of tidal forces (small gravitational torques) exerted by our planet. Also, many satellites of the outer planets orbit in lockstep with one another: for instance, the orbital period of Ganymede, Jupiter's largest moon, is twice that of Europa, which in turn has a period twice that of Io. This precise synchronization is believed to be the result of a gradual evolution of the satellites' orbits by means of tidal forces exerted by the planet they are circling.

Until recently, little provoked the idea that the orbital configuration of the planets has altered significantly since their formation. But some remarkable developments during the past five years indicate that the planets may indeed have migrated from their original orbits. The discovery of the Kuiper belt has shown that our solar system does not end at Pluto. Approximately 100,000 icy "minor planets" (ranging between 100 and 1,000 kilometers in diameter) and an even greater number of smaller



PLANETARY MIGRATION is shown in illustrations of the solar system at the time when the planets formed (*top left*) and in the present (*bottom left*). The orbit of Jupiter is believed to have shrunk slightly, while the orbits of Saturn, Uranus and Neptune expanded. (The inner planetary region was not significantly affected by this process.) According to this theory, Pluto was originally in a circular orbit. As Neptune migrated outward, it swept Pluto into a 3:2 resonant orbit, which has a period proportional to Neptune's (*above*). Neptune's gravity forced Pluto's orbit to become more eccentric and inclined to the plane of the other planets' orbits.

DON DIXON; LAURIE GRACE (*graph*)

bodies occupy a region extending from Neptune's orbit—about 4.5 billion kilometers from the sun—to at least twice that distance. The distribution of these objects exhibits prominent nonrandom features that cannot be readily explained by the current model of the solar system. Theoretical models for the origin of these peculiarities suggest the intriguing possibility that the Kuiper belt bears traces of the orbital history of the gas-giant planets—specifically, evidence of a slow spreading of these planets' orbits subsequent to their formation.

What is more, the recent discovery of several Jupiter-size companions orbiting nearby sunlike stars in peculiarly small orbits has also focused attention on planetary migration. It is difficult to understand the formation of these putative planets at such small distances from their parent stars. Hypotheses for their origin have proposed that they accreted at more comfortable distances from their parent stars—similar to the distance between Jupiter and the sun—and then migrated to their present positions.

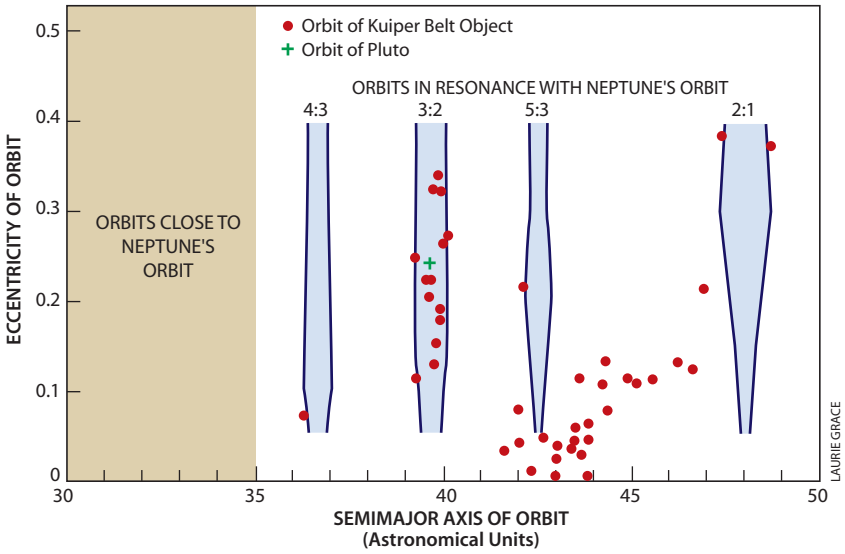
Pluto: Outcast or Smoking Gun?

Until just a few years ago, the only planetary objects known beyond Neptune were Pluto and its satellite, Charon. Pluto has long been a misfit in the prevailing theories of the solar system's origin: it is thousands of times less massive than the four gas-giant outer planets, and its orbit is very different from the well-separated, nearly circular and co-planar orbits of the eight other major planets. Pluto's is eccentric: during one complete revolution, the planet's distance from the sun varies from 29.7 to 49.5 astronomical units (one astronomical unit, or AU, is the distance between Earth and the sun, about 150 million kilometers). Pluto also travels 8 AU above and 13 AU below the mean plane of the other planets' orbits [*see illustration at left*]. For approximately two decades in its orbital period of 248 years, Pluto is closer to the sun than Neptune is.

In the decades since Pluto's discovery in 1930, the planet's enigma has deepened. Astronomers have found that most Neptune-crossing orbits are unstable—a body in such an orbit will either collide with Neptune or be ejected from the outer solar system in a relatively short time, typically less than 1 percent of the age of the solar system. But the particular Neptune-crossing orbit in which Pluto travels is protected from close approaches to the gas giant by a phenomenon called resonance libration. Pluto makes two revolutions around the sun during the time that Neptune makes three; Pluto's orbit is therefore said to be in 3:2 resonance with Neptune's. The relative motions of the two planets ensure that when Pluto crosses Neptune's orbit, it is far away from the larger planet. In fact, the distance between Pluto and Neptune never drops below 17 AU.

In addition, Pluto's perihelion—its closest approach to the sun—always occurs high above the plane of Neptune's orbit, thus maintaining Pluto's long-term orbital stability. Computer simulations of the orbital motions of the outer planets, including the effects of their mutual perturbations, indicate that the relationship between the orbits of Pluto and Neptune is billions of years old and will persist for billions of years into the future. Pluto is engaged in an elegant cosmic dance with Neptune, dodging collisions with the gas giant over the entire age of the solar system.

How did Pluto come to have such a peculiar orbit? In the past, this question has stimulated several speculative and ad hoc explanations, typically involving planetary encounters. Recently, however, significant advances have been made in understanding the complex dynamics of orbital resonances and in identifying their Jekyll-and-Hyde role in producing both chaos and exceptional stability in the solar system. Drawing on this body



KUIPER BELT OBJECTS occupy a torus-shape region beyond Neptune's orbit (*right*). The theory of planetary migration predicts that concentrations of these objects would be found in orbits in resonance with Neptune's (*inside blue brackets in illustration above*). Recent observations indicate that about one third of the Kuiper belt objects for which orbits are known (*red dots*) are in 3:2 resonant orbits similar to Pluto's (*green cross*). Few objects are expected to be found in orbits that are very close to Neptune's (*shaded area*).

of knowledge, I proposed in 1993 that Pluto was born somewhat beyond Neptune and initially traveled in a nearly circular, low-inclination orbit similar to those of the other planets but that it was transported to its current orbit by resonant gravitational interactions with Neptune. A key feature of this theory is that it abandons the assumption that the gas-giant planets formed at their present distances from the sun. Instead it proposes an epoch of planetary orbital migration early in the history of the solar system, with Pluto's unusual orbit as evidence of that migration.

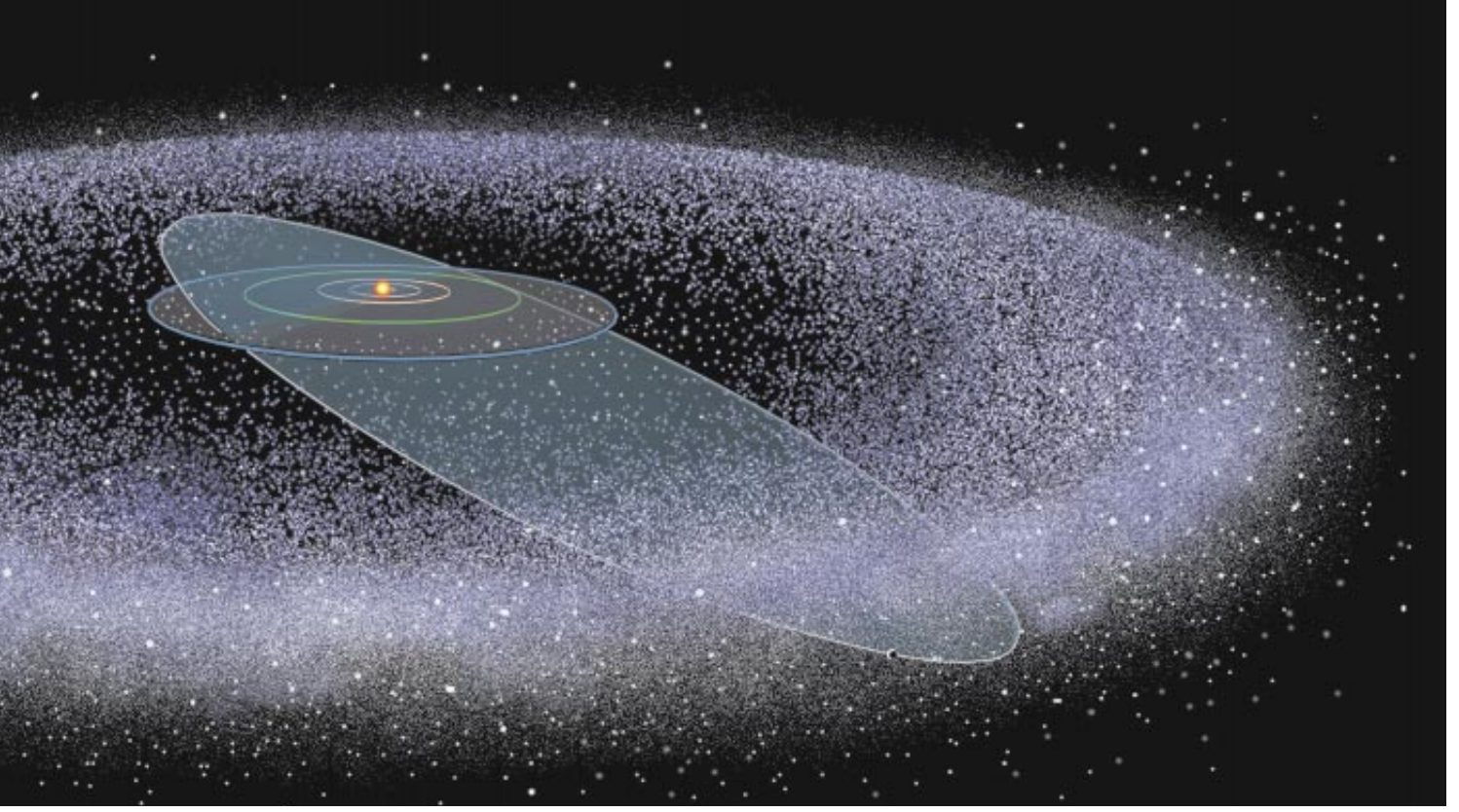
The story begins at a stage when the process of planetary formation was almost but not quite complete. The gas giants—Jupiter, Saturn, Uranus and Neptune—had nearly finished coalescing from the solar nebula, but a residual population of small planetesimals—rocky and icy bodies, most no larger than a few tens of kilometers in diameter—remained in their midst. The relatively slower subsequent evolution of the solar system consisted of the scattering or accretion of the planetesimals by the major planets [*see illustration on page 56*]. Because the planetary scattering ejected most of the planetesimal debris to distant or unbound orbits—essentially throwing the bodies out of the solar system—there was a net loss of orbital energy and angular momentum from the giant planets' orbits. But because of their different masses and distances from the sun, this loss was not evenly shared by the four giant planets.

In particular, consider the orbital evolution of the outermost giant planet, Neptune, as it scattered the swarm of planetesimals in its vicinity. At first, the mean specific orbital energy of the planetesimals (the orbital energy per unit of mass) was equal to that of Neptune itself, so Neptune did not gain or lose energy from its gravitational interactions with the bodies. At later times, however, the planetesimal swarm near Neptune was depleted of the lower-energy objects, which had moved into the gravitational reach of the other giant planets. Most of these planetesimals were eventually ejected from the solar system by Jupiter, the heavyweight of the planets.

Thus, as time went on, the specific orbital energy of the planetesimals that Neptune encountered grew larger than that of Neptune itself. During subsequent scatterings, Neptune gained orbital energy and migrated outward. Saturn and Uranus also gained orbital energy and spiraled outward. In contrast, Jupiter lost orbital energy; its loss balanced the gains of the other planets and planetesimals, hence conserving the total energy of the system. But because Jupiter is so massive and had so much orbital energy and angular momentum to begin with, its orbit decayed only slightly.

The possibility of such subtle adjustments of the giant planets' orbits was first described in a little-noticed paper published in 1984 by Julio A. Fernandez and Wing-Huen Ip, a Uruguayan and Taiwanese astronomer duo working at the Max Planck Institute in Germany. Their work remained a curiosity and escaped any comment among planet formation theorists, possibly because no supporting observations or theoretical consequences had been identified.

In 1993 I theorized that as Neptune's orbit slowly expanded, the orbits that would be resonant with Neptune's also expanded. In fact, these resonant orbits would have swept by Pluto, assuming that the planet was originally in a nearly circular, low-inclination orbit beyond Neptune. I calculated that any such objects would have had a high probability of being "captured" and pushed outward along the resonant orbits as Neptune migrated. As these bodies moved outward, their orbital eccentricities and inclinations would have been driven to larger values by the resonant gravitational torque from Neptune. (This effect is analogous to the pumping-up of the amplitude of a playground swing by means of small periodic pushes at the swing's natural frequency.) The final



maximum eccentricity would therefore provide a direct measure of the magnitude of Neptune's migration. According to this theory, Pluto's orbital eccentricity of 0.25 suggests that Neptune has migrated outward by at least 5 AU. Later, with the help of computer simulations, I revised this to 8 AU and also estimated that the timescale of migration had to be a few tens of millions of years to account for the inclination of Pluto's orbit.

Of course, if Pluto were the only object beyond Neptune, this explanation of its orbit, though compelling in many of its details, would have remained unverifiable. The theory makes specific predictions, however, about the orbital distribution of bodies in the Kuiper belt, which is the remnant of the primordial disk of planetesimals beyond Neptune [see "The Kuiper Belt," by Jane X. Luu and David C. Jewitt; SCIENTIFIC AMERICAN, May 1996]. Provided that the largest bodies in the primordial Kuiper belt were sufficiently small that their perturbations on the other objects in the belt would be negligible, the dynamical mechanism of resonance sweeping would work not only on Pluto but on all the trans-Neptunian objects, perturbing them from their original orbits. As a result, prominent concentrations of objects in eccentric orbits would be found at Neptune's two strongest resonances, the 3:2 and the 2:1. Such orbits are ellipses with semimajor axes of 39.5 AU and 47.8 AU, respectively. (The length of the semimajor axis is equal to the object's average distance from the sun.)

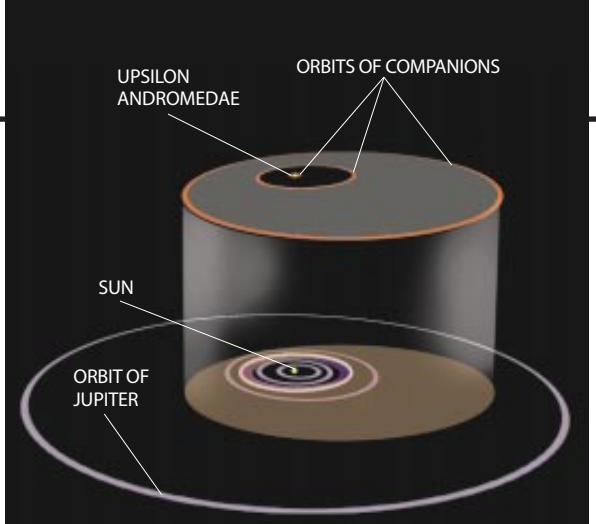
More modest concentrations of trans-Neptunian bodies would be found at other resonances, such as the 5:3. The population of objects closer to Neptune than the 3:2 resonant orbit would be severely depleted because of the thorough resonance sweeping of that region and because perturbations caused by Neptune would destabilize the orbits of any bodies that remained. On the other hand, planetesimals that accreted beyond 50 AU from the sun would be expected to be largely unperturbed and still orbiting in their primordial distribution.

Fortunately, recent observations of Kuiper belt objects, or KBOs, have provided a means of testing this theory. More than 174 KBOs have been discovered as of mid-1999. Most have orbital periods in excess of 250 years and thus have been tracked for less than 1 percent of their orbits. Nevertheless, reasonably reliable orbital parameters have been determined for about 45 of the known KBOs [*see illustration on opposite page*]. Their orbital distribution is not a pattern of uniform, nearly circular, low-inclination orbits, as would be expected for a pristine, unperturbed planetesimal population. Instead one finds strong evidence of gaps and concentrations in the distribution. A large fraction of these KBOs travel in eccentric 3:2 resonant orbits similar to Pluto's, and KBOs in orbits interior to the 3:2 orbit are nearly absent—which is consistent with the predictions of the resonance sweeping theory.

Still, one outstanding question remains: Are there KBOs in the 2:1 resonance comparable in number to those found in the 3:2, as the planet migration theory would suggest? And what is the orbital distribution at even greater distances from the sun? At present, the census of the Kuiper belt is too incomplete to answer this question fully. But on Christmas Eve 1998 the Minor Planet Center in Cambridge, Mass., announced the identification of the first KBO orbiting in 2:1 resonance with Neptune. Two days later the center revealed that another KBO was traveling in a 2:1 resonant orbit. Both these objects have large orbital eccentricities, and they may turn out to be members of a substantial population of KBOs in similar orbits. They had previously been identified as orbiting in the 3:2 and 5:3 resonances, respectively, but new observations made last year strongly indicated that the original identifications were incorrect. This episode underscored the need for continued tracking of known KBOs in

A Planetary System at Last?

In April 1999 astronomer R. Paul Butler of the Anglo-Australian Observatory and his colleagues announced the discovery of what is apparently the first known case of a planetary system with several Jupiter-mass objects orbiting a sunlike star. (Previously, only systems with one Jupiter-mass companion had been detected.) The star is Upsilon Andromedae; it is approximately 40 light-years from our solar system and is slightly more massive and about three times more luminous than our sun.



UPSILON ANDROMEDAE SYSTEM is believed to include three Jupiter-mass companions orbiting the star (*top*). Their theorized orbits are much tighter than Jupiter's orbit in our solar system (*bottom*).

DON DIXON

The astronomers say their analysis of the observations shows that Upsilon Andromedae harbors three companions. The innermost object is at least 70 percent as massive as Jupiter and is moving in a nearly circular orbit only 0.06 AU—or about nine million kilometers—from the star. The outermost companion object is at least four times as massive as Jupiter and travels in a very eccentric orbit with a mean radius of 2.5 AU—half the radius of Jupiter's orbit. The intermediate object is at least twice as massive as Jupiter and has a moderately eccentric orbit with a mean radius of 0.8 AU.

If confirmed, the architecture of this system would pose some interesting challenges and opportunities for theoretical models of the formation and evolution of planetary systems. A number of dynamicists (including myself) have already determined that the orbital configuration of this putative system is at best marginally stable. The system's dynamical stability would improve greatly if there were no middle companion. This is noteworthy, as the observational evidence for the middle companion is weaker than that for the other two.

The Upsilon Andromedae system appears to contradict all the theorized mechanisms that would cause giant planets to migrate inward from distant birthplace orbits. If disk-protoplanet interactions caused the orbits to decay, the more massive planet would most likely be the earliest born and hence found at the shortest distance from the star—contrary to the pattern in the Upsilon Andromedae system. If only the innermost and outermost companions are real, the system could represent an example of the planet-planet scattering model in which two massive planets migrate to nearby orbits, then gravitationally scatter each other, eventually yielding one in a close, nearly circular orbit and the other in a distant, eccentric orbit. A difficulty with this scenario is that the more massive companion would be expected to evolve to the small orbit and the less massive one to the distant orbit—again, contrary to the characteristics of the Upsilon Andromedae system.

Could this system represent a hybrid case of these two scenarios—that is, orbital decay caused by disk-protoplanet interactions

order to map their orbital distribution correctly. We must also acknowledge the dangers of overinterpreting a still small data set of KBO orbits.

In short, although other explanations cannot be ruled out yet, the orbital distribution of KBOs provides increasingly strong evidence for planetary migration. The data suggest that Neptune was born about 3.3 billion kilometers from the sun and then moved about 1.2 billion kilometers outward—a journey of almost 30 percent of its present orbital radius. For Uranus, Saturn and Jupiter, the magnitude of migration was smaller, perhaps 15, 10 and 2 percent, respectively; the estimates are less certain for these planets because, unlike Neptune, they could not leave a direct imprint on the Kuiper belt population.

Most of this migration took place over a period shorter than 100 million years. That is long compared with the timescale for the formation of the planets—which most likely took less than 10 million years—but short compared with the 4.5-billion-year age of the solar system. In other words, the planetary migration occurred in the early history of the solar system but during the later stages of planet formation. The total mass of the scattered planetesimals was about three times Neptune's mass. The question arises whether even more drastic orbital changes might occur in planetary systems at earlier times, when the primordial disk of dust and gas contains more matter and perhaps many protoplanets in nearby orbits competing in the accretion process.

Other Planetary Systems?

In the early 1980s theoretical studies by Peter Goldreich and Scott Tremaine, both then at the California Institute of Technology, and others concluded that the gravitational forces between a protoplanet and the surrounding disk of gas, as well as the energy losses caused by viscous forces in a gaseous medium, could lead to very large exchanges of energy and angular momentum between the protoplanet and the disk. If the torques exerted on the protoplanet by the disk matter just inside the planet's orbit and by the matter just beyond it were slightly unbalanced, rapid and drastic changes in the planet's orbit could happen. But again, this theoretical possibility received little attention from other astronomers at the time. Having only our solar system as an example, planet formation theorists continued to assume that the planets were born in their currently observed orbits.

In the past five years, however, the search for extrasolar planets has yielded possible signs of planetary migration. By measuring the telltale wobbles of nearby stars—within 50 light-years of our solar system—astronomers have found evidence of more than a dozen Jupiter-mass companions in surprisingly small orbits around main-sequence stars. The first putative planet was detected orbiting the star 51 Pegasi in 1995 by two Swiss astronomers, Michel Mayor and Didier Queloz of the Geneva Observatory, who were actually surveying for binary stars.

in the case of the innermost object and mutual gravitational scattering for the other two companions? Perhaps entirely different formation and evolution processes are also involved, such as the fragmentation of the protostellar gas cloud that is thought to produce multiple-star systems and brown dwarf companions.

If only the innermost and outermost companions are real, the system would be architecturally similar to classic triple-stellar systems consisting of a tight binary with a distant third star in an eccentric orbit. At present, we have only speculations for the Upsilon Andromedae system. More observations and further analysis should help firm up the evidence for the number of companions and for their masses and orbital parameters.

The discovery methods employed so far are unable to detect planetary systems like our own because the stellar wobble from Earth-size planets in close orbits—or from Jupiter-size planets in more distant orbits—is below the observable threshold. Therefore, it would be premature to leap to conclusions about the astronomical frequency of Earth-like planets. Our understanding of the origin of the recently identified companions to sunlike stars is sure to evolve and thereby expand our understanding of our own solar system. *—R.M.*

Their observations were quickly confirmed by Geoffrey W. Marcy and R. Paul Butler, two American astronomers working at Lick Observatory near San Jose, Calif. As of June 1999, 20 extrasolar planetary candidates have been identified, most by Marcy and Butler, in search programs that have surveyed almost 500 nearby sunlike stars over the past 10 years. The technique used in these searches—measuring the Doppler shifts in the stars' spectral lines to determine periodic variations in stellar velocities—yields only a lower limit on the masses of the stars' companions. Most of the candidate planets have minimum masses of about one Jupiter-mass and orbital radii shorter than 0.5 AU.

What is the relationship between these objects and the planets in our solar system? According to the prevailing model of planet formation, the giant planets in our solar system coalesced in a two-step process. In the first step, solid planetesimals clumped together to form a protoplanetary core. Then this core gravitationally attracted a massive gaseous envelope from the surrounding nebula. This process must have been completed within about 10 million years of the formation of the solar nebula itself, as inferred from astronomical observations of the lifetime of protoplanetary disks around young sunlike stars.

At distances of less than 0.5 AU from a star, there is insufficient mass in the primordial disk for solid protoplanetary cores to condense. Furthermore, it is questionable whether a protoplanet in a close orbit could attract enough ambient gas to provide the massive envelope of a Jupiter-like planet. One reason is simple geometry: an object in a tight orbit travels through a smaller volume of space than one in a large orbit does. Also, the gas disk is hotter close to the star and hence less likely to condense onto a protoplanetary core. These considerations have argued against the formation of giant planets in very short-period orbits.

Instead several theorists have suggested that the putative extrasolar giant planets may have formed at distances of several AU from the star and subsequently migrated inward. Three mechanisms for planetary orbital migration are under discussion. Two involve disk-protoplanet interactions that allow planets to move long distances from their birthplaces as long as a massive disk remains.

With the disk-protoplanet interactions theorized by Goldreich and Tremaine, the planet would be virtually locked to the inward flow of gas accreting onto the protostar and might either plunge into the star or decouple from the gas when it drew close to the star. The second mechanism is interaction with a planetesimal disk rather than a gas disk: a giant planet embedded in a very massive planetesimal disk would exchange energy and angular momentum with the disk through gravitational scattering and resonant interactions, and its orbit would shrink all the way to the disk's inner edge, just a few stellar radii from the star.

The third mechanism is the scattering of large planets that either formed in or moved into orbits too close to one another for long-term stability. In this process, the outcomes would be quite unpredictable but generally would yield very eccentric orbits for both planets. In some fortuitous cases, one of the scattered planets would move to an eccentric orbit that would come so near the star at its closest approach that tidal friction would eventually circularize its orbit; the other planet, meanwhile, would be scattered to a distant eccentric orbit. All the mechanisms accommodate a broad range of final orbital radii and orbital eccentricities for the surviving planets.

These ideas are more than a simple tweak of the standard model of planet formation. They challenge the widely held expectation that protoplanetary disks around sunlike stars commonly evolve into regular planetary systems like our own. It is possible that most planets are born in unstable configurations and that subsequent planet migration can lead to quite different results in each system, depending sensitively on initial disk properties. An elucidation of the relation between the newly discovered extrasolar companions and the planets in our solar system awaits further theoretical and observational developments. Nevertheless, one thing is certain: the idea that planets can change their orbits dramatically is here to stay. SA

The Author

RENU MALHOTRA did her undergraduate studies at the Indian Institute of Technology in Delhi and received a Ph.D. in physics from Cornell University in 1988. After completing postdoctoral research at the California Institute of Technology, she moved to her current position as a staff scientist at the Lunar and Planetary Institute in Houston. In her research, she has followed her passionate interest in the dynamics and evolution of the solar system and other planetary systems. She also immensely enjoys playing with her four-year-old daughter, Mira.

Further Reading

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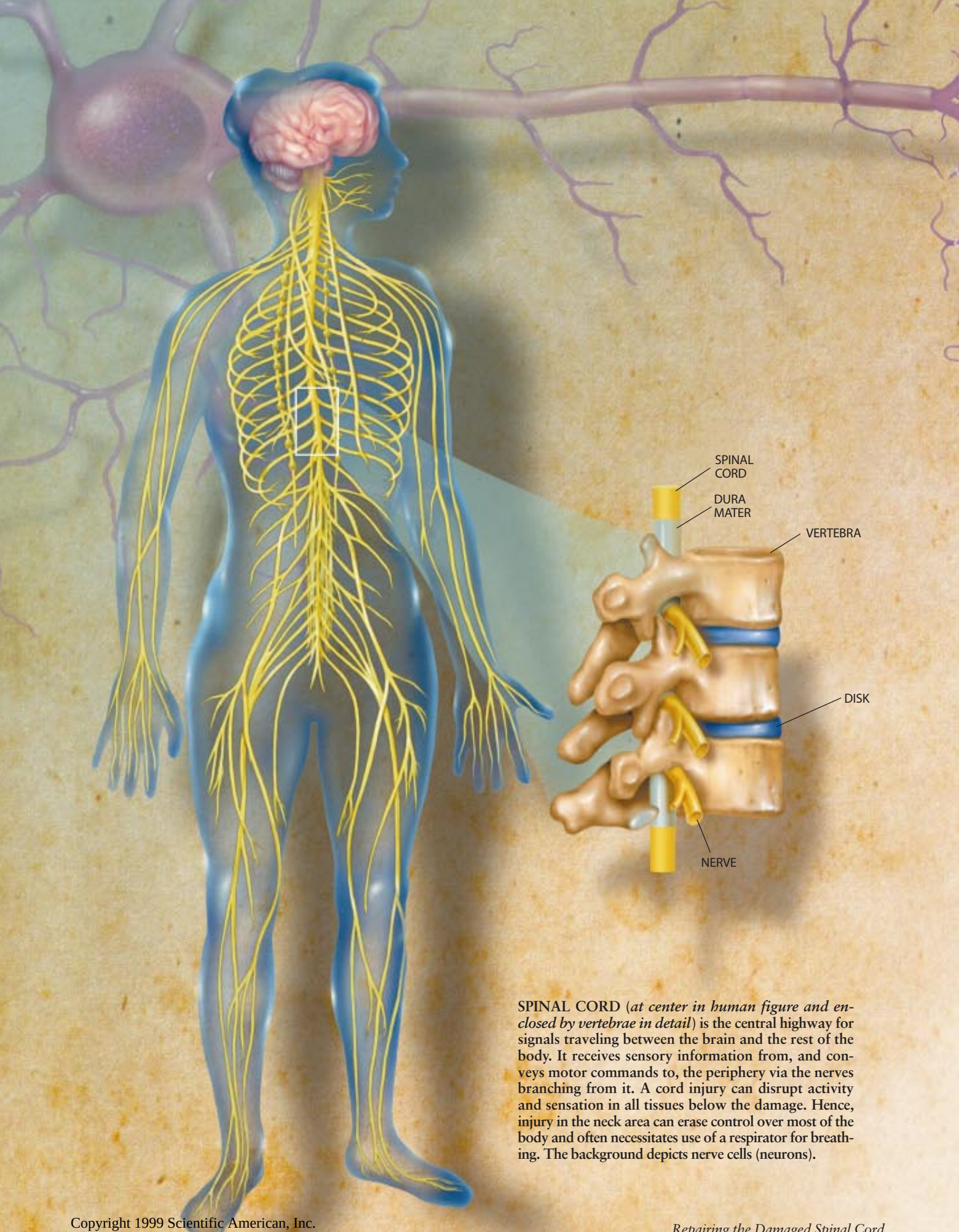
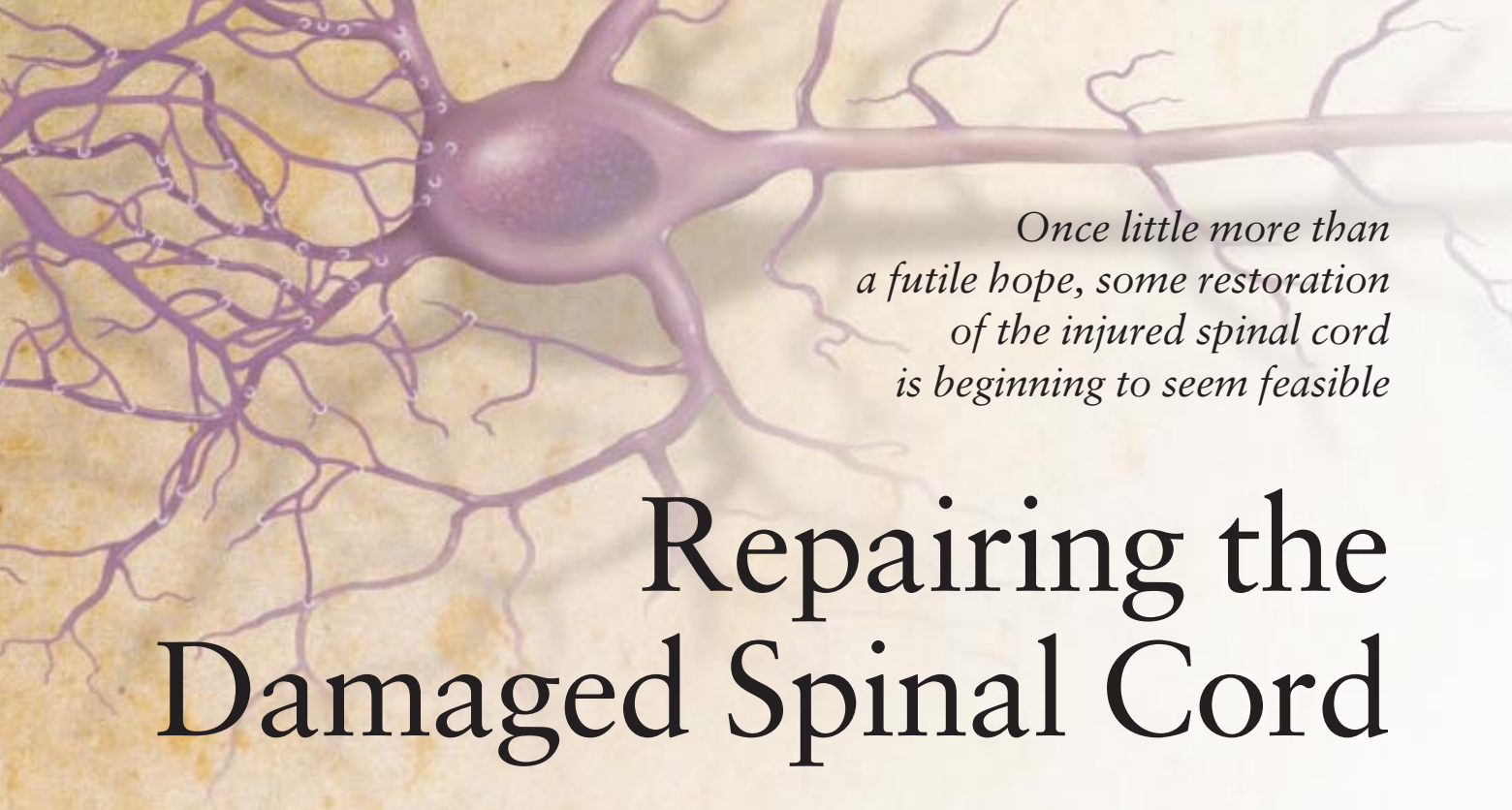


SPINAL CORD (*at center in human figure and enclosed by vertebrae in detail*) **is the central highway for signals traveling between the brain and the rest of the body. It receives sensory information from, and conveys motor commands to, the periphery via the nerves branching from it. A cord injury can disrupt activity and sensation in all tissues below the damage. Hence, injury in the neck area can erase control over most of the body and often necessitates use of a respirator for breathing. The background depicts nerve cells (neurons).**



Once little more than a futile hope, some restoration of the injured spinal cord is beginning to seem feasible

Repairing the Damaged Spinal Cord

by John W. McDonald and the Research Consortium of the Christopher Reeve Paralysis Foundation

For Chinese gymnast Sang Lan, the cause was a highly publicized headfirst fall during warm-ups for the 1998 Goodwill Games. For Richard Castaldo of Littleton, Colo., it was bullets; for onetime football player Dennis Byrd, a 1992 collision on the field; and for a child named Samantha Jennifer Reed, a fall during infancy. Whatever the cause, the outcome of severe damage to the spinal cord is too often the same: full or partial paralysis and loss of sensation below the level of the injury.

Ten years ago doctors had no way of limiting such disability, aside from stabilizing the cord to prevent added destruction, treating infections and prescribing rehabilitative therapy to maximize any remaining capabilities. Nor could they rely on the cord to heal itself. Unlike tissue in the peripheral nervous system, that in the central nervous system (the spinal cord and brain) does not repair itself effectively. Few scientists held out hope that the situation would ever change.

Then, in 1990, a human trial involving multiple research centers revealed that a steroid called methylprednisolone could preserve some motor and sensory function if it was administered at high doses within eight hours after injury. For the first time, a therapy had been proved to reduce dysfunction caused by spinal cord trauma. The improvements were modest, but the success galvanized a search for additional therapies. Since then, many investigators—including us—have sought new ideas for treatment in studies of why an initial injury triggers further damage to the spinal cord and why the disrupted tissue fails to reconstruct itself.

In this article we will explain how the rapidly burgeoning knowledge might be harnessed to help people with spinal cord injuries. We should note, however, that workers have also been devising strategies that compensate for cord damage instead of repairing it. In the past two years, for example, the U.S. Food and Drug Administration has approved two electronic systems that regulate muscles by sending electrical signals through implanted wires. One returns certain hand movements (such as grasping a cup or a pen) to patients who have shoulder mobility; another restores a measure of control over the bladder and bowel [*see box on pages 72 and 73*].

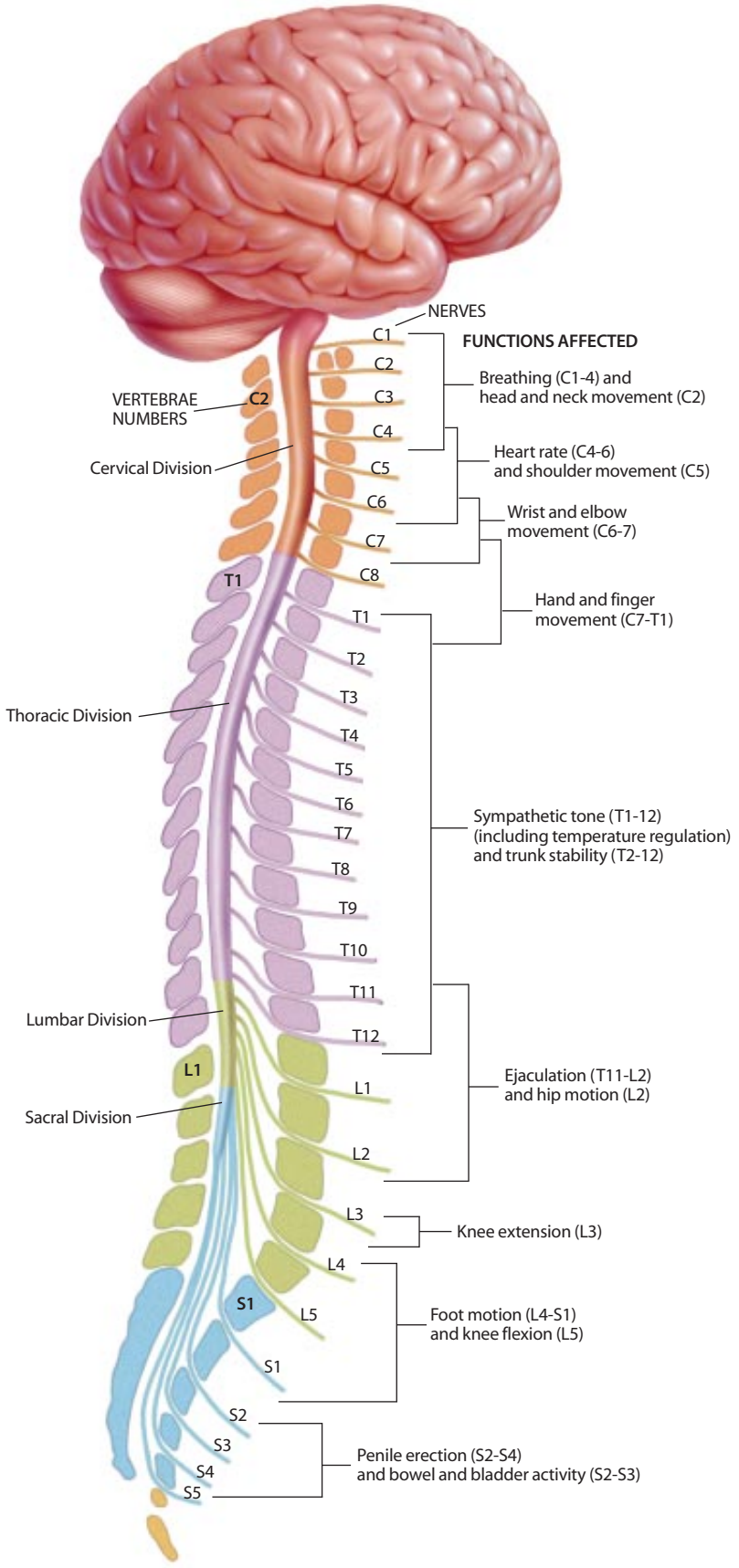
A different approach can also provide grasping ability to certain patients. Surgeons identify tendons that link paralyzed forearm muscles to the bones of the hand, disconnect them from those muscles and connect them to arm muscles regulated by parts of the spine above the injury (and thus still under voluntary control). Further, many clinicians suspect that initiating rehabilitative therapy early—exercising the limbs almost as soon as the spine is stabilized—may enhance motor and sensory function in limbs. Those perceptions have not been tested rigorously in people, but animal studies lend credence to them.

The Cord at Work

The organ receiving all this attention is no thicker than an inch but is the critical highway of communication between the brain and the rest of the body. The units of communication are the nerve cells (neurons), which consist of a bulbous cell body (home to the nucleus), trees of signal-detecting dendrites, and an axon that extends from the cell body and carries signals to other cells. Axons branch toward their ends and can maintain connections, or synapses, with many cells at once. Some traverse the entire length of the cord.

The soft, jellylike cord has two major systems of neurons. Of these, the descending, motor pathways control both smooth

ALEXANDER AND TURNER STUDIO



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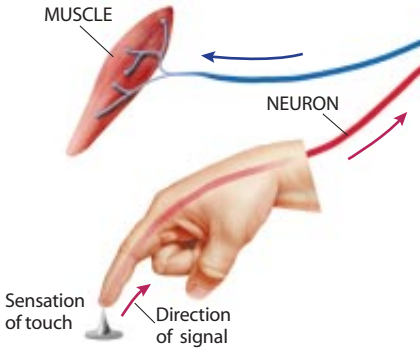
FOUR DIVISIONS of the spinal cord and their associated nerves serve specific areas of the body. In general, the cervical nerves link to the neck, the arms and the respiratory apparatus; the thoracic nerves control posture and many internal organs; the lumbar nerves work the legs; and the sacral nerves regulate the bladder and the bowel and play a role in sexual function.

muscles of internal organs and striated muscles; they also help to modulate the actions of the autonomic nervous system, which regulates blood pressure, temperature and the body's circulatory response to stress. The descending pathways begin with neurons in the brain, which send electrical signals to specific levels, or segments, of the cord. Neurons in those segments then convey the impulses outward beyond the cord.

The other main system of neurons—the ascending, sensory pathways—transmit sensory signals received from the extremities and organs to specific segments of the cord and then up to the brain. Those signals originate with specialized, "transducer" cells, such as sensors in the skin that detect changes in the environment or cells that monitor the state of internal organs. The cord also contains neuronal circuits (such as those involved in reflexes and certain aspects of walking) that can be activated by incoming sensory signals without input from the brain, although they can be influenced by messages from the brain.

The cell bodies in the trunk of the cord reside in a gray, butterfly-shaped core that spans the length of the spinal cord. The ascending and descending axonal fibers travel in a surrounding area known as the white matter, so called because the axons are wrapped in myelin, a white insulating material. Both regions also house glial cells, which help neurons to survive and work properly. The glia include star-shaped astrocytes, microglia (small cells that resemble components of the immune system) and oligodendrocytes, the myelin producers. Each oligodendrocyte myelinates as many as 40 different axons simultaneously.



The precise nature of a spinal cord injury can vary from person to person. Nevertheless, certain commonalities can be discerned.

When Injury Strikes

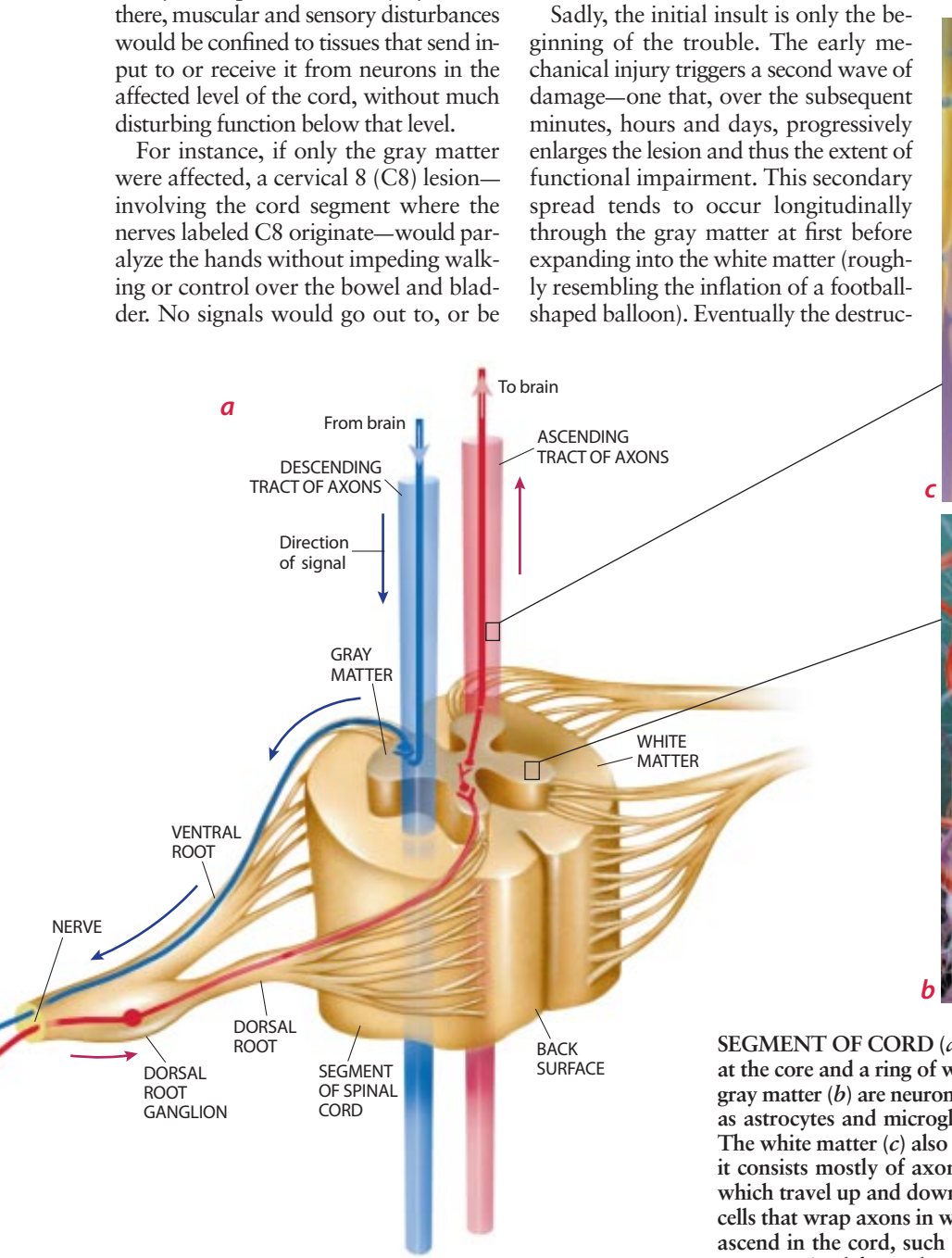
When a fall or some other force fractures or dislocates the spinal column, the vertebral bones that normally enclose and protect the cord can crush it, mechanically killing and damaging axons. Occasionally, only the gray matter in the damaged area is significantly disrupted. If the injury ended there, muscular and sensory disturbances would be confined to tissues that send input to or receive it from neurons in the affected level of the cord, without much disturbing function below that level.

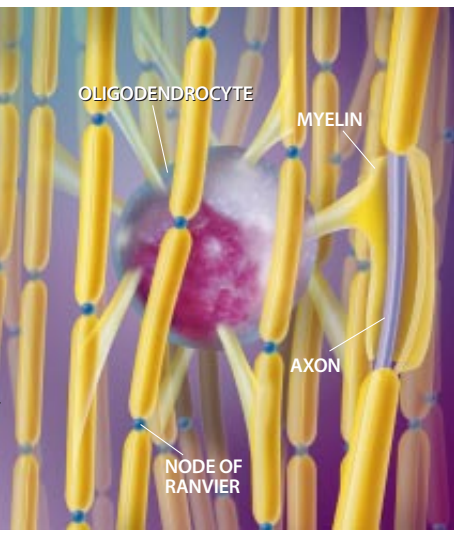
For instance, if only the gray matter were affected, a cervical 8 (C8) lesion—involving the cord segment where the nerves labeled C8 originate—would paralyze the hands without impeding walking or control over the bowel and bladder. No signals would go out to, or be received from, the tissues connected to the C8 nerves, but the axons conveying signals up and down the surrounding white matter would keep working.

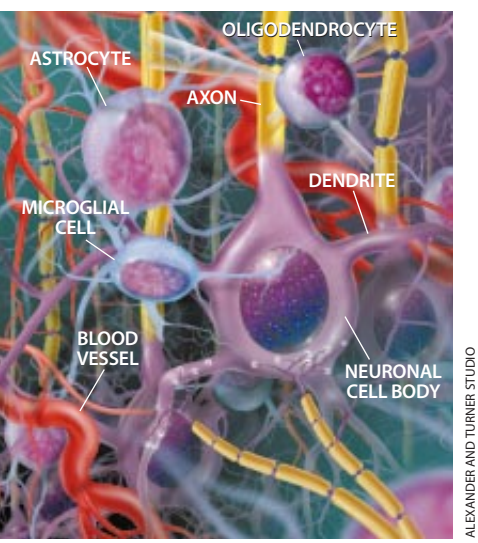
In contrast, if all the white matter in the same cord segment were destroyed, the injury would now interrupt the vertical signals, stopping messages that originated in the brain from traveling below the damaged area and blocking the flow to the brain of sensory signals coming from below the wound. The person would become paralyzed in the hands and lower limbs and would lose control over urination and defecation.

Sadly, the initial insult is only the beginning of the trouble. The early mechanical injury triggers a second wave of damage—one that, over the subsequent minutes, hours and days, progressively enlarges the lesion and thus the extent of functional impairment. This secondary spread tends to occur longitudinally through the gray matter at first before expanding into the white matter (roughly resembling the inflation of a football-shaped balloon). Eventually the destruction can encompass several spinal segments above and below the original wound.

The end result is a complex state of disrepair. Axons that have been damaged become useless stumps, connected to nothing, and their severed terminals disintegrate. Often many axons remain intact but are rendered useless by loss of their insulating myelin. A fluid-filled cavity, or cyst, sits where neurons, other cells and axons used to be. And glial cells proliferate abnormally, creating clusters termed glial scars. Together the cyst and







ALEXANDER AND TURNER STUDIO

SEGMENT OF CORD (*a*) reveals the butterfly-shaped gray matter at the core and a ring of white matter. The main components of the gray matter (*b*) are neuronal cell bodies, but so-called glial cells (such as astrocytes and microglia) and blood vessels are present as well. The white matter (*c*) also contains astrocytes and blood vessels, but it consists mostly of axons (signal-carrying neuronal projections), which travel up and down the cord, and of oligodendrocytes—glial cells that wrap axons in white, insulating myelin. Axonal tracts that ascend in the cord, such as the red one in *a*, convey sensory messages received from elsewhere in the body; the descending tracts, such as that shaded blue, carry motor commands to muscles.

Targets for Therapy

A spinal injury often affects a small area at first, but it triggers secondary processes that expand the destruction. Many axons then end up either cut or partly shorn of their insulating myelin and unable to propagate signals past the affected areas (*diagram*).

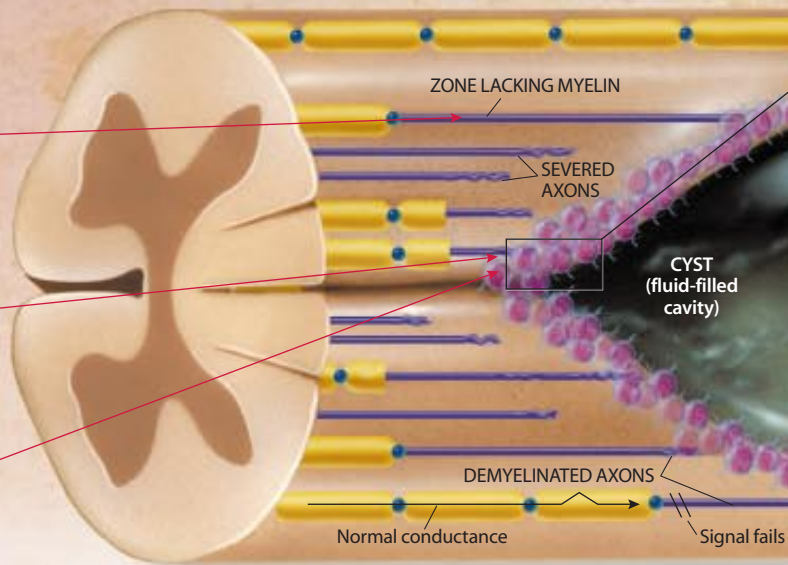
Axons normally do not regrow or become adequately remyelinated. But even if they did, they would still meet critical barriers to full repair. One is an impenetrable, fluid-filled cavity—a cyst—that forms where cells have died and axons have been cut away. This cyst is often surrounded by glial "scars"—clusters of activated glial cells that are physically penetrable but release or display substances that inhibit axonal growth. In many people, only a small fraction of axons at the periphery of the cord remain in service.

Eventually therapy is likely to include a combination of several treatments, such as those listed below. Most treatments would be delivered directly into the injured area. Limiting destruction will be easier than repairing it. And once the damage is established, compensating for demyelination will be easier than coaxing axons to regrow and to form appropriate synapses. *—J.W. McD.*

COMPENSATE FOR DEMYELINATION
- Supply chemicals that prevent nerve impulses from dissipating at demyelinated areas
- Provide agents that spur surviving oligodendrocytes to remyelinate axons
- Replenish lost oligodendrocytes (see "Replace Dead Cells" box on next page)

PROMOTE AXONAL REGENERATION
- Deliver agents that overcome natural inhibitors of regeneration
- Administer compounds that induce axonal regrowth

DIRECT AXONS TO PROPER TARGETS
- Somehow supply needed guidance molecules at the right sites
- Administer compounds that induce surviving cells to produce or display guidance molecules



ALEXANDER AND TURNER STUDIO

scars pose a formidable barrier to any cut axons that might somehow try to regrow and connect to cells they once innervated. A few axons may remain whole, myelinated and able to carry signals up or down the spine, but often their numbers are too small to convey useful directives to the brain or muscles.

First, Contain the Damage

If all these changes had to be fully reversed to help patients, the prospects for new treatments would be grim. Fortunately, it appears that salvaging normal activity in as little as 10 percent of the standard axon complement would sometimes make walking possible for people who would otherwise lack that capacity. In addition, lowering the level of injury by just a single segment (about half an inch) can make an important difference to a person's quality of life. People with a C6 injury have no power over their arms, save some ability to move their shoulders and flex their elbows. But individuals with a lower, C7 injury can move the shoulders and elbow joints and extend the wrists; with training and sometimes a tendon transfer, they can make some use of their arms and hands.

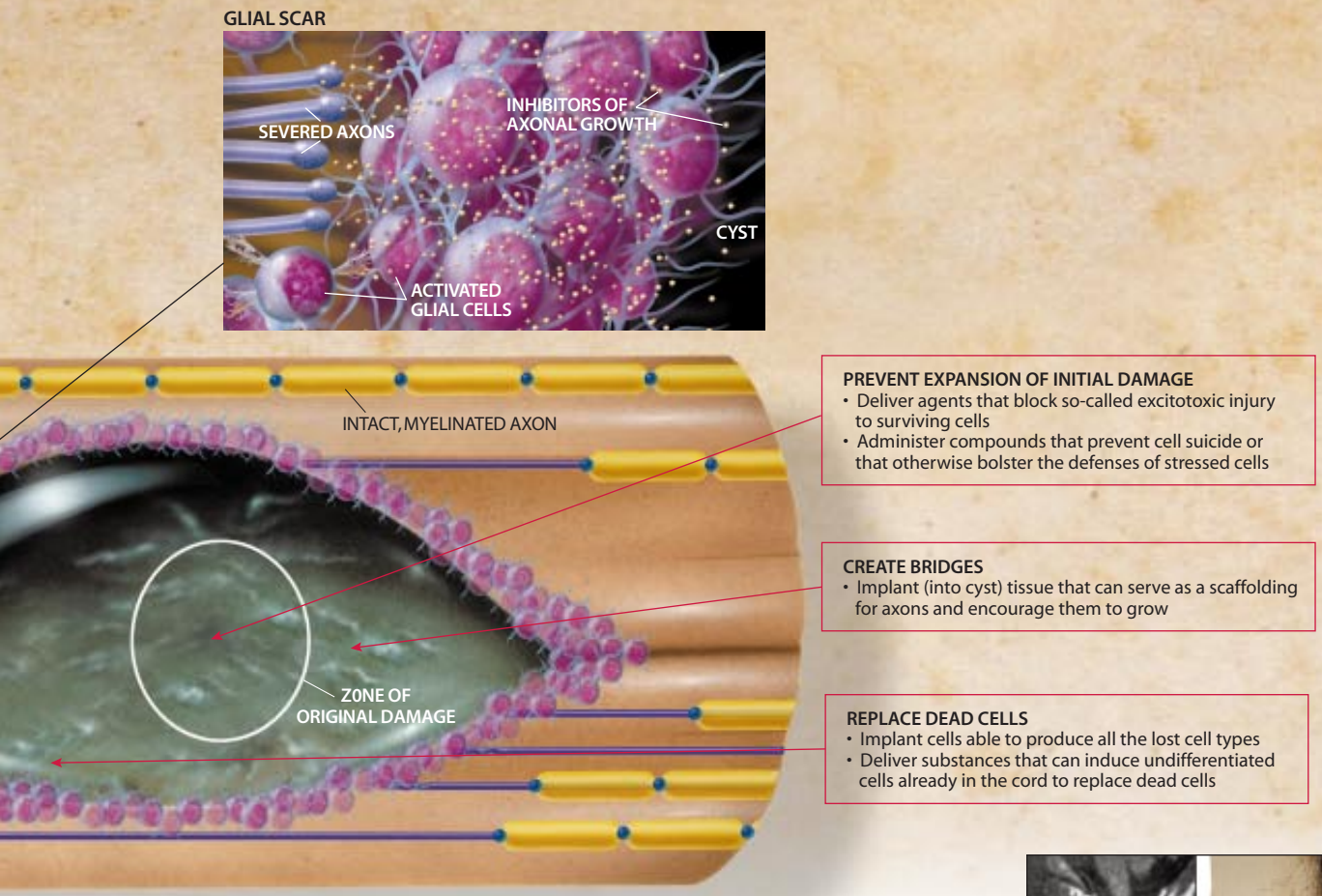
Because so much damage arises after the initial injury, clarifying how that secondary destruction occurs and blocking those processes are critical. The added wreckage has been found to result from many interacting mechanisms.

Within minutes of the trauma, small hemorrhages from broken blood vessels appear, and the spinal cord swells. The blood vessel damage and swelling prevent the normal delivery of nutrients and oxygen to cells, causing many of them to starve to death.

Meanwhile damaged cells, axons and blood vessels release toxic chemicals that go to work on intact neighboring cells. One of these chemicals in particular triggers a highly disruptive process known as excitotoxicity. In the healthy cord the end tips of many axons secrete minute amounts of glutamate. When this chemical binds to receptors on target neurons, it stimulates those cells to fire impulses. But when spinal neurons, axons or astrocytes are injured, they release a flood of glutamate. The high levels overexcite neighboring neurons, inducing them to admit waves of ions that then trigger a series of destructive events in the cells—including production of free radicals. These highly reactive molecules can attack membranes and other components of formerly healthy neurons and kill them.

Until about a year ago, such excitotoxicity, also seen after a stroke, was thought to be lethal to neurons alone, but new results suggest it kills oligodendrocytes (the myelin producers) as well. This effect may help explain why even unsevered axons become demyelinated, and thus unable to conduct impulses, after spinal cord trauma.

Prolonged inflammation, marked by an influx of certain immune system cells, can exacerbate these effects and last for days. Normally, immune cells stay in the blood, unable to enter tissues of the central nervous system. But they can flow in readily where blood vessels are dam-



V. DIETZ *Balchrist Hospital, Zurich (left);* CHRISTIAN BROESAMLE *University of Zurich (right)*

CYST can be seen in images of injured spinal cords. The cavity that formed in a person hurt in the neck (*left*) appears as a darkened area (*boxed*). That in a rat (*right*) is outlined by dots; damaged axons that inappropriately terminate outside the cyst (*dark lines*) are also visible.

aged. As they and microglia become activated in response to an injury, the activated cells release still more free radicals and other toxic substances.

Methylprednisolone, the first drug found to limit spinal cord damage in humans, may act in part by reducing swelling, inflammation, the release of glutamate and the accumulation of free radicals. The precise details of how it helps patients remain unclear, however.

Studies of laboratory animals with damaged spinal cords indicate that drugs able to stop cells from responding to excess glutamate could minimize destruction as well. Agents that selectively block glutamate receptors of the so-called AMPA class, a kind abundant on oligodendrocytes and neurons, seem to be particularly effective at limiting the final extent of a lesion and the related disability. Certain AMPA receptor antagonists have already been tested in early human trials as a therapy for stroke, and related compounds could enter safety studies in patients with spinal cord injury within several years.

Much of the early cell loss in the injured spinal cord occurs by necrosis, a process in which cells essentially become passive victims of murder. In the past few years, neurobiologists have also documented a more active form of cell death, somewhat akin to suicide, in the cord. Days or weeks after the initial trauma, a wave of this cell suicide, or apoptosis, frequently sweeps through oligodendrocytes as many as four segments from the trauma site. This discovery, too, has opened new doors for protective therapy. Rats given apoptosis-inhibiting drugs retained more ambulatory ability after a traumatic spinal cord injury than did untreated rats.

In the past few years, biologists have identified many substances, called neurotrophic factors, that also promote neuronal and glial cell survival. A related substance, GM-1 ganglioside (Sygen), is now being evaluated for limiting cord injury in humans. Ultimately, interventions for reducing secondary damage in the spinal cord will probably enlist a variety of drugs given at different times to thwart specific mechanisms of death in distinct cell populations.

The best therapy would not only reduce the extent of an injury but also repair damage. A key component of that repair would be stimulating the regeneration of damaged axons—that is, inducing their elongation and reconnection with appropriate target cells.

Although neurons in the central nervous system of adult mammals general-

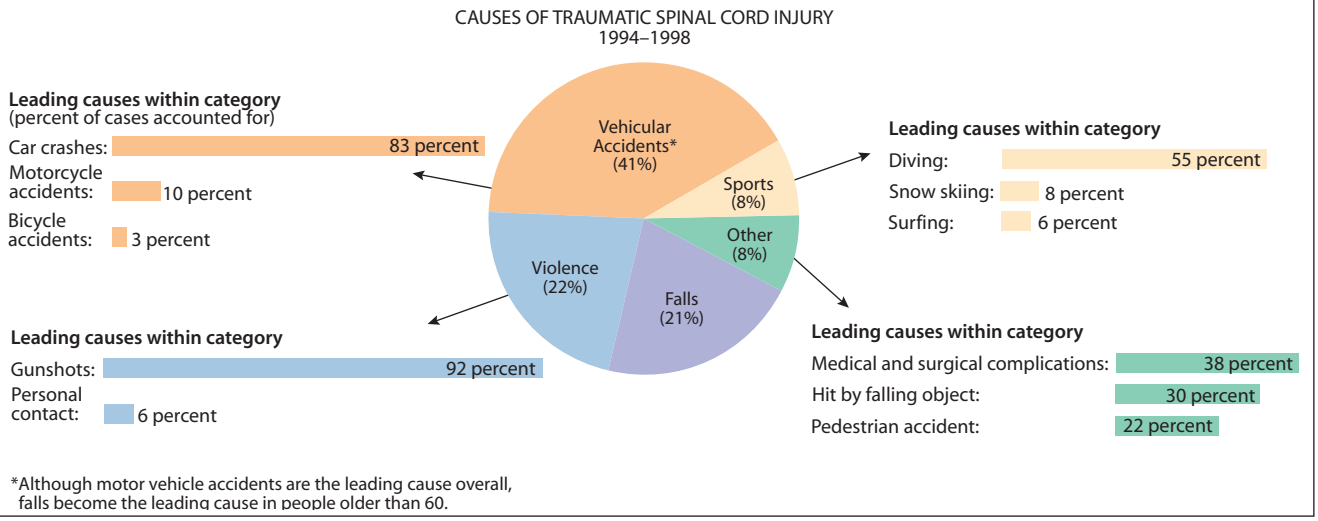
What the Numbers Say

The National Spinal Cord Injury Statistical Center, based at the University of Alabama at Birmingham, provided the U.S. figures shown here, which relate to spinal cord injuries (SCI) caused by a sudden trauma. Others estimate that acute trauma accounts for about half of cases of spinal cord damage. Causes of nontraumatic damage include such disorders as multiple sclerosis, tumors and infections (for example, tuberculosis). —*J.W.McD.*

U.S. incidence: approximately 10,000 new cases a year, 80 percent in males

U.S. prevalence: an estimated 183,000 to 230,000 are living with trauma-related SCI

Age group most commonly injured: 16–30 years (43 percent), followed by 31–45 years (28 percent)



*Although motor vehicle accidents are the leading cause overall, falls become the leading cause in people older than 60.

HEIDI NOLAND

ly fail to regenerate damaged axons, this lapse does not stem from an intrinsic property of those cells. Rather the fault lies with shortcomings in their environment. After all, neurons elsewhere in the body and in the immature spinal cord and brain regrow axons readily, and animal experiments have shown that the right environment can induce axons of the spinal cord to extend quite far.

Then, Induce Regeneration

One shortcoming of the cord environment turns out to be an overabundance of molecules that actively inhibit axonal regeneration—some of them in myelin. The scientists who discovered these myelin-related inhibitors have produced a molecule named IN-1 (inhibitor-neutralizing antibody) that blocks the action of those inhibitors. They have also demonstrated that infusion of mouse-derived IN-1 into the injured rat spinal cord can lead to long-distance regrowth of some interrupted axons. And when pathways controlling front paw activity are severed, treated animals regain some paw motion, whereas untreated animals do not. The rodent antibody would be destroyed by the human immune system, but workers are developing a humanized version for testing in people.

Many other inhibitory molecules have now been found as well, including some produced by astrocytes and a number that reside in the extracellular matrix (the scaffolding between cells). Given this array, it seems likely that combination therapies will be needed to counteract or shut down the production of multiple inhibitors at once.

Beyond removing the "brakes" on axonal regrowth, a powerful tactic would supply substances that actively promote axonal extension. The search for such factors began with studies of nervous system development. Decades ago scientists isolated nerve growth factor (NGF), a neurotrophic factor that supports the survival and development of the peripheral nervous system. Subsequently, this factor turned out to be part of a family of proteins that both enhance neuronal survival and favor the outgrowth of axons. Many other families of neurotrophic factors with similar talents have been identified as well. For instance, the molecule neurotrophin-3 (NT-3) selectively encourages the growth of axons that descend into the spinal cord from the brain.

Luckily, adult neurons remain able to respond to axon-regenerating signals from such factors. Obviously, however, natural production of these substances falls far short of the amount needed for spinal cord repair. Indeed, manufacture of some of the compounds apparently declines, instead of rising, for weeks after a spinal trauma occurs. According to a host of animal studies, artificially raising those levels after an injury can enhance regeneration. Some regeneration-promoting neurotrophic factors, such as basic fibroblast growth factor, have been tested in stroke patients. None has been evaluated as an aid to regeneration in people with spinal cord damage, but many are being assessed in animals as a prelude to such studies.

Those considering neurotrophic factors for therapy will have to be sure that the agents do not increase pain, a common long-term complication of spinal cord injury. This pain has many causes, but one is the sprouting of nascent axons where they do not belong (perhaps in a failed attempt to address the injury) and their inappropriate connection to other cells. The brain sometimes misinterprets impulses traveling through those axons as pain signals. Neurotrophic factors can theoretically exacerbate that problem and can also cause pain circuits in the spiral cord and pain-sensing cells in the skin to become oversensitive.

After axons start growing, they will have to be guided to their proper targets, the cells to which they were originally wired. But how? In this case, too,

studies of embryonic development have offered clues.

During development, growing axons are led to their eventual targets by molecules that act on the leading tip, or growth cone. In the past five years especially, a startling number of substances that participate in this process have been uncovered. Some, such as a group called netrins, are released or displayed by neurons or glial cells. They beckon axons to grow in some directions and repel growth in others. Additional guidance molecules are fixed components of the extracellular matrix. Certain of the matrix molecules bind well to specific molecules (cell adhesion molecules) on the growth cones and thus provide anchors for growing axons. During development, the required directional molecules are presented to the growth cones in specific sequences.

Establish Proper Connections

At the moment, no one knows how to supply all the needed chemical road signs in the right places. But some findings suggest that regeneration may be aided by supplying just a subset of those targeting molecules—say, a selection of netrins and components from the extracellular matrix. Substances already in the spinal cord may well be capable of supplying the rest of the needed guidance.

A different targeting approach aims to bridge the gap created by cord damage. It directs injured axons toward their proper destinations by supplying a conduit through which they can travel or by providing another friendly scaffolding able to give physical support to the fibers as they try to traverse the normally impenetrable cyst. The scaffolding can also serve as a source of growth-promoting chemicals.

For instance, researchers have implanted tubes packed with Schwann cells into the gap where part of the spinal cord was removed in rodents. Schwann cells, which are glia of the peripheral nervous system, were chosen because they have many attributes that favor axonal regeneration. In animal experiments, such grafts spurred some axonal growth into the tubes.

A second bridging material consists of olfactory-ensheathing glial cells, which are found only in the tracts leading from the nose to the olfactory bulbs of the brain. When those cells were put into the rat spinal cord where descending tracts had been cut, the implants spurred partial regrowth of the axons over the implant. Transplanting the olfactory-ensheathing glia with Schwann cells led to still more extensive growth.

In theory, a biopsy could be performed to obtain the needed olfactory ensheathing glia from a patient. But once the properties that enable them (or other cells) to be competent escorts for growing axons are determined, researchers may instead be able to genetically alter other cell types if desired, giving them the required combinations of growth-promoting properties.

Fibroblasts (cells common in connective tissue and the skin) are among those already being engineered to serve as bridges. They have been altered to produce the neurotrophic molecule NT-3 and then transplanted into the cut spinal cord of rodents. The altered fibroblasts have resulted in partial regrowth of axons. Along with encouraging axonal regrowth, NT-3 stimulates remyelination. In these studies the genetically altered fibroblasts have enhanced myelination of regenerated axons and improved hind limb activity.

Replace Lost Cells

Other transplantation schemes would implant cells that normally occur in the central nervous system. In addition to serving as bridges and potentially releasing proteins helpful for axonal regeneration, certain of these grafts might be able to replace cells that have died.

Transplantation of tissue from the fetal central nervous system has produced a number of exciting results in animals treated soon after a trauma. This immature tissue can give rise to new neurons, complete with axons that travel long distances into the recipient's tissues (up and down several segments in the spinal cord or out to the periphery). It can also prompt host neurons to send regenerating axons into the implanted tissue. In addition, transplant recipients, unlike untreated animals, may recover some limb function, such as the ability to move the paw in useful ways. What is more, studies of fetal tissue implants suggest that axons can at times find appropriate targets even in the absence of externally supplied guidance molecules. The transplants, however, are far more effective in the immature spinal cord than in the injured adult cord—an indication that young children would probably respond to such therapy much better than adolescents or adults would.

Some patients with long-term spinal cord injuries have received human fetal

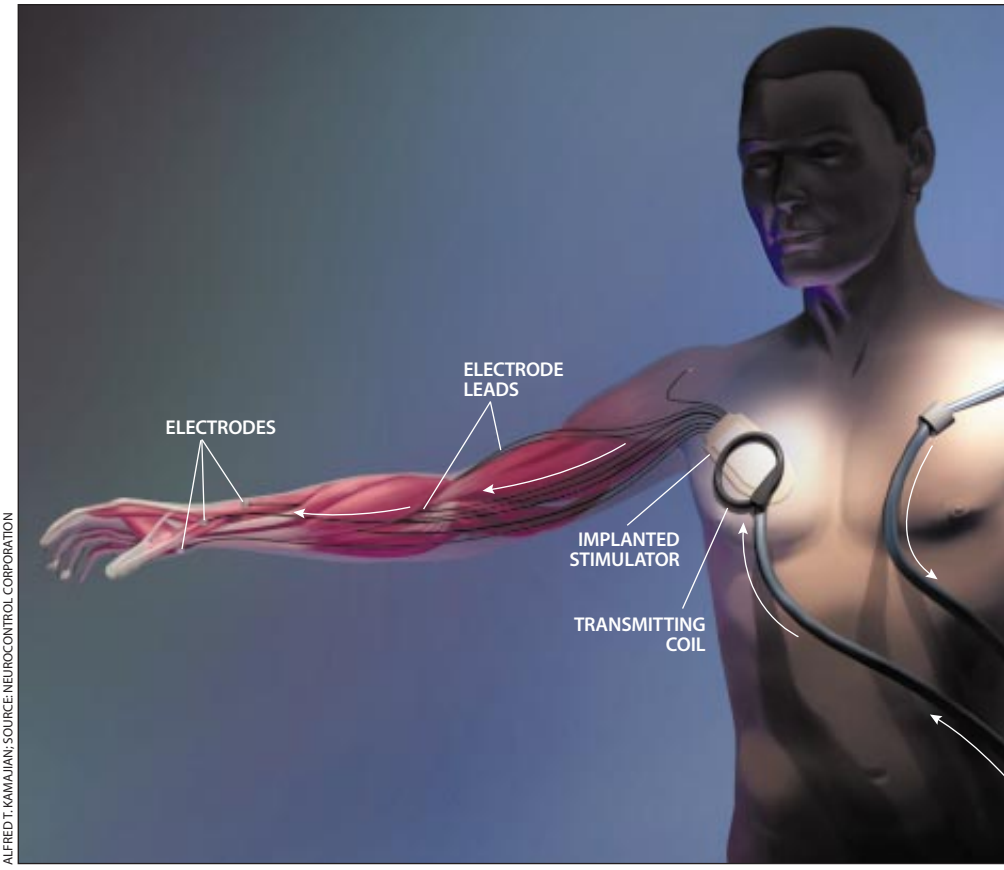
BILL HICKEY *Allsport*

DAVID DRAPKIN *NFL Photos*

DENNIS BYRD sustained an incomplete spinal cord injury near the base of his neck in a collision with a teammate during a football game in 1992, when he was with the New York Jets (*bottom*). Today (*top*) he walks with a limp. His recovery may well have been aided by the prompt administration of methylprednisolone, still the only drug proved to help limit an injury. He also received an experimental agent (Sygen) of unknown value.

tissue transplants, but too little information is available so far for drawing any conclusions. In any case, application of fetal tissue technology in humans will almost surely be limited by ethical dilemmas and a lack of donor tissue. Therefore, other ways of achieving the same results will have to be devised. Among the alternatives is transplanting stem cells: immature cells that are capable of dividing endlessly, of making exact replicas of themselves and also of spawning a range of more specialized cell types.

Various kinds of stem cells have been identified, including ones that generate all the cell types in the blood system, the skin, or the spinal cord and brain. Stem cells found in the human adult central nervous system have, moreover, been shown capable of producing neurons and all their accompanying glia, although these so-called neural stem cells seem to be quiescent in most regions of the system. In 1998 a few laboratories also obtained much more versatile stem cells from human tissue. These human embryonic stem cells (in common with embryonic stem cells obtained previously from other vertebrates) can be grown in culture and, in theory, can yield almost all the cell types in the body, including those of the spinal cord.



ALFRED T. KAMAJIAN; SOURCE: NEUROCONTROL CORPORATION

Stem Cell Strategies

How might stem cells aid in spinal cord repair? A great deal will be possible once biologists learn how to obtain those cells readily from a patient and how to control the cells' differentiation. Notably, physicians might be able to withdraw neural stem cells from a patient's brain or spinal cord, expand the numbers of the still undifferentiated cells in the laboratory and place the enlarged population in the same person's cord with no fear that the immune system will reject the implant as foreign. Or they might begin with frozen human embryonic stem cells, coax those cells to become precursors, or progenitors, of spinal cells and implant a large population of the precursors. Studies proposing to examine the effects on patients with spinal cord injuries of transplanting neural stem cells (isolated from the patients' brains by biopsy) are being considered.

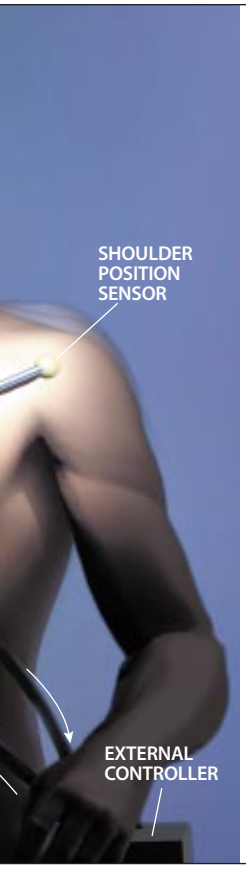
Simply implanting progenitor cells into the cord may be enough to prod them to multiply and differentiate into the needed lineages and thus to replace useful numbers of lost neurons and glial cells and establish the proper synaptic connections between neurons. Stem cells transplanted into the normal and injured nervous systems of animals can form neurons and glia appropriate for the region of transplantation. Combined with the fetal tissue results, this outcome signifies that many important cues for differentiation and targeting preexist in the injured nervous system. But if extra help is needed, scientists might be able to deliver it through genetic engineering. As a rule, to be genetically altered easily, cells have to be able to divide. Stem cells, unlike mature neurons, fit that bill.

Scenarios involving stem cell transplants are admittedly futuristic, but one day they themselves may become unnecessary, replaced by gene therapy alone. Delivery of genes into surviving cells in the spinal cord could enable those cells to manufacture and release a steady supply of proteins able to induce stem cell proliferation, to enhance cell differentiation and survival, and to promote axonal regeneration, guidance and remyelination. For now, though, technology for delivering genes to the central nervous system and for ensuring that the genes survive and work properly is still being refined.

Until, and even after, cell transplants and gene therapies become commonplace for coping with spinal cord injury, patients might gain help through a different avenue—drugs that restore signal conduction in axons quieted by demyelination. Ongoing clinical tests are evaluating the ability of a drug called 4-aminopyridine to compensate for demyelination. This agent temporarily blocks potassium ion channels in axonal membranes and, in so doing, allows axons to transmit electrical signals past zones of demyelination. Some patients receiving the drug have demonstrated modest improvement in sensory or motor function.

At first glance, this therapy might seem like a good way to treat multiple sclerosis, which destroys the myelin around axons of neurons in the central nervous system. Patients with this disease are prone to seizures, however, and 4-aminopyridine can exacerbate that tendency.

Neurotrophic factors, such as NT-3, that can stimulate remyelination of axons in animals could be considered for therapy as well. NT-3 is already entering extensive (phase III) trials in humans with spinal cord injury, though not to restore myelin. It will be administered by injection in amounts capable of acting on nerves in the gut and of enhancing bowel function, but the doses will be



Advances in Electronics

What if implanted electrodes could stimulate nerves quieted by spinal cord injury and thereby restore function to certain paralyzed muscles? In fact, such devices already exist, and two meant to increase independence have recently gained the approbation of the U.S. Food and Drug Administration. One enables certain people who retain shoulder mobility to use a hand (*illustration*). Particular movements by the opposite shoulder activate a detector that sends signals to an external control unit. That unit, in turn, relays the signals to an implanted transmitting coil connected to wires that terminate on selected arm and hand muscles.

The other device, long used in England before being tested in the U.S., aims primarily to enable people to urinate on demand. An external transmitter activates an implanted pacemakerlike device that sends electrical signals to nerves feeding into the bladder. In response, the bladder and its sphincter contract, after which the sphincter relaxes, enabling the bladder to empty. The system also stimulates the nerves to the bowel and aids in its evacuation.

Other electrical devices that are available or under study include systems that allow people to stand (for easier transfer between, say, a wheelchair and a bed or toilet), exercise the heart and lungs, assist breathing, induce coughing, improve circulation or reduce spasticity. —*Ricki L. Rusting,* staff writer

too low to yield high concentrations in the central nervous system. If the drug proves to be safe in this trial, though, that success could pave the way for human tests of doses large enough to enhance myelination or regeneration.

The Years Ahead

Clearly, the 1990s have seen impressive advances in understanding of spinal cord injury and the controls on neuronal growth. Like axons inching toward their targets, a growing number of investigators are pushing their way through the envelope of discovery and generating a rational game plan for treating such damage. That approach will involve delivery of multiple therapies in an orderly sequence. Some treatments will combat secondary injury, some will encourage axonal regrowth or remyelination, and some will replace lost cells.

When will the new ideas become real treatments? We wish we had an answer. Drugs that work well in animals do not always prove useful in people, and those that show promise in small human trials do not always pan out when examined more extensively. It is nonetheless encouraging that at least two human trials are now under way and that others could start in the next several years.

Limiting an injury will be easier than reversing it, and so treatments for ameliorating the secondary damage that follows acute trauma can be expected to enter human testing most quickly. Of the repair strategies, promoting remyelination will be the simplest to accomplish, because all it demands is the recoating of intact axons. Remyelination strategies have the potential to produce meaningful recovery of function, such as returning control over the bladder or bowel—abilities that uninjured people take for granted but that would mean the world to those with spinal cord injuries.

Of course, tendon-transfer surgery and advanced electrical devices can already restore important functions in some patients. Yet for many people, a return of independence in daily activities will depend on reconstruction of damaged tissue through the regrowth of injured axons and the reconnection of disrupted pathways.

So far, few interventions in animals with well-established spinal cord injuries have achieved the magnitude of regrowth and synapse formation that would be needed to provide a hand grasp or the ability to stand and walk in human adults with long-term damage. Because of the great complexities and difficulties involved in those aspects of cord repair, we cannot guess when reconstructive therapies might begin to become available. But we anticipate continued progress toward that end.

Traditionally, medical care for patients with spinal cord injury has emphasized compensatory strategies that maximize use of any residual cord function. That focus is now expanding, as treatments designed to repair the damaged cord and restore lost function—science fiction only a decade ago—are becoming increasingly plausible. SA

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A Case against Virtual Nuclear Testing

The U.S. Department of Energy's high-tech plan to replace nuclear testing with elaborate 3-D computer simulations is seriously flawed

by Christopher E. Paine

In August 1945 the world's first military use of atomic bombs swiftly killed 210,000 people in the Japanese cities of Hiroshima and Nagasaki. In the ensuing decades, humanity's concentration into megacities and the vastly increased power of thermonuclear weapons have elevated the lethality of a single act of atomic violence by roughly two orders of magnitude. Today one or two nuclear weapons detonated over Bombay or Tokyo could instantly annihilate some 15 million people.

With the end of the cold war, many nations came together to negotiate a treaty permanently banning nuclear explosions worldwide. By barring explosive tests, the Comprehensive Test Ban Treaty severely constrains the way nations have traditionally evaluated changes in bomb designs and confirmed the performance of weapons to be stockpiled for military use. A ban on test explosions cannot alone prevent the spread of nuclear weapons, but it does pose a significant barrier to the development of weapons that rely on fusion reactions, including lighter, more compact and more powerful missile-borne nuclear warhead designs, such as those China has allegedly acquired from the U.S. through espionage and intelligence-gathering.

Despite the test ban treaty's promise for curtailing nuclear competition among the major powers and the spread of more lethal nuclear arms to additional states, the U.S., Russia, China, India and other nuclear-capable nations have yet to ratify it. Like-minded industrial democracies—including Canada, Germany, Australia, Japan, France and the U.K.—have already done so, leaving the U.S. to lead the battle against nuclear proliferation from the rear. Countries that have ratified the treaty are scheduled to review ways to accelerate its entry into force at a conference in October. But without prior ratification by the U.S., the conference is unlikely to achieve its aim.

Although the U.S. national security establishment under President Bill Clinton's leadership is willing to contemplate a future without nuclear test explosions, it is not willing to do so without improved nuclear weapons. To ensure that the nuclear stockpile can be assessed and modified by other means, both the administration and the Republican majority in Congress have strongly supported a program known as the science-based stockpile stewardship and management program. The program seeks to meld state-of-the-art supercomputing and large-scale laboratory experiments into an unprecedented capacity for detailed, three-dimensional simulations of nuclear explosions.

Aggressive Technology

A congressional directive buried in a defense spending bill gave birth to the stewardship effort in 1993. Managed by the Department of Energy's Office of Defense Programs, stockpile stewardship by 1995 had mushroomed into a massive 15-year, $67-billion program, nearly three times the cost of the Manhattan Project or the Apollo mission. The government claims it needs a "virtual testing" capability to certify that the existing stocks of nuclear weapons can be transported and stored safely in peacetime and can perform their military missions in the event of nuclear war.

Virtual testing would at least partially replace the role of underground explosions in certifying that nuclear weapons modifications dictated by changing military requirements achieve the desired nuclear explosive performance. Such a capability could also be used to develop entirely new weapons that would be ready for explosive proof-testing should future national security concerns prompt a quick exit from the test ban treaty. This technologically vigorous program is clearly intended to placate important constituencies that have historically opposed the test ban. Failure to achieve the program's ambitious milestones could boomerang, however, creating chances for treaty opponents to urge deferral of ratification or subsequent withdrawal from the treaty until the virtual-testing approach has proved its effectiveness.

Even if the program can meet its goals, it remains seriously misguided in many ways. From a global diplomatic perspective, using virtual testing to manage the weapons stockpile ignores the opportunity to treat the test ban as a stepping-stone to achievement of the broader global nuclear disarmament objective outlined in the Nuclear Non-Proliferation Treaty of 1968. The U.S. was a major architect of this treaty, which capped the number of recognized nuclear powers at five in return for their commitment to pursue "good faith" efforts toward nuclear disarmament. With the stewardship program, however, the DOE seeks to enhance the very capabilities for nuclear weapons design that the test ban is intended to constrain. Ironically, the stewardship program now

ILLUSTRATION BY SLIM FILMS; PHOTOGRAPH: CORBIS/BETTMANN

TEST EXPLOSIONS OF NUCLEAR WEAPONS, once conducted underground and now banned by international treaty, are moving into the virtual realm of supercomputer simulation.

RANDY MONTOYA *Sandia National Laboratories*

THOUSANDS OF PROCESSORS working together inside one of the world's fastest supercomputers make three-dimensional simulation of nuclear explosions possible. At Sandia National Laboratories, an inspector checks cables connecting two of the computer's eight cabinets, which separate parts of the machine so that classified and unclassified operations can be run at the same time.

in place could ultimately stimulate political pressures for a return to nuclear explosions in countries that lack the advanced technology required for virtual testing. Furthermore, the program encourages open exchange of new nuclear research between the DOE weapons laboratories and the international scientific community. This exchange will assist and may possibly enable nations currently without thermonuclear or compact fission weapons to develop them.

Testing Moratorium

The DOE engineered the stewardship program in part to cope with nuclear weapons problems in the absence of nuclear tests, but it also gave the organization a way to breathe new life into its stagnant research laboratories. The nuclear weapons establishment and its allies in Congress had managed to resist a U.S. test ban for the duration of the cold war. In September 1992, however, Congress finally imposed a temporary moratorium on nuclear explosions and set September 30, 1996, as the deadline for both an indefinite U.S. testing cutoff and the negotiation of an international test ban treaty. President Clinton twice extended the U.S. unilateral moratorium and in August 1995 made the decision to seek a "zero yield" treaty—a ban on all test explosions, no matter how small the explosive release of nuclear energy. By that time the U.S. nuclear weapons research facilities—Los Alamos, Sandia and Lawrence Livermore national laboratories—had not conducted a nuclear test explosion for almost three years.

"Our budgets had decreased precipitously over the previous six years," recalled Los Alamos director Siegfried S. Hecker in September 1997. "Our people were looking to get out of the nuclear weapons program. The production complex appeared hopelessly broken.... This situation has turned around dramatically in the past two years with the emphasis on science-based stockpile stewardship." Indeed, the $4.5-billion annual funding for the program now exceeds the DOE's average support level of $3.7 billion a year for nuclear weapons activities during the cold war.

With this enormous financial backing the DOE engineered the ambitious stewardship program currently under way. The backbone of the program is a trio of the world's fastest supercomputers. Powered by thousands of microprocessors (like those used in desktop computers) running in parallel, the first generation of these massively parallel processor (MPP) machines at Sandia can perform two trillion calculations per second. This raw number-crunching power is what makes three-dimensional simulation of nuclear explosions possible, and the DOE seeks to develop computers 100 times faster by 2005.

Yet increased computing power alone is not sufficient. The more precise three-dimensional models of the nuclear explosion sequence require a panoply of new experimental facilities to supply detailed input data regarding the behavior of weapons materials at extreme temperature and pressure. Weapons designers will still need to run complex large-scale experiments to verify their computer predictions. For example, without underground explosions, a difficult phase to validate involves "radiation hydrodynamics"—the conversion of x-ray energy from the fission explosion of a weapon's primary stage into the high temperatures and pressures required to ignite fusion in its secondary stage.

For this reason, among others, the DOE is building massive new aboveground experimental laboratories, including the $1.7-billion National Ignition Facility now under construction at Lawrence Livermore. When this facility becomes fully operational (sometime after 2005) powerful laser beams will attempt to generate an x-ray pulse with the precise

shape and duration needed to compress and uniformly heat a tiny frozen droplet of deuterium and tritium, fusing together these heavy isotopes of hydrogen in a process hitherto only witnessed in stars and nuclear bombs.

Provoking and Enabling

Such a technically ambitious weapons research program encourages proliferation in several ways. On the diplomatic front, it is fraught with such obvious hypocrisy that it saps U.S. policy of any moral or political heft. Certain nations are likely to abide by the limitations of the test ban treaty only as long as they are convinced that the U.S. remains comparably restrained. Other nuclear states are not likely to achieve the kinds of weapons design and certification capabilities envisioned for the U.S. stewardship program on nearly the same timescale, leading to perceptions of strategic imbalance that could prompt their withdrawal from the treaty.

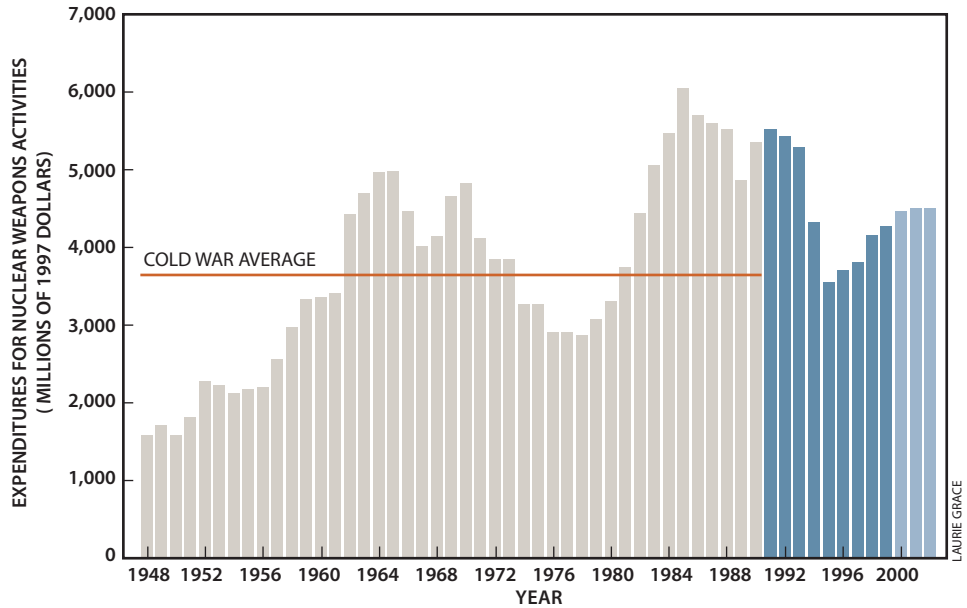
Largely oblivious to these concerns, a long-term stewardship strategy focused on virtual testing relies on markedly increased collaboration between nuclear weapons specialists and the open scientific community. Without test explosions to validate weapons performance, scientists will need to rely more heavily on the quality of their scientific judgment, proponents of the current plan say. Stephen M. Younger, director for nuclear weapons technology at Los Alamos National Laboratory, recently pressed the case that unclassified peer review of fundamental weapons research could fill nuclear testing's role as the "great arbiter" of scientific judgment.

The role that the stewardship program envisions for the unclassified research community extends far beyond peer review and the occasional presentations at meetings. It involves recruitment of top university scientists, under the DOE's academic strategic alliances program, to perform the intellectual heavy lifting required to make virtual testing a reality. Funded by five-year grants totaling tens of millions of dollars, five university research centers and a host of other investigators are creating the mathematical models and computer algorithms needed to simulate the complex physics of each stage of a nuclear explosion. The researchers use comparably complex systems in the unclassified realm, such as gas turbines, rocket engines and pulsating stars, as nuclear weapons analogues to refine and validate physics models and computational techniques that can then be applied "behind the fence" to improve the 3-D computer codes that simulate explosions.

Younger has interpreted this dissemination of cutting-edge weapons science research as a welcome form of "scientific deterrence," which will replace the visible demonstrations of nuclear force during the cold war, such as missile flight tests and nuclear explosions. As foreign scientists hear about U.S. advancements in nuclear science research, they will be left wondering whether additional results might be hidden in the classified realm.

This attitude comes with a severe downside: the unclassified character of much of the scientific work being done in connection with the current stewardship program will result in the transfer of an improved understanding of nuclear explosives phenomena to foreign nuclear establishments. Whether the nuclear weapons design expertise diffused by the U.S. stockpile stewardship program is converted into weapons obviously depends on the political circumstances in a given country or region. But in an unstable world filled with simmering conflicts, proliferating even latent capabilities for the development of improved nuclear weapons is not in the interest of U.S. or global security.

The $4.5-billion annual funding now exceeds the DOE's average support level for nuclear weapons activities during the cold war.



False Choice

In their zeal to create a technically challenging program of nuclear weapons simulation to replace the perpetual cycle of design and testing, proponents of the current stockpile stewardship plan have put policymakers and legislators between a rock and a hard place. Either buy the entire $4.5-billion-a-year virtual-testing paradigm and absorb the self-inflicted proliferation risks, they argue, or lose confidence in stockpile reliability and safety by the middle of the next decade. This is a false choice, predicated on a concatenation of fallacies.

First of all, keeping nuclear warheads safe and secure cannot alone justify a multibillion-dollar program to achieve supercomputer-based virtual testing. Nuclear weapons security is a function of fences, guards, guns, alarms and other

devices. A weapon's susceptibility to accidental nuclear detonation is a problem generally inherent in the design of the device itself, not the result of aging or other causes. The sensitivity of the chemical explosives used in nuclear warheads to sudden impact or fire does not increase with age, and the circuitry that provides electrical isolation to the warhead firing system can be tested and replaced without data from nuclear tests.

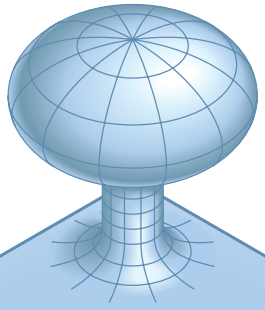
Aging effects may, however, diminish the probability that a given warhead will explode with the force intended by its designers. But the record of the U.S. stockpile surveillance program shows that the nuclear explosive components used in operational U.S. weapons can be maintained over time—as opposed to modified or improved—without test explosions. Indeed, the DOE's stockpile surveillance program revealed in a 1996 study that less than 1 percent of the 830 defects found in weapons stockpiled between 1958 and 1993 was discovered in nuclear tests. After 1970, only 11 of 387 tests were directly related to stockpile reliability. "Historically, only a small fraction of our nuclear tests were for the purpose of evaluating the stockpile's health, because we could depend on a variety of other evaluation techniques," C. Paul Robinson, director of Sandia National Laboratories, wrote in a letter outlining potential consequences of a test ban.

Because weapons scientists have so rarely depended on underground nuclear test explosions to discover and correct flaws in weapons as they age, there is no compelling link between a stewardship program designed to replace test explosions and the continuing safety and reliability of the nuclear stockpile. What the program's high-tech computer simulations and fusion experiments *are* good for is enhancing U.S. capabilities for nuclear weapons design. The need for such enhancements is questionable, however, given that the U.S. already has the technical capability to integrate existing, test-proven nuclear explosives packages into new missiles and bombs without resorting to a massive, new explosion-simulation project. Engineers can develop improved radars, altimeters, boost-gas delivery systems, neutron generators, detonators, batteries, integrated circuits and other weapons parts without modifying a weapon's explosive core.

Proponents of the DOE's virtual-testing effort also cite a need to predict when radioactive decay of warhead materials and other processes will degrade performance as the weapons age. Predictions of weapons degradation would be used to optimize future timetables for warhead remanufacture and thus avoid excess investment in warhead production. (During the era of underground testing, weapons did not need to be remanufactured, because new weapons

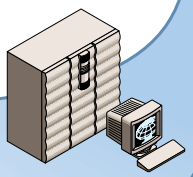
Components and Criticisms of Virtual Nuclear Testing

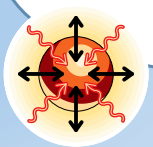
Three components of the Department of Energy's stockpile stewardship program—supercomputing, university research and fusion experiments—are working toward the goal of virtual nuclear testing. Program officials claim that this advanced simulation capability is needed to keep U.S. nuclear weapons safe and reliable without resorting to test explosions. But critics charge that such a technically ambitious program is required only to design and develop new weapons.

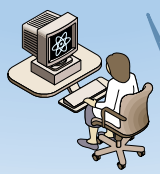


Stewardship Goal:
Continued confidence in the safety and reliability of the country's nuclear weapons

Overall Criticism:
Undermines the U.S. government's pledge to negotiate in good faith toward nuclear disarmament







SUPERCOMPUTING

Goal: Develop the world's fastest supercomputers and the complex software needed to simulate nuclear explosions in three dimensions

Criticism: Current simulation capabilities are sufficient to maintain or rebuild existing nuclear weapons

UNIVERSITY RESEARCH

Goal: Develop computer models of systems with attributes similar to nuclear explosions, such as rocket engines and exploding stars, and integrate these findings into classified weapon simulations

Criticism: Disseminating improved scientific understanding of explosive phenomena among the open scientific community is not in the U.S. or global security interest

FUSION EXPERIMENTS

Goal: Study small-scale fusion reactions in the laboratory to verify supercomputer simulations

Criticism: Fusion has never been achieved in the laboratory, and weapons can be maintained by simpler and less costly techniques

JARED SCHNEIDMAN DESIGN

designs usually replaced older models before the service life of the nuclear components could be demonstrated.)

But keeping weapons safe and reliable does not inherently require that scientists *predict* the precise point at which these effects, if left unattended, would render weapons unreliable. In the case of a bomb's full-scale explosive core, it is necessary only to *detect,* through careful inspection, that the observed deterioration is approaching the limits of acceptable performance previously demonstrated in test explosions. In the case of the far more numerous non-nuclear components, the effects of aging can be detected and corrected through rigorous testing and periodic replacement.

Whereas an approach based on detection rather than prediction might result in a less than optimal schedule for remanufacture, this incremental cost would not begin to approach the large capital investment and high annual fixed costs of the virtual-testing scheme. As the future stockpile decreases in size pursuant to arms-control agreements, any putative savings from optimizing schedules for remanufacture will be likewise reduced.

Different Priorities

Given these underlying technical and fiscal concerns, there is legitimate cause for wondering exactly what is driving the U.S. national security establishment toward unquestioning acceptance of the stewardship program's proliferation risks. The principal question facing any effective stockpile stewardship plan is how best to minimize problems that may crop up after scientists and engineers with experience in nuclear weapons testing have retired. Alternative strategies for coping with this problem have been proposed, but only one approach was ever seriously considered—training a new generation of weapons designers by challenging them with a new suite of powerful experimental facilities and supercomputers to create virtual test explosions. The result is a costly surrogate nuclear weapons program designed to sustain and replicate weaponeers rather than weapons.

A better approach, with definite political and technical advantages for nonproliferation, would be to acknowledge that the judgment of nuclear-test-certified personnel need not, should not and probably cannot be replicated in a new generation of designers without resorting to nuclear explosives tests. On the contrary, every attempt should be made to limit future changes in weapons designs in order to minimize future problems. This conservative, risk-minimizing and proliferation-sensitive approach points toward using the country's present cadre of test-certified personnel to approve future remanufacture specifications for a limited number of robust nuclear explosive package designs to be retained in the enduring stockpile. The certified components could be remanufactured with continued confidence in their performance.

A rhetorical policy favoring the global elimination of all weapons of mass destruction continues to compete with a de facto policy that seeks to maintain U.S. nuclear superiority.

A close look at the facts leads inexorably to the conclusion that a more compact, technically restrained and tightly focused U.S. stockpile stewardship program oriented around an ability to replace weapons components could ensure a safe and reliable nuclear stockpile while better serving the nation's—and the world's—nuclear nonproliferation objectives. More broadly, the self-defeating contradictions inherent in the current virtual-testing approach to nuclear weapons stewardship seem to reflect considerable confusion and uncertainty about the future role of nuclear weapons in U.S. national security.

A rhetorical policy favoring nonproliferation and progress toward the global elimination of all weapons of mass destruction continues to compete with a de facto policy that seeks to maintain U.S. nuclear superiority while sidetracking international initiatives toward nuclear disarmament. The Clinton administration and Congress have allowed this enervating duality in U.S. policy to fester, and it remains a fitting target for renewed public debate as the 2000 elections approach. SA

The Author

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Further Reading

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KAREN SHERLOCK

THE THROAT SINGERS OF TUVA

Testing the limits of vocal ingenuity, throat-singers can create sounds unlike anything in ordinary speech and song—carrying two musical lines simultaneously, say, or harmonizing with a waterfall

by Theodore C. Levin and Michael E. Edgerton

From atop one of the rocky escarpments that criss-cross the south Siberian grasslands and taiga forests of Tuva, one's first impression is of an unalloyed silence as vast as the land itself. Gradually the ear habituates to the absence of human activity. Silence dissolves into a subtle symphony of buzzing, bleating, burbling, cheeping, whistling—our onomatopoeic shorthand for the sounds of insects, beasts, water, birds, wind. The polyphony unfolds slowly, its colors and rhythms by turns damped and reverberant as they wash over the land's shifting contours.

For the seminomadic herders who call Tuva home, the soundscape inspires a form of music that mingles with these ambient murmurings. Ringed by mountains, far from major trade routes and overwhelmingly rural, Tuva is like a musical Olduvai Gorge—a living record of a protomusical world, where natural and human-made sounds blend.

Among the many ways the pastoralists interact with and represent their aural environment, one stands out for its sheer ingenuity: a remarkable singing technique in which a single vocalist produces two distinct tones simultaneously. One tone is a low, sustained fundamental pitch, similar to the drone of a bagpipe. The second is a series of flutelike harmonics, which resonate high above the drone and may be musically stylized to represent such sounds as the whistle of a bird, the syncopated rhythms of a mountain stream or the lilt of a cantering horse.

In the local languages, the general term for this singing is *khöömei* or *khoomii,* from the Mongolian word for "throat." In English it is commonly referred to as throat-singing. Some contemporary Western musicians also have mastered the practice and call it overtone singing, harmonic singing or harmonic chant. Such music is at once a part of an expressive culture and an artifact of the acoustics of the human voice. Trying to understand both these aspects has been a challenge for Western students of music, and each of us—one a musical ethnographer (Levin), the other a composer with an interest in extended vocal techniques (Edgerton)—has had to traverse the unfamiliar territory of the other.

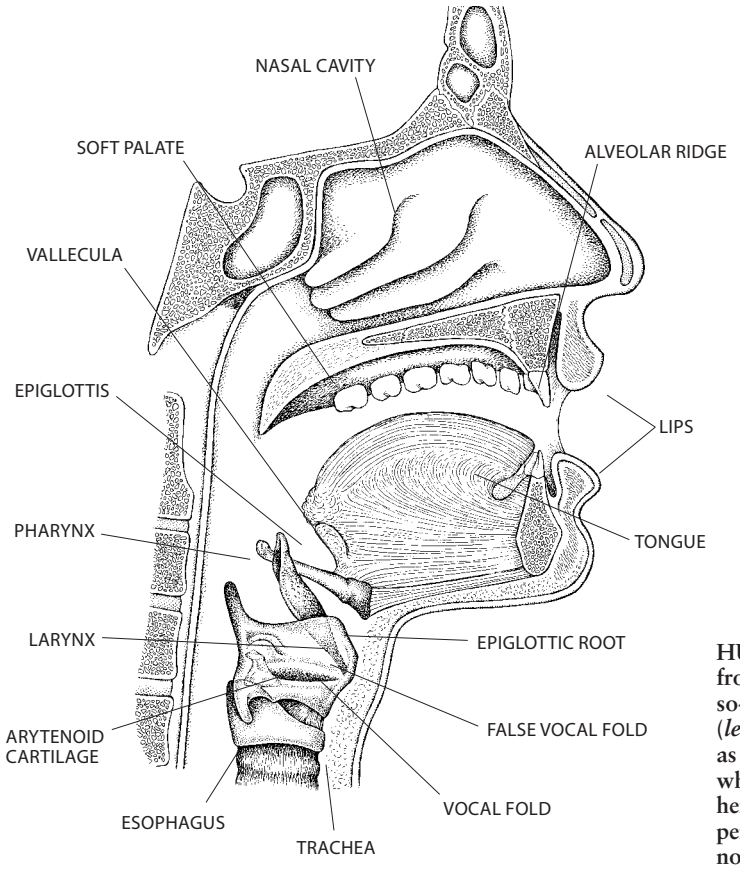
Sound Mimesis

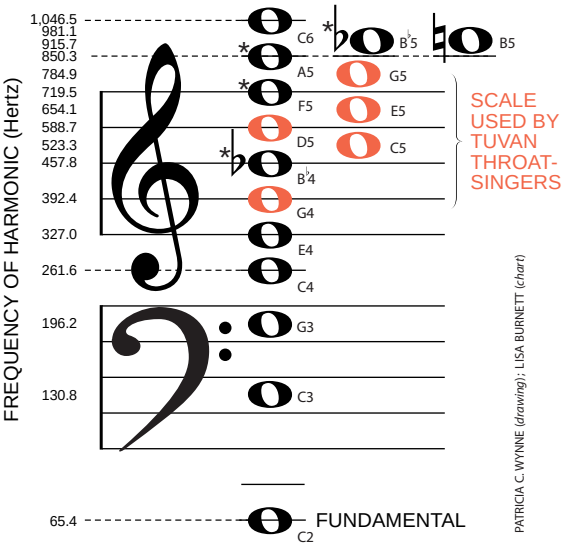
In Tuva, legends about the origins of throat-singing assert that humankind learned to sing in such a way long ago. The very first throat-singers, it is said, sought to duplicate natural sounds whose timbres, or tonal colors, are rich in harmonics, such as gurgling water and swishing winds. Although the true genesis of throat-singing as practiced today is obscure, Tuvan pastoral music is intimately connected to an ancient tradition of animism, the belief that natural objects and phenomena have souls or are inhabited by spirits.

According to Tuvan animism, the spirituality of mountains and rivers is manifested not only through their physical shape and location but also through the sounds they produce or can

VOICE OF A HORSE in Tuvan music, the *igil*—played here by Andrei Chuldum-ool on the grasslands of southern Siberia (*also above*)—is a two-stringed upright fiddle made from horse hide, hair and gut and used to re-create equine sounds. Sound mimicry, the cultural basis of Tuvan music, reaches its culmination in throat-singing.

THEODORE C. LEVIN



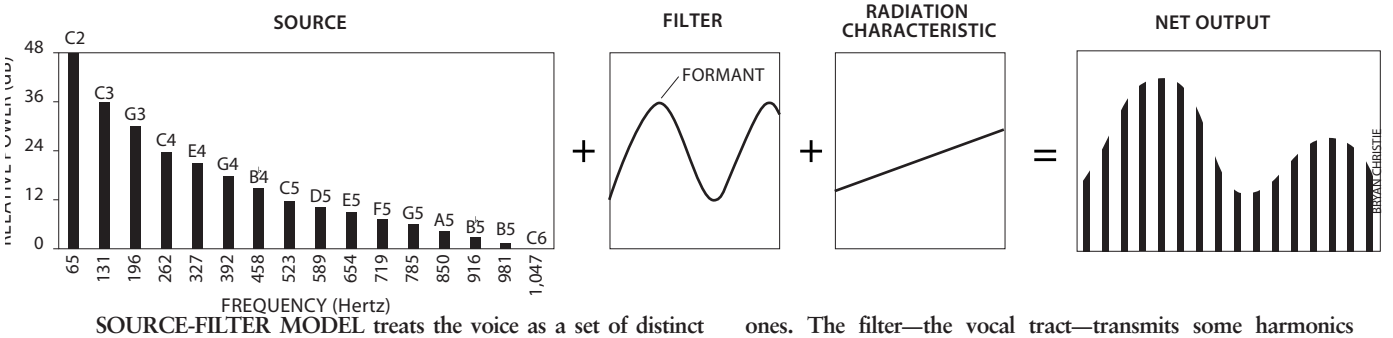


HUMAN VOICE is a complex musical instrument: the buzz from the vocal folds (and, in some throat-singing, from the so-called false folds) is shaped by the rest of the vocal tract (*left*). The buzz is a composite of a fundamental tone (such as low C, with a frequency of 65.4 hertz) and its harmonics, whose frequencies are integral multiples (*above*). Shown here are the nearest corresponding notes in the equal-tempered musical scale; the asterisks indicate harmonics that do not closely align with equal temperament.

be made to produce by human agency. The echo off a cliff, for example, may be imbued with spiritual significance. Animals, too, are said to express spiritual power sonically. Humans can assimilate this power by imitating their sounds.

Among the pastoralists, emulating ambient sounds is as natural as speaking. Throat-singing is not taught formally (as music often is) but rather picked up, like a language. A large percentage of male herders can throat-sing, although not everyone is tuneful. A taboo against female throat-singers, based on a belief that it causes infertility, is gradually receding, and younger women are beginning to practice the technique as well. The popularity of throat-singing among Tuvan herders seems to have arisen from a coincidence of culture and geography: on the one hand, the animistic sensitivity to the subtleties of sound, especially its timbre, and on the other, the ability of reinforced harmonics to project over the broad open landscape of the steppe. In fact, two decades ago concert performances were uncommon because most Tuvans regarded the music as too "down home" to spend money on. But now it leads a parallel public life. Professional ensembles have achieved celebrity status, and the favorite singers are symbols of national cultural identity.

The most virtuosic practices of throat-singing are concentrated in Tuva (now officially called Tyva), an autonomous republic within Russia on its border with Mongolia, and in the surrounding Altai region, particularly western Mongolia. But vocally reinforced harmonics can also be heard in disparate parts of central Asia. Among the Bashkirs, a Turkic-speaking people from the Ural Mountains, musicians sing melodies with breathy reinforced harmonics in a style called *uzliau*. Epic singers in Uzbekistan, Karakalpakstan and Kazakhstan introduce hints of reinforced harmonics in



SOURCE-FILTER MODEL treats the voice as a set of distinct components. The source—the vocal folds—produces a blend of harmonics that are louder at lower frequencies than at higher ones. The filter—the vocal tract—transmits some harmonics (those that line up with its formants) more readily than others. The radiation characteristic of the outside air is a second filter.

FORMING FORMANTS

Although the vocal folds can produce an amazing variety of sounds, it is the vocal tract that molds the raw sounds into language and music. The tract imposes a pattern on the folds' composite sound by picking out a certain combination of tones: namely, those that match the natural resonant frequencies of the air within the tract. As people speak or sing, they raise and lower the resonant frequencies—also known as formant frequencies—by moving their tongue, lips and so on.

These movements are normally perceived as shifts in vowel articulation. The frequency of the first formant, F_1, is inversely related to tongue height (F_1 falls as the tongue rises, as during the change from /a/ in "hot" to /i/ in "heed"). The frequency of the second formant, F_2, is related to tongue advancement (F_2 rises as the tongue moves forward, as when /o/ in "hoe" moves toward /i/ in "heed"). Theoretically, the vocal tract has an infinite number of formants, but the arrangement of the first two or three accounts for most of the difference among vowel sounds (*below, right*).

To understand why the formant frequencies shift, imagine that the vocal tract is a tube closed at one end (the folds) and open at the other (the lips). Next, imagine that the tube is uniform in cross section, in which case the resonant frequencies are fixed by the length of the tube. For a tube 17.5 centimeters (seven inches) long—roughly equivalent to the vocal tract of an adult male—F_1 peaks at 500 hertz, F_2 at 1,500 hertz, F_3 at 2,500 hertz and so on.

Each resonance represents a standing wave within the tube. In other words, the oscillations of air pressure (which convey the sound) assume a definite pattern; so does the back-and-forth jiggling of molecules that occurs in response to the changing pressure differences along the tube. At certain positions called pressure nodes, the pressure remains constant while the molecules must traverse their greatest distance. At other positions called pressure antinodes, the pressure fluctuates by its maximum amount while the molecules stay put. (One can ignore their random thermal motion, which is not relevant to the choreography of wave motion.) Because the closed end of the tube prevents molecules from moving, it must be a pressure antinode. The end open to the outside air must be a pressure node. Each higher formant adds another pair of node and antinode (*below, left*).

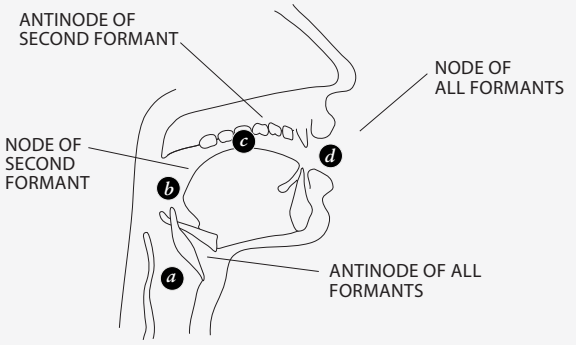
Now suppose that the tube is squeezed, as happens when the tongue constricts the tract. The nodes and antinodes still alternate, but the frequency changes in proportion to the amount of squeezing. A constriction near a pressure node lowers the formant frequency, whereas a constriction near a pressure antinode raises it. Enlargement has the opposite effect. These rules of thumb were first explained by Lord Rayleigh a century ago.

At a node, squeezing the tube forces the molecules to pass through a narrower opening. Assuming the pressure difference that propels them remains roughly the same, the air needs more time to complete its motion. The wave must slow down—that is, its frequency must decrease.

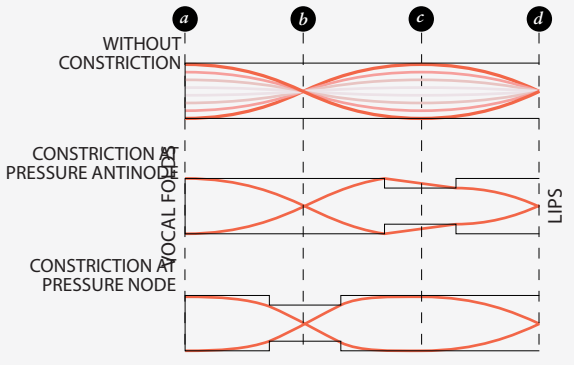
At a pressure antinode, the molecules do not move, but their density varies as pressure fluctuations alternately pull surrounding molecules toward the antinode and push them away. Because squeezing reduces the volume of the tube near the antinode, the addition of a given number of molecules produces a larger increase in density, hence pressure. In effect, the system has become stiffer. It responds faster, so the wave frequency increases. A rigorous explanation, based on so-called perturbation theory, considers the new shape the standing wave is forced to assume (*bottom*).

Throat-singers routinely apply these principles. When they press the base of the tongue to the back of the throat, where the second formant has a pressure node, they lower the frequency of that formant. In the Tuvan *sygyt* style, they push up the middle of the tongue to constrict the antinode of the second formant, thus elevating its frequency. —*George Musser,* staff writer

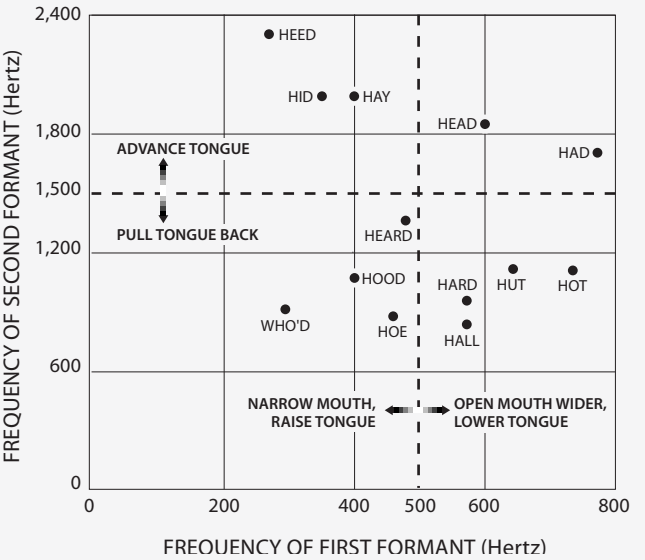
POSITION OF NODES AND ANTINODES IN VOCAL TRACT



STANDING WAVE PATTERNS FOR SECOND FORMANT



RELATION AMONG TONGUE POSITION, FORMANT PITCHES AND VOWEL SOUNDS



BRYAN CHRISTIE; SOURCE: DAVID BERNERS *Stanford University*

oral poetry, and certain forms of Tibetan Buddhist chant feature a single reinforced harmonic sustained over a fundamental pitch. Beyond Asia, the use of vocal overtones in traditional music is rare but not unknown. It turns up, for example, in the singing of Xhosa women in South Africa and, in an unusual case of musical improvisation, in the 1920s cowboy songs of Texan singer Arthur Miles, who substituted overtone singing for the customary yodeling.

The ways in which singers reinforce harmonics and the acoustical properties of these sounds were little documented until a decade ago, when Tuvan and Mongolian music began to reach a worldwide audience. Explaining the process is best done with the aid of a widely used model of the voice, the source-filter model. The source—the vocal folds—provides the raw sonic energy, which the filter—the vocal tract—shapes into vowels, consonants and musical notes.

Hooked on Harmonics

At its most basic, sound is a wave whose propagation changes pressure and related variables—such as the position of molecules in a solid or fluid medium—from moment to moment. In speech and song the wave is set in motion when the vocal folds in the larynx disturb the smoothly flowing airstream out from (or into) the lungs. The folds open and close periodically, causing the air pressure to oscillate at a fundamental frequency, or pitch. Because this vibration is not sinusoidal, it also generates a mixture of pure tones, or harmonics, above the fundamental pitch. Harmonics occur at whole number multiples of the fundamental frequency. The lowest fundamental in operatic repertoire, for example, is a low C note whose conventional frequency is 65.4 hertz; its harmonics are 130.8 hertz, 196.2 hertz and so on [*see illustrations on page 82*]. The strength of the harmonics diminishes as their frequencies rise, such that the loudness falls by 12 decibels (a factor of roughly 16 in sonic energy) with each higher octave (a factor of two in pitch).

The second component of the source-filter model, the vocal tract, is basically a tube through which the sound travels. Yet the air within the tract is not a passive medium that simply conveys sound to the outside air. It has its own acoustical properties—in particular, a natural tendency to resonate at certain frequencies. Like the whistling sound made by blowing across the top of a glass, these resonances, known as formants, are set in motion by the buzz from the vocal folds. Their effect is to amplify or dampen sound from the folds at distinctive pitches, transforming the rather boring buzz into a meaningful clutch of tones.

The sculpting of sound does not end once it escapes from the mouth. As the wave wafts outward, it loses energy as it spreads over a larger area and sets the freestanding air in motion. This external filtering, known as the radiation characteristic, dampens lower frequencies to a greater extent than it does higher frequencies. When combined, the source, filter and radiation characteristic produce sound whose harmonics decrease in power at the rate of six decibels (dB) per octave—except for peaks around certain frequencies, the formants [see "The Acoustics of the Singing Voice," by Johan Sundberg; Scientific American, March 1977; and "The Human Voice," by Robert T. Sataloff; Scientific American, December 1992].

In normal speech and song, most of the energy is concentrated at the fundamental frequency, and harmonics are perceived as elements of timbre—the same quality that distinguishes the rich sound of a violin from the purer tones of a flute—rather than as different pitches. In throat-singing, however, a single harmonic gains such strength that it is heard as a distinct, whistlelike pitch. Such harmonics often sound disembodied. Are they resonating in the vocal tract of the singer, in the surrounding physical space or merely in the mind of the listener? Recent research by us and by others has made it clear that the vocally reinforced harmonics are not an artifact of perception but in fact have a physical origin.

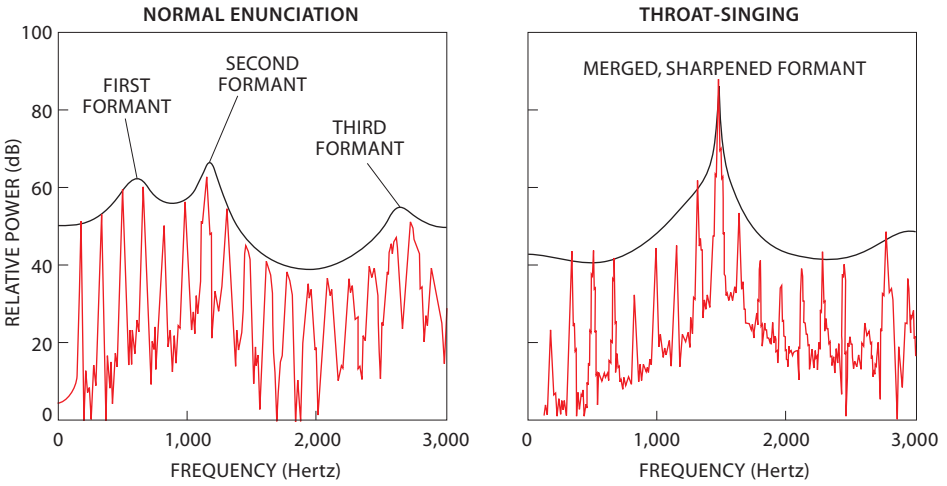
Biofeedback

The mechanism of this reinforcement is not fully understood. But it seems to involve three interrelated components: tuning a harmonic in the middle of a very narrow and sharply peaked formant; lengthening the closing phase of the opening-and-closing cycle of the vocal folds; and narrowing the range of frequencies over which the formant will affect harmonics. Each of these processes represents a dramatic increase of the coupling between source and filter. Yet despite a widespread misconception, they do not involve any physiology unique to Turco-Mongol peoples; anybody can, given the effort, learn to throat-sing.

To tune a harmonic, the vocalist adjusts the fundamental frequency of the buzzing sound produced by the vocal folds, so as to bring the harmonic into alignment with a formant. This procedure is the sonic equivalent of lifting or lowering a ladder in order to move one of its higher steps to a certain height. Acoustic analysis has verified the precision of the tuning by comparing two different harmonics, the first tuned to the center of a formant peak and the second detuned slightly. The former is much stronger. Singers achieve this tuning through biofeedback: they raise or lower the fundamental pitch until they hear the desired harmonic resonate at maximum amplitude.

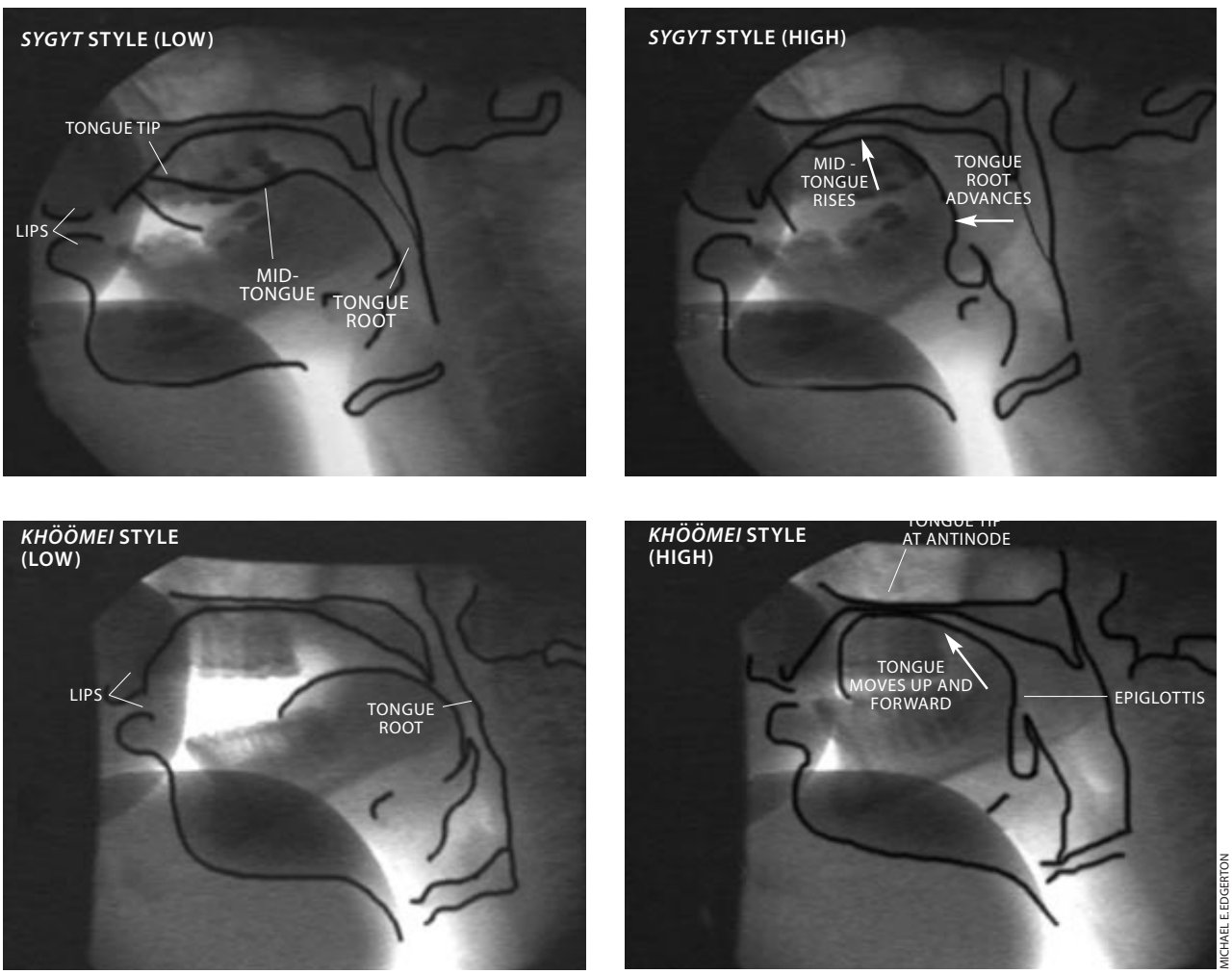
Throat-singers tweak not only the rate at which the vocal folds open and close but also the manner in which they do so. Each cycle begins with the folds in contact and the glottis—the space between the folds—closed. As the lungs expel air, pressure builds to push the folds apart until the glottis opens. Elastic and aerodynamic forces pull them shut again, sending a puff of air into the vocal tract. Electroglottographs, which use transducers placed on the neck to track the cycle, show that throat-singers keep the folds open for a smaller fraction of the cycle and shut for longer. The more abrupt closure naturally puts greater energy into the higher harmonics. Moreover, the longer closing phase helps to maintain the resonance in the vocal tract by, in essence, reducing sound leakage back down the windpipe. Both effects lead to a spectrum that falls off less drastically with frequency, which further accentuates the desired harmonics.

The third component of harmonic isolation is the assortment of techniques that throat-singers use to increase the amplification and selectivity provided by the vocal tract. By refining the resonant properties normally used to articulate vowels, vocalists reposition, heighten and sharpen the formants [*see box on page 83*]. In so doing, they strengthen the harmonics that align with the narrow formant peak, while simultaneously weakening the harmonics that lie outside of this narrow peak [*see upper illustration on opposite page*]. Thus, a single overtone can project above the others. In addition, singers move their jaws forward and protrude, narrow and round their lips. These contortions reduce energy loss and feed the resonances back to the vocal-fold vibration, further enhancing the resonant peak.



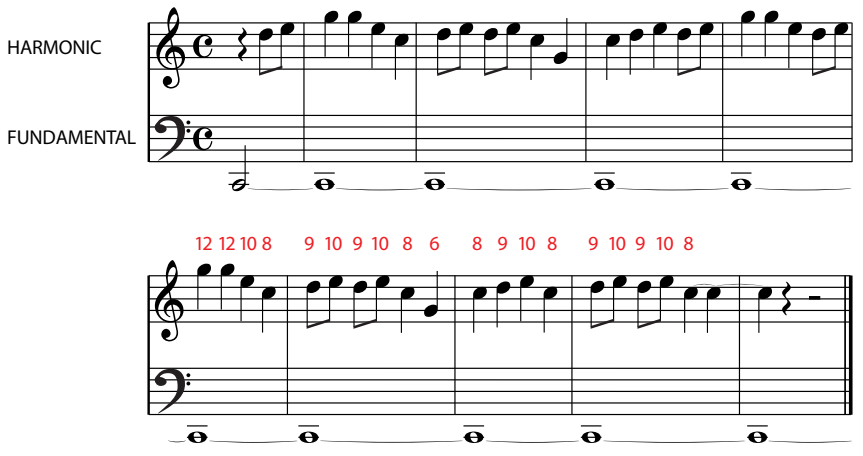
LAURIE GRACE; SOURCE: MICHAEL E. EDGERTON

SOUND SPECTRA show the difference between normal enunciation of the vowel /a/ in "hot" (*left*) and throat-singing (*right*). In both cases the power is concentrated at distinct frequencies—the harmonics produced by the vocal folds (*red*). When harmonics align with the formant frequencies of the vocal tract (*black*), they gain in strength.



MICHAEL E. EDGERTON

X-RAYS show throat-singers in action. In the Tuvan *sygyt* style (*top row*), vocalists keep the tongue tip behind the upper teeth, near the alveolar ridge. To shift from low harmonics (*top left*) to high harmonics (*top right*), they bring the middle of the tongue up and the root of the tongue forward. In the *khöömei* style, the pitch rises as the entire tongue moves from low and back (*bottom left*) to high and front (*bottom right*). These motions are obvious in the movies available at www.sciam.com/1999/0999issue/0999levin.html.



LISA BURNETT; SOURCE: THEODORE C. LEVIN

ARTY-SAYIR **("the far side of a dry riverbed") is a melody performed by throat-singer Vasili Chazir. The numbers identify the harmonic relative to the fundamental, transcribed here as a sustained low C note. The actual performance, available at www.sciam.com/1999/0999issue/0999levin.html, is about a semitone lower.**

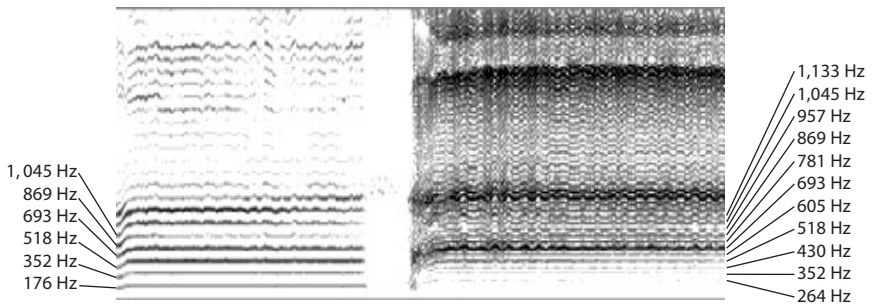
In a study of both Tuvan and Western overtone singers conducted at the University of Wisconsin's hospitals and clinics with support from the National Center for Voice and Speech, video fluoroscopy (motion x-ray) and nasoendoscopy (imaging the vocal folds using a miniature camera) have confirmed that singers manipulate their vocal tracts to shift the frequency of a formant and align it with a harmonic. By reinforcing different harmonics in succession, they can sing a melody. The nine musicians in the study demonstrated at least four specific ways to accomplish the shifting. Other methods may also be possible.

In the first, the tip of the tongue remains behind the upper teeth while the midtongue rises to intone successively higher harmonics. Additionally, vocalists fine-tune the formant by periodically opening their lips slightly. In Tuvan the style of music produced by this means is known as *sygyt* ("whistle").

In the second method, singers move the tongue forward, an act that in normal speech changes the vowel sound /o/ ("hoe") to /i/ ("heed"). The lowest formant drops, and the second rises. By precisely controlling how much the formants separate, a Tuvan musician can tune each to a separate harmonic—thereby reinforcing not one but two pitches simultaneously, as sometimes occurs in the *khöömei* style.

The third approach entails movement in the throat rather than in the mouth. For lower harmonics, vocalists place the base of the tongue near the rear of the throat. For mid-to-high harmonics, they move the base of the tongue forward until a gap appears in the vallecula—the space between the rear of the tongue and the epiglottis (the flap of cartilage that prevents food from entering the lungs). For the highest harmonics, the epiglottis swings forward to close the vallecula.

In the fourth method, vocalists widen the mouth in precise increments. The acoustical effect is to shorten the vocal tract, raising the frequency of the first formant. The uppermost harmonic that can be reinforced is limited primarily by radiation losses, which worsen as the mouth widens. Depending on the pitch of the fundamental, a singer can isolate up to the 12th harmonic. Tuvans combine this technique with a second vocal source to create the *kargyraa* style, in which one may reinforce harmonics as unbelievably high as the 43rd harmonic.



BRYAN CHRISTIE; SOURCE: MICHAEL E. EDGERTON

TWICE AS MANY TONES are available to a vocalist when he or she switches from normal song (*left*) to the *kargyraa* style of throat-singing (*right*). The vocal folds continue to intone a fundamental on the F note near 176 hertz, while the singer's so-called false folds also come into play, producing a low F at half the frequency.

Two Voices

This additional source is another fascinating aspect of throat-singing. Singers draw on organs other than the vocal folds to generate a second raw sound, typically at what seems like an impossibly low pitch. Many such organs are available throughout the vocal tract. *Kargyraa* utilizes flexible structures above the vocal folds: the so-called false folds (paired tissues that occur directly above the true folds and are also capable of closing the airstream); arytenoid cartilages (which sit in the rear of the throat and, by rotating side to side and back and forth, help to control phonation); aryepiglottic folds (tissue that connects the arytenoids and the epiglottis); and the epiglottic root (the lower part of the epiglottic cartilage). A different technique, which produces much the same sound but probably does not figure in *kargyraa,* combines a normal glottal pitch with the low-frequency, pulselike vibration known as vocal fry.

Because *kargyraa* resembles the sound of Tibetan Buddhist chant, some researchers have used the term "chant mode" to describe it. It generally, though not always, assumes a 2:1 frequency ratio, with supraglottal closure at every other vocal-fold closure. A typical fundamental pitch would be the C at 130.8 hertz, with the false folds vibrating one octave below at 65.4 hertz. Spectral analysis shows that when a singer switches into chant mode, the number of frequency components doubles, verifying that the second source is periodic and half the normal pitch. Chant mode also affects the resonant properties of the vocal tract. Because use of the false folds shortens the vocal tract by one centimeter (about half an inch), formant frequencies shift higher or lower depending on the location of the constriction on the selected formant.

Engrossing as all these vocal techniques are, Tuvan interest in throat-singing also focuses on the expressive sound world that it opens. As in every culture, music embodies a set of individual and social preferences as well as physical abilities. For example, in the seven-note scale between the sixth and 12th harmonics—the segment of the spectrum used by Tuvan and Mongolian singers—performers scrupulously avoid the seventh and 11th harmonics, because the local musical syntax favors pentatonic (five-tone) melodies, like that of the hymn "Amazing Grace."

Another cultural preference is for extended pauses between breaths of throat-singing. (These breaths may last as long as 30 seconds.) To a Western listener, the pauses seem unmusically long, impeding the flow of successive melodic phrases. But Tuvan musicians do not conceive of phrases as constituting a unitary piece of music. Rather each phrase conveys an independent sonic image. The long pauses provide singers with time to listen to the ambient sounds and to formulate a response—as well as, of course, to catch their breath.

The stylistic variations all reflect the core aesthetic idea of sound mimesis. And throat-singing is just one means used by herder-hunters to interact with their natural acoustic environment. Tuvans employ a range of vocalizations to imitate the calls and cries of wild and domestic animals. They play such instruments as the *ediski,* a single reed designed to mimic a female musk deer; *khirlee,* a thin piece of wood that is spun like a propeller to emulate the sound of wind; *amyrga,* a hunting horn used to approximate the mating call of a stag; and *chadagan,* a zither that sings in the wind when Tuvan herders place it on the roofs of their yurts. Players of the *khomus,* or jew's harp, re-create not only natural sounds, like that of moving or dripping water, but also human sounds, including speech itself. Good *khomus* players can encode texts that an experienced listener can decode.

Yet it is throat-singing that Tuvans recognize as the quintessential achievement of their mimesis, the revered element of an expressive language that begins where verbal language ends. For the herders, it expresses feelings of exultation and independence that words cannot. And as is often a defining feature of traditional art, inner freedom blooms within the strictest of constraints—in this case, the physical limits of the harmonic series.

THEODORE C. LEVIN

SHAMANS in Tuva use a variety of sound makers as tools of spiritual healing. Animism has shaped Tuvan music and has helped to keep throat-singing a vibrant custom.

The Authors

THEODORE C. LEVIN and MICHAEL E. EDGERTON began working together last year when approached by *Scientific American.* Levin has been conducting musical fieldwork in Central Asia since 1977 and, in 1987, became the first American allowed to study music in Tuva. The authorities welcomed him with a mixture of delight and terror. Entire villages were repainted, and meals of boiled sheep were served on linen-covered tables set up on the steppe. Since 1991 Levin has taught at Dartmouth College. He has organized many a concert tour, recording project and cultural exchange. Edgerton is a musical composer who has performed worldwide and directed vocal ensembles in the U.S. and Korea. His works, published primarily by CP Press Publications, often utilize uncommon performance gestures. Currently he is a postdoctoral fellow at the University of Wisconsin Vocal Function Laboratory and is funded by the National Center for Voice and Speech (NIH grant no. P60DC00976).

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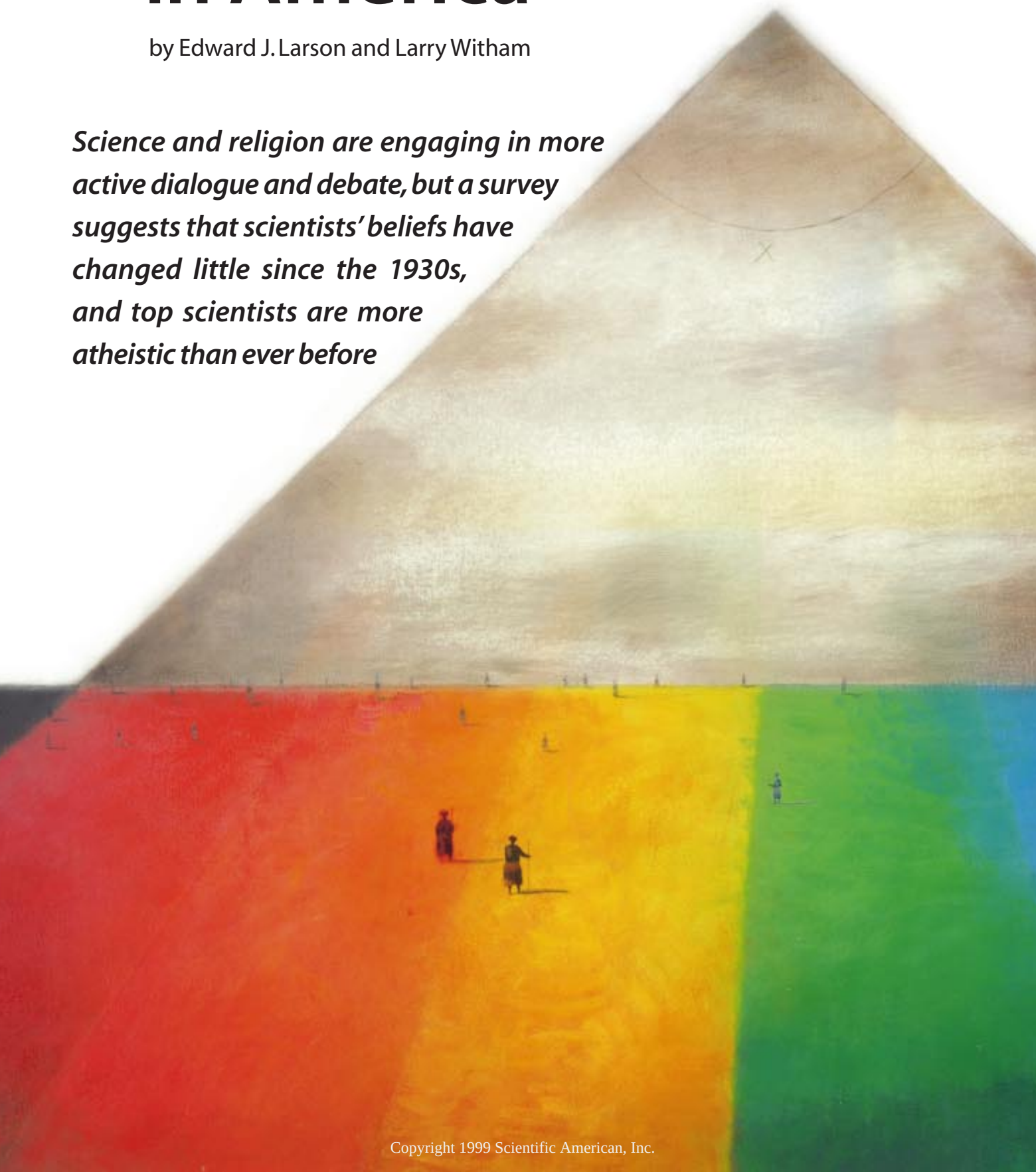
Scientists and Religion in America

by Edward J. Larson and Larry Witham

Science and religion are engaging in more active dialogue and debate, but a survey suggests that scientists' beliefs have changed little since the 1930s, and top scientists are more atheistic than ever before



A stone's throw from the Potomac River in Washington, D.C., a bronze statue of Albert Einstein reposes in a garden beside the National Academy of Sciences. Could there be a more fitting individual than this mythic figure to symbolize the highest echelon of scientists in America?

Having fled to the U.S. from the secular horrors of Nazi Germany because of his religious heritage, Einstein never ceased musing about religion and once challenged quantum uncertainty by famously denying that God plays dice with the universe. Late in life, however, he concluded, "In their struggle for the ethical good, teachers of religion must have the stature to give up the doctrine of a personal God."

Now, at the turn of the millennium, comes a movement bent on reconciling science and religion. New books hail the divine in physics, biology, even computer information theory. Last year "SCIENCE FINDS GOD" emblazoned the cover of *Newsweek*, and other leading newsmagazines picked up the theme. More conferences than ever feature dialogues between the "two ways of knowing." By one report, U.S. higher education now boasts 1,000 courses for credit on science and faith, whereas a student in the sixties would have long dug in hardscrabble to find even one. Scientists who are older and tenured, it is said, feel it is time to give witness to their once closeted or newly found faith.

The movement is far from spontaneous, however. The cover stories followed a major symposium at the University of California at Berkeley, "Science and the Spiritual Quest," underwritten by the deep pockets of the Templeton Foundation, whose founder, financier-philanthropist Sir John Templeton, is profoundly interested in reconciling religious belief with modern science. He calls it "humility theology," emphasizing the need for partisans on both sides to recognize limits to their way of knowing and leave room for the other. The Templeton Foundation has also supported many of those new college courses on the topic, created cash awards for scholarly papers, and financed countless other academic lectures and conferences—all designed to stimulate scholarly discussion of the relationship between science and religion within the framework of humility theology. Striving to keep pace, some evangelical Protestant organizations—most notably the well-funded Campus Crusade for Christ—have sponsored conferences and collegiate lectures pitching their views on the subject.

Yet in institutional science, where the brightest men and women do their work, the wheels grind slowly and exceedingly fine. For many, the result is an intellectual aversion to the supernatural. Even if science were to find God, as *Newsweek* reported in what would have been (if true) the news story of the century, would scientists recognize it?

Charles Darwin is honored as an exemplar of the scientific spirit. Patiently, Darwin doubted and tested his theory of evolution for 20 years before he published it. He fretted even longer over religion before opting for agnosticism. "I feel most deeply that the whole subject is too profound for the human intellect," he wrote late in life. "A dog might as well speculate on the mind of Newton. Let each man hope and believe what he can."

And what does the typical scientist hope and believe? An early pioneer who sought to answer that question was Bryn Mawr College psychologist James H. Leuba. In 1914 and again in 1933 Leuba surveyed American biological and physical scientists on their views regarding what he described as "the two central beliefs of the Christian religion": a God influenced by worship, and an afterlife. He maintained that without these "fundamental dogmas" Christianity could not survive. And it was appropriate to inquire about these beliefs among scientists, he asserted, because scientists "enjoy great influence in the modern world, even in matters religious."

To see if scientists' beliefs had changed since his day, in 1996 and in 1998 we again asked American scientists Leuba's two questions: Do you believe in (1) "a God in intellectual and affective communication with man … to whom one may

ILLUSTRATIONS BY SCIAM STUDIOS

pray in expectation of receiving an answer" and (2) "personal immortality." Yes, no, and don't know or agnostic were the only options offered. Responses were strictly anonymous.

Our surveys' questions generated significant criticism, as they did in Leuba's day. "Why such a narrow definition [of God]?" asked one of our respondents, writing in the survey margin. "I believe in God, but I don't believe that one can expect an answer to prayer." Another respondent added, "I consider it quite possible to be a deeply religious person while rejecting belief in a personal God or in personal immortality."

Leuba resolutely defended his questions in response to similar complaints. "I chose to define God as given above because that is the God worshipped in every branch of the Christian religion," he wrote. Because we could track changes over time only by using Leuba's precise questions, we accepted the risk that responses could understate religious belief.

"In their struggle for the ethical good, teachers of the stature to give up the doctrine of a personal God."

The polling closely tracked Leuba's methods. First we surveyed a random sample of biological and physical scientists (the latter included mathematicians) listed in the standard reference work *American Men and Women of Science,* just as Leuba did in 1914 with the then *American Men of Science*. Leuba's second quarry, "greater scientists," was based on a random sample of persons so designated by stars next to their listings. That distinction is no longer made in *American Men and Women of Science,* so we fell back on the much more elite membership rolls of the National Academy of Sciences (NAS), whose core biological and physical science sections we surveyed in their entirety. By survey response standards, the two questions touched a nerve then and now, with better than half those polled responding each time.

The 40-Percent Solution

One number rings down through more than eight decades: 40 percent. Four in 10 of Leuba's scientists believed in God as defined in his survey. The same is true today. Somewhat more, about 50 percent, held to an afterlife in Leuba's day, but now that figure is also 40 percent.

Thus, one of Leuba's predictions, which we shall call his general theory of disbelief, failed. Progress in science, he wrote around 1914, would demand "a revision of public opinion regarding … the two cardinal beliefs of official Christianity." He expected religious disbelief to grow among both American scientists and Americans in general. But scientists today no more jettison Christianity's "two cardinal beliefs" than their counterparts did in 1914. Gallup surveys suggest the same about the general population.

In the second part of Leuba's survey—his poll of the scientific elite—he found much higher levels of disbelief and doubt. In 1914 fewer than one in three of Leuba's "greater" scientists expressed belief in God and only a slightly larger fraction in immortality. In 1933 more than 80 percent of top natural scientists rejected both cardinal beliefs of traditional Christianity.

We shall call Leuba's second theory his special theory of disbelief. The "greater" scientists were less accepting of the supernatural than were "lesser" scientists, Leuba postulated, because of their "superior knowledge, understanding, and experience." The special theory is alive and well today: "You clearly can be a scientist and have religious beliefs," University of Oxford chemist Peter Atkins told the British press when the 40-percent result was announced in 1997. "But I don't think you can be a real scientist in the deepest sense of the word, because they are such alien categories of knowledge."

The 1998 NAS members perhaps provide a more immaculate sample of the elite than Leuba's starred entries did. Congress created the National Academy of Sciences in 1863, and after naming its first members Congress empowered them and their successors to choose all later members. Its current membership of 1,800 remains the closest thing to peerage in American science.

And their responses validate Leuba's prediction of the beliefs of topflight scientists generations from his time. Disbelief among NAS members responding to our survey exceeded 90 percent. The increase may simply reflect that they are more elite than Leuba's "greater" scientists, but this interpretation would also please Leuba. NAS biologists are the most skeptical, with 95 percent of our respondents evincing atheism and agnosticism. Mathematicians in the NAS are more accepting: one in every six of them expressed belief in a personal God.

Ziggurat of Belief

Nevertheless, what stands out is an image of American natural science that has not fundamentally changed since 1914. Measured by religious belief, professional science is like a pyramid, or a three-tiered ziggurat. At the top is acute disbelief. Scientists in the middle are significantly less believing (by more than half) than citizens in general. The wide and heavy base is more firmly sunken into religious America—evidence suggests that there is more personal religion among physicians, engineers and members of other technological occupations that involve applied science.

Unveiling this pyramid would strike many learned people as much ado about the obvious. "Today the higher the educational attainment, or the higher the scores earned on intelligence or achievement tests, the less likely are individuals to be Christians," notes intellectual historian Paul K. Conkin. He could say the same of higher income, too.

Some risk lies in sorting aside the "lesser" scientists to crown the "greater" ones, but the distinction does have its value. Of course, theists can scratch their heads and ask, Were not Copernicus, Kepler and Newton also great? Were not each of them profoundly and personally religious? Why are there not more theistic Newton types in the upper echelons today? Are the deepest contemporary scientific minds drawn to atheism, or, to paraphrase Darwin, does the environment of an elite science society select for the trait of disbelief?

Legendary evolutionary biologist Ernst Mayr, an NAS member since 1954, made a study of disbelief among his Harvard University colleagues in the academy. "It turned out we were all atheists," he recalls. "I found that there were two sources." One Mayr typified as, "Oh, I became an atheist very early. I just couldn't believe all that supernatural stuff." But others told him, "I just couldn't believe that there could be a God with all

this evil in the world." Mayr adds, "Most atheists combine the two. This combination makes it impossible to believe in God."

University of Washington sociologist Rodney Stark, an early researcher on the spread of secularization in a religious society, points out, "There's been 200 years of marketing that if you want to be a scientific person you've got to keep your mind free of the fetters of religion." He argues that although demographics make a difference—a professor teaching in South Dakota is likely to be more religious than an academic in Chicago—higher education on the whole winnows out the idea of God or people who hold to it. In research universities, "the religious people keep their mouths shut," Stark says. "And the irreligious people discriminate. There's a reward system to being irreligious in the upper echelons." Stark suggests that perhaps more NAS members are religious than think it politic to admit.

religion must have — Albert Einstein

The NAS, like many scientific organizations, lives off the commonweal. The academy's primary work (done in conjunction with the National Research Council) is to produce on average one technical report a day to advise Congress and other lawmakers, calm unwarranted public fears about science hazards, lobby for research funds, and promote good science and public interest in the field. The NAS is mindful of its obligation to serve the public, but it can be a delicate course to maneuver. Disbelief and belief have often become a major public relations issue for science in religious America.

"I asked some people at the NAS why they don't have a section on evolution," says William B. Provine, an evolutionist and science historian at Cornell University. "Too controversial." Yet, to its credit, in 1998 the NAS issued a report proudly promoting the teaching of evolution in public school. "Whether God exists or not is a question about which science is neutral," the report cautiously begins, before launching its broadside of scientific arguments against religious objections to teaching evolution. But the irony is remarkable: a group of specialists who are nearly all nonbelievers—and who believe that science compels such a conclusion—told the public that "science is neutral" on the God question.

Religion was an unavoidable subject at the news conference at which the report was released. Eminent panelists reiterated that most religions have no conflict with evolution and that many scientists are religious. "There are many outstanding members of this academy who are very religious people, people who believe in evolution, many of them biologists," offered NAS president Bruce Alberts. Of course, he did not claim that these "very religious" NAS members believed in a God as defined in Leuba's survey—traditional Jewish, Christian or Muslim theism, that is—but that would have been a natural interpretation of his statement by many in the general public.

Balancing Act or Cowardice?

The NAS showed similar concern for public opinion in a 1981 policy statement it adopted as a rearguard action after two states mandated equal time for "creation science" in public school biology classes. "Religion and science are separate and mutually exclusive realms of human thought whose presentation in the same context leads to misunderstanding of both scientific theory and religious belief," it said.

These rules of the game suit many in the broad middle but are less satisfying to some scientific atheists and to many scientific religionists. British zoologist Richard Dawkins calls the NAS statement "a cowardly cop-out. I think it's an attempt to woo the sophisticated theological lobby and to get them into our camp and put the creationists into another camp. It's good politics. But it's intellectually disreputable." Antievolutionists such as Phillip E. Johnson, a Berkeley law professor and frequent speaker for the Campus Crusade for Christ, thrive on such clarity and find Dawkins the perfect foil. "My colleagues and I want to separate the real science from the materialist philosophy," Johnson countered on a PBS *Firing Line* debate.

Dawkins is well known for his uncompromising views and has likened belief in God to belief in fairies. He considers it intellectually dishonest to live with contradictions such as doing science during the week and attending church on Sunday.

Eugenie C. Scott, director of the anticreationist National Center for Science Education, is mindful of the public relations dividends at stake when combatants such as Johnson and Dawkins insist that the debate between science and religion, belief and nonbelief, evolution and creation, brooks no compromise. One of her showdowns came in the fall of 1997. On the agenda for the board of the National Association of Biology Teachers (NABT) was a vote about its 1995 "Statement on the Teaching of Evolution." The statement had become infamous in creationist circles because it said that evolution is "an unsupervised, impersonal, unpredictable and natural process"—which to some implied atheism.

Two reputable scholars, religious historian Huston Smith and philosopher Alvin Plantinga, suggested that the board drop the words "unsupervised, impersonal," to save biology teachers the grief of having to defend them. The board voted down this proposal. Then, with only hours to spare, Scott persuaded the board to reverse itself. NABT director Wayne W. Carley said the change was good, honest science. "To say that evolution is unsupervised is to make a theological statement."

Are the deepest contemporary scientific minds drawn to atheism, or do the higher echelons of academia select for the trait of disbelief?

But the vote came across in the popular press as scientists kowtowing to creationists, and thus began what Scott calls "*l'affaire* NABT." A counter group of biologists disparaged her concern for public relations, insisting that indeed evolution *is* unsupervised and impersonal.

Such is the balancing act that materialists in science must play, living and working as they do in a traditionally Christian culture. Matt Cartmill, president of the American Association of Physical Anthropologists, weighs into the debate mostly on the side of humility in science. "Many scientists are atheists or agnostics who want to believe that the natural world they

study is all there is, and being only human, they try to persuade themselves that science gives them the grounds for that belief," he wrote in *Discover* magazine last year. "It's an honorable belief, but it isn't a research finding."

Some scientists try to make it so, however. At its 1997 annual symposium in New Orleans, the Society for Neuroscience heard about the "God module," a spot in the brain that apparently produces religious feelings. The evidence came from the gold mine of brain research, the mentally damaged: patients with temporal lobe epilepsy have religious experiences in their seizures. Christian antievolutionist Johnson shot back: "You may be sure that scientific materialists will never discover a 'materialist module,' meaning a brain part that causes people to fantasize that they can explain the mind in strictly materialist terms."

The story of evolution is "a rich resource for seeking a theistic presence in their lives."

At the 1998 Science and the Spiritual Quest conference in Berkeley, funded by the Templeton Foundation, more than 20 scientists, including a physics Nobel laureate, testified that science either led them to God or was not an obstacle to faith. The conference encouraged scientists to engage in public discussion of God, including (but not predominantly) Leuba's God who answers prayers.

Some pointed out that both science and faith make big presumptions, whereas others suggested that the cosmos contains hints of a mind. Astronomer Jocelyn Bell Burnell, a devout Quaker best known for her discovery of pulsars, finds a place for both science and religion in her life. "I don't think God created the world in any physical sense," she told the gathering of 350 people. "But that's not to say there isn't a God." For her, God just *is*—a private, interior experience tells her so. She said that some people want to put God in that little nanosecond gap after the big bang, but her faith did not need God in any gap.

Late in his distinguished career, astronomer Allan Sandage stumbled on the question theists in science love to ask their agnostic colleagues: Why is there something rather than nothing? "I never found the answer in science," he confided to the Berkeley assembly. "To stop the divine discomfort, I had to do something." He simply "decided to believe," Sandage explained, adding that the belief "turned out to be correct." Sandage's conversion experience makes him a rare "bridge person," linking different camps of theists. His testimonial approach appeals to evangelicals, yet he also fits right into venues organized by liberal Christians. The same could be said of noted Princeton geologist and NAS member John Suppe, who also "got religion" after getting scientific fame, in his case arriving at faith through a search for meaning.

Intelligent Design and Noah's Flood

Quite a different wing of the debate was evident in 1996 at the Mere Creation Conference on science and God sponsored by the Campus Crusade for Christ, convened at conservative Biola University (formerly the Bible Institute of Los Angeles). An impressive succession of orators spoke on evidence in science for a God. This wing is populated mostly by "old-earth" creationists. They admire conventional science, with its evolved cosmos and eons of time, and can accept everything about evolution except the hard parts: turning chemicals into life and fish brains into human consciousness. They hanker for a science that is God-friendly, a discipline allowing such terms as "intelligent design" and "theistic science." Behind this movement is the Leuba-defined God of early 20th-century Protestantism who answers prayers and promises an afterlife.

Further to the theological right loom the so-called scientific creationists. They seek to give the Bible's "young earth"—created rapidly a few thousand years ago as dated by the genealogies in Genesis—a good name in science. Their central research program is flood geology, which seeks evidence of a Noachian worldwide flood and uses this catastrophe to account for the earth's major geologic features. They would have been in enemy territory, so to speak, at the spiritual quest conference in Berkeley, with its vague personal gods and poetic interpretations of Genesis. A few flood geologists with secular doctorates in science attended the Biola meeting, but the old-earth camp wants to convert such people to ancient time, to work together on poking holes in orthodox neo-Darwinian evolution, which they find implicitly atheistic.

Bishops and Ecology

Yet it is in evolution that some scientists find a secular religion. One such is cell biologist Ursula Goodenough, a past president of the Institute for Religion in an Age of Science [see the review of her book *The Sacred Depths of Nature;* SCIENTIFIC AMERICAN, May]. For her, there can be religion without a God or the supernatural. "I consider myself a nontheist," she told the "Epic of Evolution" conference at Chicago's Field Museum in 1997. Her religion, she explained, goes by the name "religious naturalism" (as distinct from philosophical naturalism) and puts forth the evolution story as a rich resource for those seeking a theistic presence in their lives.

Concern for the environment has provided common ground for nonbelieving, humanist scientists and liberal religionists. Carl Sagan broke the ice between these camps with his 1990 open letter welcoming and challenging the religious community to get on board the movement to save the planet. The next year Sagan stood beside a robed Episcopal bishop in Manhattan's Cathedral of St. John the Divine as they co-chaired the joint appeal by science and religion for the environment.

Last fall a similar alliance strolled the halls of Evolution Central, the American Museum of Natural History in New York City. One paleontologist at the museum, the noted anticreationist Niles Eldredge, says it was all to the good. But, he is quick to add, the environment may be the only thing science and religion can civilly discuss. "There's an ecological component to all concepts of God," Eldredge told the *New York Times*. For those wary of public relations debacles, the friendly focus on ecology can easily obscure the troublesome

God question, a welcome side effect for scientists concerned about public support for their discipline.

This rapprochement over the environment is all the more remarkable considering that among all the categories of scientists polled, NAS biologists wanted the least to do with the supernatural. "The modern biologist really thinks that if we go down to the level of DNA, we understand things," biologist Lewis Wolpert commented on our survey results. "If you are a physicist, in a world of quantum mechanics and the big bang, it is so bizarre and ludicrous that the concept of understanding almost disappears." Thus, a physicist may see gaps left for God. Similarly, mathematicians can be Platonic and perceive the beautifully concocted math of the human mind as charting the order of a divine intellect.

persons who are
— Ursula Goodenough

Fred Hoyle, who coined the term "big bang" in derision, is famously quoted (speaking in support of ideas like the anthropic principle) as saying that it is staggering to see the universe so fine-tuned when there is no God to have done it. Of course, theists contend that that's the point: How else could the big bang have generated the precise conditions needed to produce carbon-based life? But to an evolutionary biologist such as NAS member John C. Avise, "Only natural selection comes close to omnipotence, but even here no intelligence, foresight, ultimate purpose or morality is involved. Natural selection is merely an amoral force, as inevitable and uncaring as gravity."

Avise simply does not see a too-orderly-for-chance world in his science. "By all objective scientific evidence, our immediate biological fates, like those of other species, are influenced profoundly by genetic gods and other natural forces," he notes in his 1998 book, *The Genetic Gods*, before quoting the words of William Provine: "Our modern understanding of evolution implies … that ultimate meaning in life is nonexistent."

Philosopher of science Michael Ruse has made a career of studying how biologists do their work and spin their theories. And he's all for naturalism; it is matter only, all the way down. Yet as an early member of the modern historical school of science, he cannot but see social factors influencing both disbelief among biologists and membership selection in the NAS. Do great minds tend to turn atheistic, or do such academies welcome only atheists? "It is a bit of both," Ruse says. Overtly religious members would doubtless feel tension, especially if their beliefs were theologically conservative.

Lutheran theologian Philip Hefner is no fan of fundamentalists and sees himself as pro-science. His journal *Zygon* is dedicated to linking science and faith while avoiding the extremes of either camp. As a student of theologian Paul Tillich, Hefner is on personal terms with symbols and myths. Myths can overpower at times, he says, and science is at fault as much as religion. Sadly for America, its greatest myth about science and religion is a legal melodrama, the 1925 John Scopes "monkey trial." This myth has clung tenaciously to American intellectual life ever since, Hefner says.

"The myth is," he continues, "that scientists are courageous loners who are willing to die for the truth. Organized religion is ipso facto opposed to intellectual freedom and the freedom of truth. Organized religion is the enemy. When heave comes to shove, organized religion will kill the courageous scientist." Hefner sighs over this predominant morality play. "History is just showing that it's not true," he says. "But you'll never get that across."

So the debate goes on, largely pressed by those on the side of religion—conservative, moderate and liberal—who seek the authority of science for their views. In an earlier age, it was scientists who sought the imprimatur of the church, but now that the power and the glory have shifted to science, most modern scientists seem not to care what the church thinks of their science. They generally view religion as a relic of the past or as a private matter beyond the realm of scientific discourse. Yet thanks perhaps to Templeton's influence and the rise of postmodern relativism, many on both sides now sound willing to admit limits to their way of knowing. And at least in the U.S., where the government funds basic research and regulates its applications, some politically savvy scientists recognize the value in downplaying the negative implications for the supernatural that arise from their study of the natural. SA

"A dog might as well speculate on the mind of Newton. Let each man hope and believe what he can."
— Charles Darwin

The Authors

EDWARD J. LARSON and LARRY WITHAM had the idea of redoing James H. Leuba's survey while Witham was interviewing Larson on the topic of American scientists' religious beliefs. Witham did the legwork for the survey; Larson, the analysis. Larson, the Richard B. Russell Professor of History and Law at the University of Georgia, won the 1998 Pulitzer Prize in history for his book *Summer for the Gods*. He attends a United Methodist church in Athens, Ga. Witham has written several fiction and nonfiction books and covers religion news for the *Washington Times*. Reared as a Lutheran, Witham is comfortable with Leuba's God.

Further Reading

SCIENCE AND RELIGION: SOME HISTORICAL PERSPECTIVES. John Hedley Brooke. Cambridge University Press, 1991.

THE SOUL OF THE AMERICAN UNIVERSITY: FROM PROTESTANT ESTABLISHMENT TO ESTABLISHED NONBELIEF. George M. Marsden. Oxford University Press, 1994.

SUMMER FOR THE GODS: THE SCOPES TRIAL AND AMERICA'S CONTINUING DEBATE OVER SCIENCE AND RELIGION. Edward J. Larson. BasicBooks, 1997.

LEADING SCIENTISTS STILL REJECT GOD. E. J. Larson and L. Witham in *Nature*, Vol. 394, page 313; July 23, 1998.

WHEN ALL THE GODS TREMBLED: DARWINISM, SCOPES, AND AMERICAN INTELLECTUALS. Paul K. Conkin. Rowman & Littlefield, 1998.

SKEPTICAL INQUIRER: SPECIAL ISSUE: SCIENCE & RELIGION, Vol. 23, No. 4; July/August 1999.

by Shawn Carlson

Counting Atmospheric Ions

Replenished by the thousands of thunderstorms that constantly pummel our planet, the earth's electric charge produces an electric field that is typically around 100 volts per meter of elevation and that can surge to thousands of volts per meter when a thundercloud rolls overhead. In my July column I explained how to measure these fields with a delightful instrument called a field mill. I also mentioned that we would all be electrocuted instantly were it not for the fact that the atmosphere contains very little free charge (ions and unattached electrons), and so these large fields simply cannot generate dangerous currents. In this issue I thought I would show you how to measure the density of these charges.

Every fraction of a second, cosmic rays strip electrons from some of the normally neutral molecules in our atmosphere. Ionization is also triggered by ultraviolet light, fires and the radioactive decay of certain elements. These processes leave some air molecules positively charged while simultaneously creating a diffuse mist of electrons, some of which are picked up by other atoms. The atmosphere thus contains both positively and negatively charged ions.

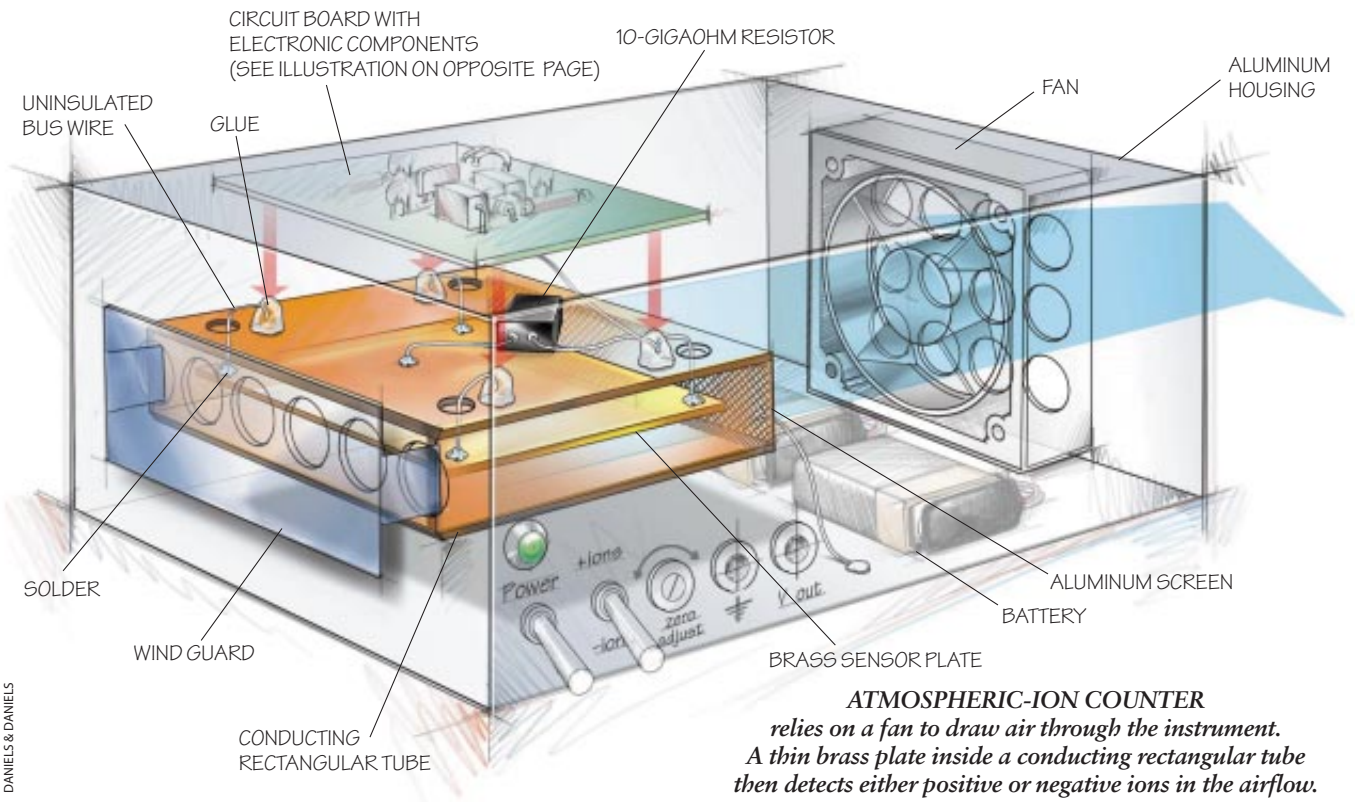
These particles are extremely scarce. Of the 2.5×10^{19} molecules that reside in each cubic centimeter of air inside your home, only a scant 200 carry an excess negative charge, whereas 250 are positively charged. (The concentrations are often higher outside.) Nevertheless, an instrument that can be built for under $60 readily detects that tiny number. The homemade device, which owes its origin to Bill Lee of AlphaLab in Salt Lake City, is a simplified version of a sophisticated commercial unit AlphaLab (801-487-9492; www.trifield.com) sells for about $580.

The instrument uses a small fan, like the ones used to cool personal computers, to draw air through a conducting rectangular tube. Inside the tube the air travels over a thin brass plate that is fixed at ground while the tube's electrical potential is set to either +5 or −5 volts. The former repels positive ions toward the central plate, where they pick up electrons and are neutralized. The latter drives negatively charged ions to the plate, where they deposit their excess electrons. Either action causes a current to flow through a resistor, creating a proportional voltage drop that a simple circuit can amplify for you to measure.

You can construct the conducting rectangular tube, measuring 7.6 by 7.6 by 1 centimeters, from four plates of double-sided copper-clad circuit board. The inner surfaces should all be connected electrically so that they can be energized with either +5 or −5 volts. The topmost outer surface must be held at ground, however, and needs to be isolated electrically.

For the brass sensor plate, almost any hobby shop sells sheets of the alloy that can be cut. You'll need a 6.4-centimeter square, but purchase some extra to construct a small wind guard for outdoor operation of your instrument.

To prevent stray electric fields from ruining your measurements, cover the



DANIELS & DANIELS

***ATMOSPHERIC-ION COUNTER** relies on a fan to draw air through the instrument. A thin brass plate inside a conducting rectangular tube then detects either positive or negative ions in the airflow.*

downstream opening with an aluminum screen that is electrically connected with the inside of the tube. Note that just a 9-volt battery runs the 12-volt fan.

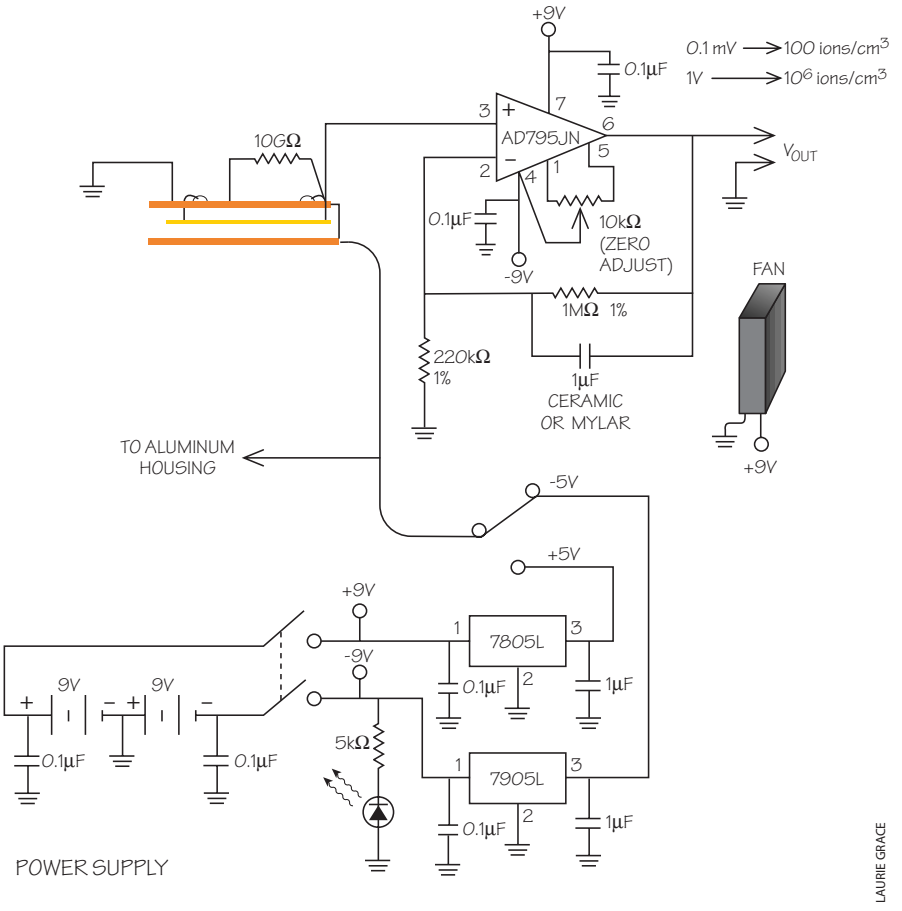
The signal current will be fantastically small—the ions in the air inside your home might generate only 10^{-15} amps. (Outside sources should produce a somewhat larger current.) To become a detectable signal, such a tiny current must pass through a huge resistance—in our case, about 10 gigaohms. Ohmcraft in Honeoye Falls, N.Y., sells such monster resistors for about $10 each.

When forced through such a large resistance, the tiny signal will generate about 10 microvolts, which a high-impedance operational amplifier, such as the reliable AD795JN, can magnify. Unfortunately, other circuit components do not perform as well, so to achieve the necessary level of precision you will have to take a few precautions.

The circuit board you use to mount the electronic components must be kept clean of surface contamination; otherwise excess current could flow about. Cleanse the board with alcohol and thereafter wash your hands thoroughly with soap before touching it.

Also, tiny currents can pass directly through the smidgen of circuit board that separates the operational amplifier's pin 4 (connected to the power supply) from pin 3 (the input signal). Because these currents can swamp a delicate signal, bend up pin 3 to keep it from touching the circuit board. You will need to connect the sensor wire from the 10-gigaohm resistor directly to this pin. Finally, to prevent any stray electric fields from forming between the aluminum housing of the device and the tube, connect the two electrically.

For your ion counter to work properly, you must ground the brass sensor plate through the 10-gigaohm resistor. Solder four pieces of uninsulated bus wire (20 gauge or thicker), one to each of the four corners of the plate. Then drill four oversize holes in the top surface of the tube so you can pass the wires through them. Secure three of the wires well above the conductive surface of the tube by encasing them inside a mound of glue from a hot glue gun [*see illustration on opposite page*]. The glue is a surprisingly good electrical insulator, but if any of the adhesive comes in contact with the metal on the inside surface



ELECTRONIC CIRCUITRY
for the ion counter must be able to detect a minute current, just 10^{-15} amp. To do so, a 10-gigaohm resistor forces the tiny signal to generate about 10 microvolts, which a high-impedance operational amplifier can then magnify.

of the tube, enough current will flow to destroy your measurements. So be careful to keep it well away from the holes. Next, solder one end of the 10-gigaohm resistor to the top surface of the tube and the other end to the remaining fourth wire. Also solder the signal wire to that junction and secure it onto the tube's top surface with hot glue, as shown in the illustration. Last, attach the other end of the signal wire to pin 3 of the operational amplifier.

When you are ready to use your device, first block the opening so that no air gets through and adjust the potentiometer in the circuit until your voltmeter reads zero. Then turn the fan on and let indoor air be drawn into the instrument. Your voltmeter should indicate about 0.2 millivolt, which corresponds to roughly 200 ions per cubic centimeter, and the reading should jump if you hold a flame near the inlet. Your device should detect about 66 percent of the ions present. (To learn how to measure the detection efficiency and to calibrate your instrument precisely, check out the Society for Amateur Scientists's Web site.)

With this device, you can observe how the ion count changes during the day, throughout the course of the year and during big storms. And because radon gas increases the number of ions in an enclosed space, you can use this detector as a presumptive test for this dangerous element. As always, please share your findings on the society's Web page. SA

As a service to the amateur community, the Society for Amateur Scientists is making the electronic components (but not the mechanical ones) for this project available until September 2000 for $35. For more information about this and other projects from this column, check out the Society for Amateur Scientists's Web page at www.thesphere.com/sas/WebX.cgi. You may write the society at 4735 Clairemont Square PMB 179, San Diego, CA 92117, or call 619-239-8807.

by Ian Stewart

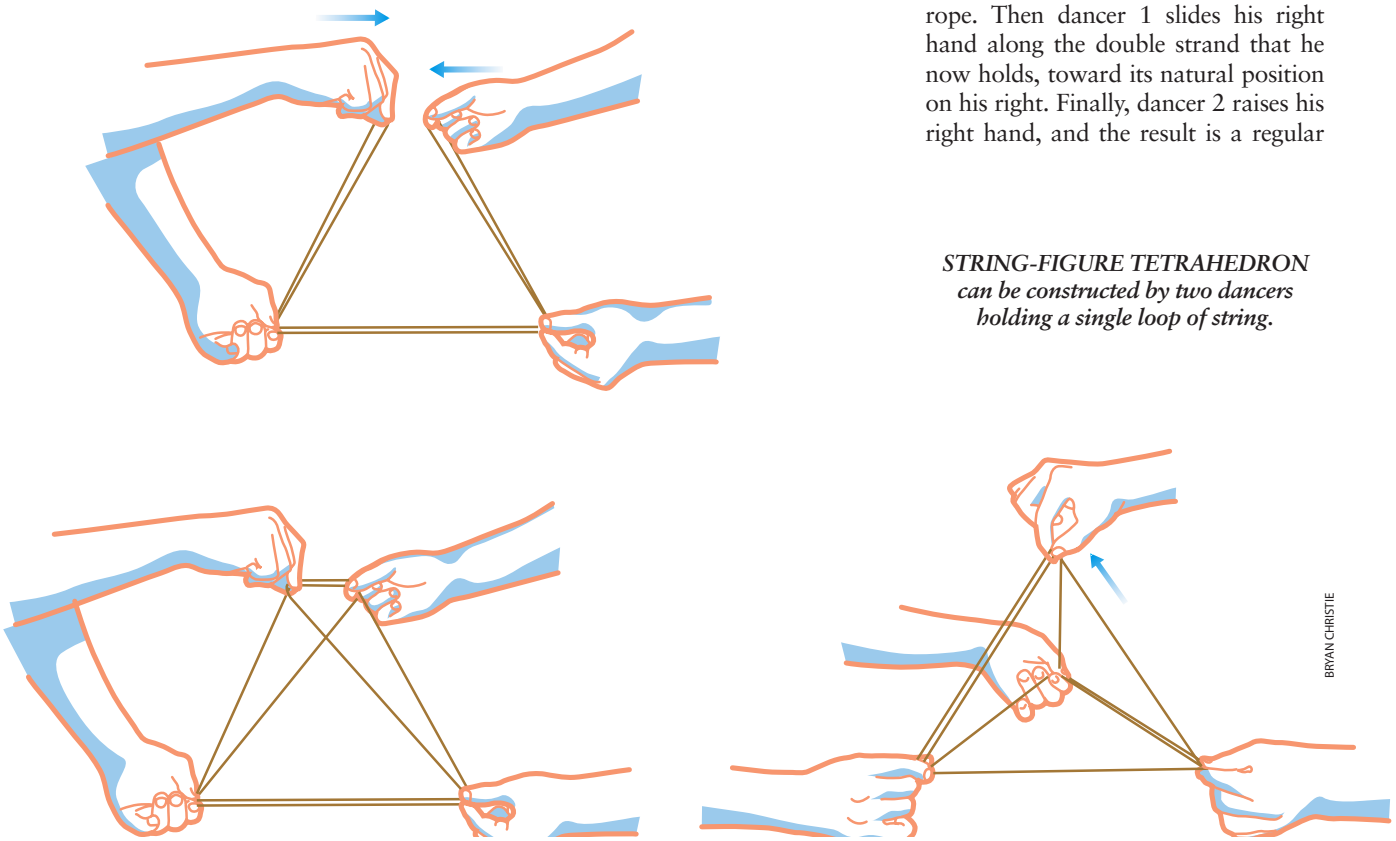
Dances with Dodecahedra

The ancient art of string figures appeals to many recreational mathematicians, even though it isn't overtly mathematical. I chose the title "Cat's Cradle Calculus Challenge" [December 1997] for my last column on string figures to raise the possibility of developing a system to describe their intricate geometry. My confidence that the subject really was mathematical was rapidly justified by a series of communications from readers, including members of the International String Figure Association. Some of these letters explained various systems of mathematical notation for string figures. One letter, however, raised an unanticipated topic: the connections between string figures, mathematics and dance.

There are plenty of links between mathematics and the arts: the use of perspective in painting, for example, or the ratios that occur in musical scales. But the only connection between mathematics and dance that I had previously seen was an analysis of the symmetries of English country dancing carried out some years ago by my colleague Chris J. Budd, a mathematician at the University of Bath. The letter—from Karl Schaffer, co-founder of the Dr. Schaffer and Mr. Stern Dance Ensemble in Santa Cruz, Calif.—told me about something very different: the conscious use of mathematics to create dances. Schaffer detailed several dances based on the use of loops of string to construct regular polyhedra and other mathematical figures.

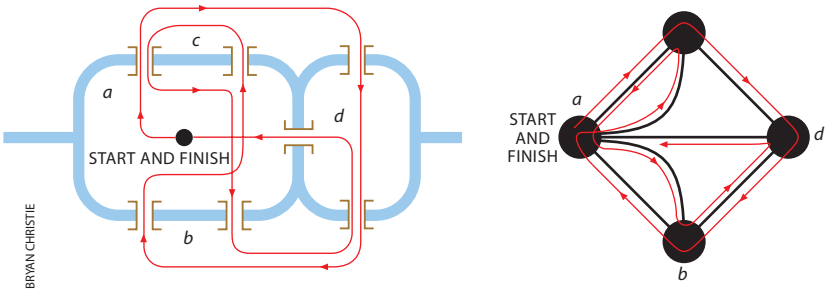
Schaffer started by saying that he and fellow dancer Scott Kim had become interested in polyhedral string figures in 1994 when they conceived a dance performance called "Through the Loop, in Search of the Perfect Square," which they continue to perform in schools in the San Francisco Bay area. It is one of the ensemble's five mathematical dance shows, all intended to dramatize ideas about geometry and symmetry. The development of the show involved a local string-figure enthusiast, the late Greg Keith, who taught Schaffer and Kim some traditional two-person string-figure dances. They soon came up with new ideas of their own, including three-dimensional string patterns based on polyhedra.

The illustration below shows how two dancers can make a tetrahedron using a single loop of rope. Dancer 1 stands to the left and dancer 2 to the right, with the loop passing between them. Each holds the end of the loop in his right hand while grasping both strands a little farther along with the left hand. Simultaneously, dancer 1 crosses his right hand over his left, while dancer 2 separates his left and right hands. Then both reach forward with their right hands until they almost touch. Next, each uses the right hand to grasp one strand of the other's rope while continuing to hold on to his own portion of rope. Then dancer 1 slides his right hand along the double strand that he now holds, toward its natural position on his right. Finally, dancer 2 raises his right hand, and the result is a regular



BRYAN CHRISTIE

STRING-FIGURE TETRAHEDRON can be constructed by two dancers holding a single loop of string.



BRIDGES OF KÖNIGSBERG
puzzle **(left)** *can be turned into a graph* **(right).**
A closed path **(red)** *cannot pass over each bridge only once.*

tetrahedron in which two sides are double strands of rope and the other four sides are single strands.

In a similar way, six dancers holding six loops of rope or ribbon can produce the semiregular polyhedron known as a cuboctahedron, which has six square faces and eight triangular faces. An even more elaborate dance begins with a single long loop held by three people. The loop starts as a triangle and is manipulated first into a tetrahedron and then into an octahedron—a solid with eight triangular faces. Then a fourth dancer joins in and helps to transform the octahedron into a cube. Finally, six more dancers join the dance, and the cube becomes first a dodecahedron (with 12 pentagonal faces) and then an icosahedron (with 20 triangular faces). All five Platonic solids—tetrahedron, cube, octahedron, dodecahedron and icosahedron—are represented in the dance.

Schaffer remarks that transformations of this kind are easier to discover by using actual strings than by making drawings on paper. Moreover, the search for new forms and transformations is necessarily a group activity, because you need enough hands to hold the strings. Usually each vertex of the polyhedron is held by only one hand (which is why 10 people are needed to form a dodecahedron, with its 20 vertices). But arranging the dancers so that the shape they are constructing can actually be seen by an audience is decidedly tricky.

String-figure dances can illuminate some serious mathematical ideas. For example, keeping track of which edges have to be doubled leads to a consideration of Euler cycles in graphs. A graph is a collection of nodes (dots) linked by edges (lines), and an Euler cycle is a closed path that passes along every edge. In the dances the nodes are the hands of the participants, and the edges are the sections of rope that bound the polyhedron being made. Yet some of the edges of the polyhedron are bounded by two or more strands of rope. Why is this so? Can dancers form polyhedra with only one strand per edge?

The answer, in general, is no. Suppose for the sake of illustration that there is only one loop of rope. Then the rope forms a closed cycle that traverses every edge of the polyhedron. In 1735 Swiss-born mathematician Leonhard Euler encountered this question in connection with the famous Bridges of Königsberg puzzle. In the city of Königsberg—then in Germany but now a part of Russia and

renamed Kaliningrad—there are two islands in the Pregel River. At that time, seven bridges linked the islands to the riverbank and to one another [*see illustration on preceding page*]. The townspeople, so it is said, had spent many years trying to find a walking tour that passed over each bridge exactly once. Euler proved that no such path exists.

How did he prove this? First, he considered the four landmasses—the two islands (*a* and *d*) and two riverbanks (*b* and *c*)—to be nodes and the seven bridges to be edges, thereby turning the problem into a graph. Then he proved that if a closed cycle is required to pass along each edge of the graph exactly once, an even number of edges must meet at every node. The key idea is that whenever the cycle encounters a node along one edge, it must leave the node along another edge. Thus, the edges that meet at the node must fall into pairs—and hence must be even in number. This evenness condition is obviously not the case for the Königsberg bridges graph—three edges meet at nodes *b*, *c* and *d*, and five edges meet at node *a*—and therefore, a closed cycle cannot pass along each edge only once. More significantly, Euler also proved the converse of the evenness condition: for any connected (all in one piece) graph with the evenness property, a closed cycle passing along each edge exactly once must exist.

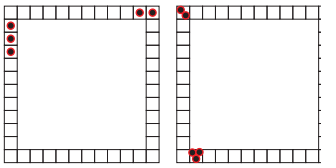
This theorem lets us make sense of the doubled edges that turn up in the dances. Consider, for instance, the dodecahedron. Here there are 20 nodes—the dodecahedron's vertices—linked by 30 edges. Three edges (an odd number) meet at each vertex, so there cannot be a cycle in which each edge is traversed only once. But if an edge is doubled up, then the vertex at each end is now met by four edges, which is even. Can you find 10 edges that, when doubled up, produce an even number at every vertex? If not, you could double all the edges: in that case, six meet at every vertex. But do you really need that many?

As this example shows, string-figure dances can introduce students to three-dimensional thinking. But the dances are also enormous fun. In particular, they are great for breaking the ice at parties. (The Dr. Schaffer and Mr. Stern Dance Ensemble can be contacted at P.O. Box 8055, Santa Cruz, CA 95061, or at www.scottkim.com/dance via the World Wide Web.)

SA

FEEDBACK

In "The Synchronicity of Firefly Flashing" [March], I asked whether the game of Flash could, instead of leading to complete synchrony, evolve to a periodic cycle with the checkers arrayed on more than one square. This does not happen in the standard mathematical model of firefly synchronization, where the "phase" in the cycle is a continuous variable, but it becomes a possibility in Flash, which is the analogous discrete-state problem. William J. Evans of Irvine, Calif., has discovered that if the game is played on the perimeter of a 12-by-12 checkerboard with five fireflies, one initial position (*below left*) will lead, after 27 moves, to a second configuration (*below right*) that repeats after another 38 moves. The 38-move cycle then continues indefinitely. —*I.S.*



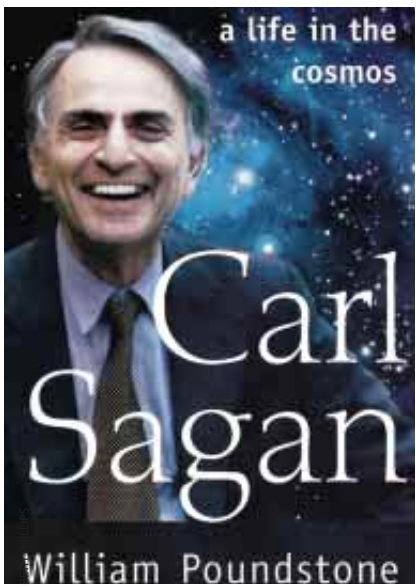
BRYAN CHRISTIE

ONE LIFE, TWO TAKES

Review by Philip Morrison

Carl Sagan: A Life
BY KEAY DAVIDSON
John Wiley & Sons, 1999 ($30)

Carl Sagan: A Life in the Cosmos
BY WILLIAM POUNDSTONE
Henry Holt and Company, 1999 ($30)



Space probe Voyager I launched in 1977, its appointed scans completed, drifted for a dozen years out past Neptune. In 1990 NASA unexpectedly radioed, "Look back, Voyager." Six light-hours out from the sun, snap those planets now in view. From there Earth is seen as a featureless bluish dot, like what the unaided eye has always made of the other planets. In Carl Sagan's visionary 1994 book entitled *Pale Blue Dot,* you can see for yourself that unifying view of Earth among its sibs.

His text accompanying the photograph runs: "On it everyone you love … every human being who ever was, lived out their lives … every hunter and forager, every hero and coward, every creator and destroyer of civilization, every king and peasant … every 'supreme leader,' every saint and sinner in the history of our species lived there—on a mote of dust." Carl was not only its eloquent assayer but a major proponent of the belated effort that finally brought Earth to pose among the other planets. He was directly engaged in the task *Pale Blue Dot* celebrates. Personal persuasion allowed his originality to act in institutions as complex as NASA. His presence would rise to high celebrity, reaching even the comic strips, and glow on video screens the world around—though not yet 10 parsecs out.

From his pioneering astrobiological Ph.D. in 1960 at the University of Chicago's Yerkes Observatory on through a postdoc at Berkeley and a Harvard junior faculty post, he went to lifelong tenure at Cornell in 1968, not yet 34. He would remain for the young "that cool astronomer" in Ithaca, but his second campus was the Jet Propulsion Laboratory in Pasadena, Calif. He was author or co-author of 27 books between 1960 and his early death in 1996. The list includes one audacious astronovel (with Ann Druyan), bent a little into an important feature film (*Contact*); two monographs on planetary atmospheres; two popular books (one with Ann Druyan) that examine the human mind through its evolution (his *Dragons of Eden: Speculations on the Evolution of Human Intelligence* won the 1978 Pulitzer Prize for general nonfiction); six works that treat astronomy and life elsewhere in the universe for the general reader; and two books on nuclear winter.

A sample of these books will serve as markers in this brief overview of his life, but do not forget the 100 strong scientific papers by Sagan that authenticate him as versatile planetologist. In 1973 *Cosmic Connections,* engaging and even rhapsodic, became a best-seller. At the end of that year Carl appeared twice on late-night TV to some 10 million devoted watchers of the *Tonight Show,* brought before them by its celebrity host. Easygoing Johnny Carson found people with ideas interesting, although they might have to share billing, as Carl did on his first appearance, with a talking crow (which sat mute). Sagan was camera-ready: he stood six feet two and robust, deep-set eyes striking, voice aptly varying, phrases stressed or softened to project meaning. His "flawless extemporizing" and appealing analogies drew and held attention. He spoke out of conviction, ready to sparkle with wit or to glow in awe. Surprisingly, Sagan's television presence with Carson amounted to only 26 appearances during more than a dozen years, but they lifted him into celebrity.

In 1978 the Los Angeles public television station approached Sagan to undertake a 13-hour series of his own. Soon enough all parties closed with a talented and successful BBC producer. Carl and his wife, Linda, moved to Los Angeles for two years of consuming effort and travel. The series first aired in the fall of 1980; a smash hit, its eventual viewership is said to have been one tenth of our species! But the imperious producer and Carl never spoke again; their mutual distrust had become too deep. As one viewer, I still feel that the director may have deliberately turned Carl subtly foolish by inducing overacting in certain set pieces. The runaway best-seller book of the

Easygoing Johnny Carson found people with ideas interesting, although they might have to share billing, as Carl did on his first appearance, with a talking crow.

show, *Cosmos,* is still in print, a bargain in all its graphic richness. Its speculative chapters remain enticing, even prescient, envisioning a fictional encyclopedia of the planets of our galaxy before we knew of any planets at all outside our solar family. Now we can point at a score of planets, although not yet are we able to point at other life.

Cornell's half-time professor was now more of a writer/lecturer and a hard-working millionaire. He had a small devoted staff of his own, not only to serve his publications but even for lab studies on the chemistry of planetary atmospheres. His papers appeared at the old rate of two dozen a year. The cold war was still intense, and so indeed was its political opposition. Carl turned toward speeches and lobbying for many causes: antiwar, environment (nuclear winter), human rights, planetary studies and the rational investigation of the paranormal.

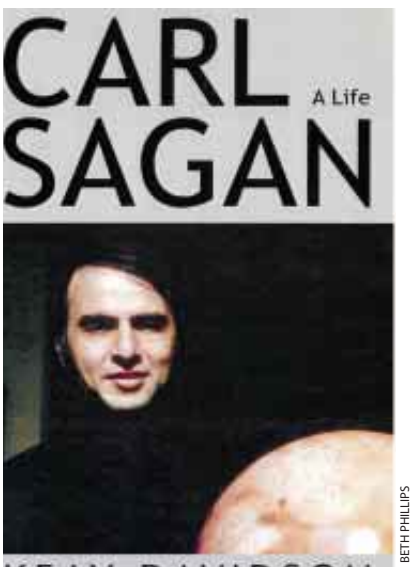
The Person in the Persona

This has so far been an abridged and bookish guide to Carl's work. But life flows deeper than word and image. He married three times and fathered five children, one born in each decade from 1950 to 2000. Baldly put, was this man a womanizer? The clear answer is no. To a man (to a woman, too!), friends report that bachelor Carl, although he enjoyed the company of women, was not a predator. There was passion, affection and intellectual partnership in all three marriages. It is the individual qualities of these three women that command our admiration.

Sagan's first marriage came during graduate student days, when he was 23, to Lynn Alexander. It lasted seven years, and two sons were born. Carl demanded too much time and attention for himself, leaving too little for Lynn's brilliant mind and high ambition. It was she who ended the union, before she published her powerful book in evidence that key organelles in our cells had long ago been bacterial symbionts. That is now part of the canon. Lynn Margulis (her name after remarriage) is an outstanding cell biologist and teacher, an authority on the ecology of microbial life and its ancient feedback with environment, and the author of a number of fresh and popular books, mainly in biology. Her frequent co-author is her talented firstborn son, writer Dorion Sagan. It is philosopher Dorion who among the Sagan children had suffered most from the breakups. Lynn would ever after remain an acute and friendly ally of Carl and of his causes. "The divorce was more successful than the marriage."

Linda Salzman was his second wife, strikingly attractive, a Boston student painter immersed in the milieu of the arts, who drew Carl with her. Carl won her with kindness, and they married in 1969. Her drawings of classical nudes informed the plaques put on two outward-bound Pioneer spacecraft in 1972, ostensibly to depict and locate our species for the unknowns who might in the future fish them out of the interstellar ocean, but much more for the disputatious public of our own day, for whom they became icons of fancy. Son Nicholas was born in 1970; by 1976 the family was back in Ithaca again, famous, very well-to-do, though now a little quarrelsome. Carl left a year or so later for another.

Sagan and Ann Druyan, his third



BETH PHILLIPS

wife, fell in love without surely knowing it. In June 1977 they spoke by phone of the joint tasks they had just faced to make ready the recording of images and music that Voyager would carry afar (a book came of this as well), and somehow they agreed to marry one day, before they had ever kissed or voiced an acknowledgment of the attraction between them. That third marriage lasted until Carl's death, giving them a daughter, Sasha, and a son, Sam, and brought him his best prose collaborator, a guide to a wise and happy life, and a woman who charmed Sagan's formidable and doting mother, Rachel, and after Rachel almost everyone else.

That includes both Davidson and Poundstone, the otherwise differing authors of these two excellent biographies. Poundstone, a science writer from Los Angeles, is closer to the man and his family, more careful in details, and a friend to optimistic science. Davidson, a San Francisco writer, is a skeptic to the claims of science and acts as a keen critic to Sagan's works and their vast uncertainties. Commonplaces those science skeptics accept without examination are often flawed more than the imperfectly tested tentatives of science. This reviewer is a believer in successive approximation.

Sagan died after two years of terrible wasting from myelodysplasia, an uncommon malignancy of the stem cells of the bone marrow. The last of his books that he saw in print is a set of direct, readable essays called *The Demon-Haunted World: Science as Candle in the Dark*. Its recollections of childhood, its integrity and self-examination, its unique mix of generosity and sharp polemic all advance his quiet dissection of the follies and fancies of our times, perhaps even for many who do not share his principles.

After Carl's death as 1996 ended, memorial services were held in Pasadena, Ithaca and New York City. Linda, still understandably bruised, came to the Pasadena gathering. In New York the theologians opened their Cathedral. They are the very men and women with whom Carl had long struck a wonderful truce: let us disagree on how Earth was made but come together strongly over how to care for it. Among others, Vice President Al Gore spoke very warmly, and so did Jeremy Sagan, Carl's second son, and at the end Ann Druyan. I left blinking away my tears.

PHILIP MORRISON, emeritus professor of physics at M.I.T., wrote the book review column for this magazine from 1966 to 1995. This month he takes a brief leave from his current column, "Wonders," to discuss these forthcoming biographies of his close friend and colleague.

THE EDITORS RECOMMEND

SUDDEN ORIGINS: FOSSILS, GENES, AND THE EMERGENCE OF SPECIES. Jeffrey H. Schwartz. John Wiley & Sons, New York, 1999 ($27.95).

Do new species arise by way of gradual changes in precursor creatures or through abrupt, large-scale reorganization of entire anatomical systems? Debates on this subject go way back. Schwartz, a professor of anthropology at the University of Pittsburgh, reviews the debates in detail and comes down on the side of leapfrog evolution, offering a provocative new theory to explain how species arise.

FROM *SUDDEN ORIGINS*

Central to his theory are homeobox genes—discovered in the 1980s—which are crucial in controlling an organism's development. Mutations affecting homeobox genes, Schwartz argues, can have dramatic effects, giving rise to new species. A homeobox mutation could spread through a population as a recessive gene variant, unnoticed until so many carriers existed that they would begin by chance to mate with one another—eventually producing offspring that had two copies of the recessive variant and expressed the new trait. The mutation would take generations to spread, yet the novel feature would appear suddenly and in multiple individuals. The reason that species remain reproductively separate entities, he suggests, may be that individuals recognize potential mates on the basis of similar new traits.

THE AMBER FOREST: A RECONSTRUCTION OF A VANISHED WORLD. George Poinar, Jr., and Roberta Poinar. Princeton University Press, Princeton, N.J., 1999 ($29.95).

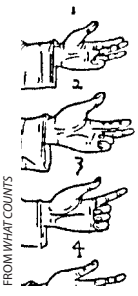
"Step back in time and explore with us a primeval forest that flourished some 15–45 million years ago and then disappeared, leaving testimony of its existence in amber from the Dominican Republic." Thus the Poinars begin; by the end, they have adroitly used the evidence provided by many small, fossilized objects to piece together a picture of the forest. Their specimens, trapped during life in resin from the forest's dominant algarrobo trees, are preserved in exquisite detail. George Poinar, professor emeritus of entomology at the University of California at Berkeley, specializes in studying biological specimens preserved in amber; Roberta Poinar, his wife, is an electron microscopist who has focused her instrument on many such specimens. They buttress their tale with an abundance of riveting photographs of denizens of that ancient forest.

SILICON SKY: HOW ONE SMALL START-UP WENT OVER THE TOP TO BEAT THE BIG BOYS INTO SATELLITE HEAVEN. Gary Dorsey. Perseus Books, Reading, Mass., 1999 ($26).

The small start-up of the title, now a darling of investors, is Orbital Satellite Corporation. At a time when the U.S. government's space programs had slid into a pattern of what aerospace historian Alex Roland called gargantuan missions, overwrought technology and excessive budgets, David Thompson—the driving spirit and CEO of Orbital—saw an opportunity for commercial success in space. His idea was to put up a constellation of small satellites in orbit a few hundred miles above the earth to provide such consumer services as telecommunications, position finding and vehicle navigation. The company succeeded by developing small satellites and rockets to launch them. By 1998 Orbital had become one of the 10 largest satellite-related firms in North America, with earnings estimated at $750 million. Dorsey, a journalist, spent the period from 1992 to 1995 closely observing the company's activities. His breezy account of the adventure is an entry in the Sloan Technology Series.

WHAT COUNTS: HOW EVERY BRAIN IS HARDWIRED FOR MATH. Brian Butterworth. Free Press, New York, 1999 ($25).

Butterworth is a neuropsychologist (professor of cognitive neuropsychology at University College London) rather than a mathematician, but he has thought and read extensively about how people deal with math and has concluded that a basic mathematical ability is inborn. He notes that "everyone can count or tally up small collections of objects, and can carry out simple arithmetical operations, whether they are Cambridge graduates or tribesmen in the remote fastnesses of the New Guinea highlands." Why, then, do so many people have a hard time with more advanced forms of mathematics? Because "maths more than any other subject is sensitive to earlier failures to understand." And how well children understand "depends on how well they learn at each stage, and this in turn depends on how well the curriculum is designed and the teaching is carried out." Butterworth writes engagingly about the hardwiring of the brain for mathematical fundamentals and about the amazing quantity of numbers that each of us confronts every day.



FROM *WHAT COUNTS*

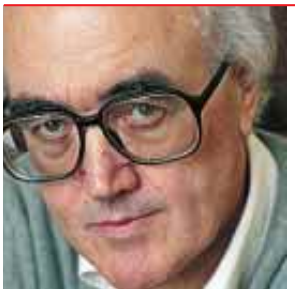
REQUIEM FOR NATURE. John Terborgh. Island Press, Washington, D.C., 1999 ($24.95).

Development by humans is rapidly overwhelming the natural environment, according to Terborgh. Already, he says, "the global balance stands at roughly 5 percent for nature (counting only parks and other strict nature preserves) and 95 percent for humans," and the inevitable growth of the human population will make matters worse. Moreover, parks as they are now operated rarely work well. Even in developed countries, they are often too small to encompass the full spectrum of plant and animal life, and in developing countries they are poorly run. Terborgh, a professor of environmental science and botany at Duke University, has a few suggestions for improving the situation—national conservation trust funds, strict policing of protected areas and the internationalization of nature protection—but he does not seem optimistic that they will be widely adopted.

THE MYSTERIOUS FLAME: CONSCIOUS MINDS IN A MATERIAL WORLD. Colin McGinn. Basic Books, New York, 1999 ($24).

McGinn, a professor of philosophy at Rutgers University, asks several deep questions about consciousness and then answers them in clear and entertaining prose. "What *is* consciousness? Where does it come from? … What does the activity of the brain have to do with it?"

His answer: "My thesis is that consciousness depends upon an unknowable natural property of the brain." The inability of the human intellect to resolve the mind-body problem arises because "our minds are not equipped to solve it, rather as the cat's mind is not up to discovering relativity theory." McGinn supposes that brains capable of understanding consciousness might be developed by breeding advanced thinkers or by a "genetically engineered supermind," but he warns that one must consider what such a superbrained person might lose as the cost of what he gains. "As they say, be careful what you wish for!"



CONNECTIONS

by James Burke

Or Maybe Not

DUSAN PETRICIC

With all the academic research available these days about what it was really like back in the Dark Ages when the European cultural lights went out (or maybe not), it's a pity Hollywood continues to churn out all that anachronistic garbage about King Arthur. You know—people using terminology from 900 years later, knights in fancy armor (from 700 years later), coats of arms and chivalry (600 years later), turreted castles with drawbridges (600 years later), riders using stirrups (500 years later) and so on.

Mind you, clearing up these anachronisms would probably go over like a lead balloon at the box office. Which is how it went with one of history's greatest exposés of a similar nature. The box office in question was that of the Catholic Church, whose 15th-century boss was a pope with as much political clout as spiritual. Or so he thought. Till in 1440 a philological scribbler (a.k.a. humanist scholar) named Lorenzo Valla went looking for a bit of dirt on the papacy (his boss, the king of Naples, was having a row with the Vatican about who ruled what). Valla used his Latin smarts to point out that the language and terminology used in the hitherto unquestioned document of the Donation of (Byzantine emperor) Constantine—which had given the Roman pope secular authority over Europe—were (like the language and terminology of Hollywood King Arthur screenplays) bogus and that the donation was a fake, written 400 years after the supposed event. Which of course blew away the pope's claim to temporal power. Everything Curial hit the fan.

Everything Curial hit the fan.

Valla only kept his head (literally) because he had a well-placed cardinal pal, the influential Nicholas of Cusa, who had the papal ear and smoothed things over. Nicholas was a kind of Vatican ambassador-at-large and the church's chief egghead. In the mid-15th century, ahead of Copernicus, he opined that the earth turned on its axis and wasn't the center of the universe. Also that there might be other inhabited planets. He advocated experimental methods (such as dropping things to measure their speed of fall and noting their air resistance) 200 years before Galileo. He talked about relativity 500 years before Mach or Einstein.

Nicholas's big hero was a guy he had met when they were students at Padua University (the M.I.T. of the time), name of Paolo Toscanelli, whom Nicholas described as the best mathematician alive. Toscanelli was more than that, as would be proved. To start with, after graduation he went home to Florence and told an architect friend all about the new Arab perspective geometry he had been studying. The friend (Filippo Brunelleschi) used the info to develop stuff like converging lines of sight and vanishing points, which excited an artist nicknamed Masaccio to kick off the whole of Renaissance art with his *Trinity* painting. Which was so realistic people thought they were looking at the scene through a hole in the wall.

By the time Toscanelli turned up at Nicholas of Cusa's funeral in 1464, he was also deeply into cartography. He had read up on Marco Polo's trip and used Polo's data to work out the distance from Italy to Japan, which he then greatly exaggerated to make his alternate route look better (that is, shorter by some 10,000 kilometers than it really was). At Nick's funeral Toscanelli talked the route over with a Portuguese priest called Fernão Martins de Roriz, who happened to head his country's permanent commission on exploration. Eleven years later Toscanelli sent him a show-and-tell map for the king, who turned the idea down. So eventually Toscanelli offered the map to an Italian sailor keen to get to Japan, where they said the roofs were made of gold. And for whom Toscanelli's route west to Japan—across the Atlantic Ocean, with nothing in the way but water—was exciting enough to make him drum up the funds and go for it. On August 2, 1492, Columbus boarded ship for his straight shot to Japan, headed for the biggest surprise in history.

That same day, others left Spain for very different reasons. For Spanish Jews, August 2 was shape-up-or-ship-out day, on which you turned Christian, left Spain or were executed. Portugal was the nearest safe haven for one particular family named Spinoza. Until 1580, when Spain (and the Inquisition) took over Portugal, and the nearest refuge became Amsterdam. So the Spinozas by and by fetched up there and settled into the only truly tolerant country in Europe. In 1670 their philosopher son, Baruch, strained even Holland's broad-minded authorities with a publication calling for total freedom of thought and speech, denying miracles and the afterlife, and dumping religion in favor of numbers as the only way to explain the universe.

By this time Spinoza's math had already attracted the attention of such Dutch science biggies as Christiaan Huygens, who introduced Spinoza to Henry Oldenburg, the English-speaking German who was secretary to Lon-

don's Royal Society. On behalf of which Henry set up a network of correspondents all over Europe and spent night and day writing and receiving letters about matters scientific and, on occasion (when the writers inserted a bit of "for your eyes only" espionage), not so scientific. This latter material Oldenburg passed on to the relevant authorities, as a result of which the society was excused postal charges. One of Henry's other charges was Dora Dury (his ward), whom he married after his first wife died. Dora's father, John, was an Anglican clergyman who worked hard all over Europe to reconcile the various Protestant sects (he failed) and was, at one point, in Sweden trying to persuade Queen Christina to help (he failed). Christina had other fish to fry, and besides, as an about-to-become-Catholic, she was the last person to ask.

Christina's brain was famous, and she would often invite known gurus to come and stimulate her. One such was Hugo de Groot, Dutch legal eagle and the first (in 1609) to formulate a law of the sea, in which he said oceans belonged to nobody. This went over very badly with the English, who had recently clobbered a Dutch ship returning from Greenland with a cargo of 22 walruses, on the grounds that Greenland's waters were English. And codified as such, in a rebuttal of Hugo's case, by English megastar jurist and adviser to the king John Selden. Who did himself a favor in 1618 with an essay dedicated to the new Lord Chancellor (top lawyer), Francis Bacon. Of whom so much can be said I'll just note that he wrote about the advancement of human knowledge, which he wanted everybody to share (he would have loved this mag).

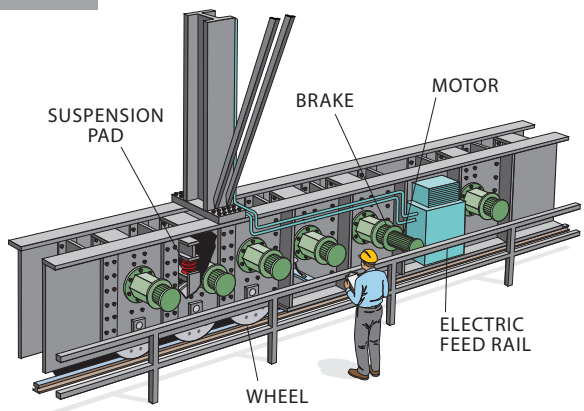
One of Bacon's minor observations was how the continents on each side of the Atlantic seemed to fit together. It took until 1912 for a German meteorologist, Alfred Wegener, to come up with the explanation: continental drift. Geologists pooh-poohed the idea for 50 years, sneering that Wegener was only a weatherman and was seeing things. Interestingly, Wegener's other obsession was mirages. One of the most complex of which is known as the mirage of Morgan le Fay, after a famous witch of medieval legend. Who had one other claim to fame. She was King Arthur's sister.

Or maybe not.

RETRACTABLE STADIUM ROOFS

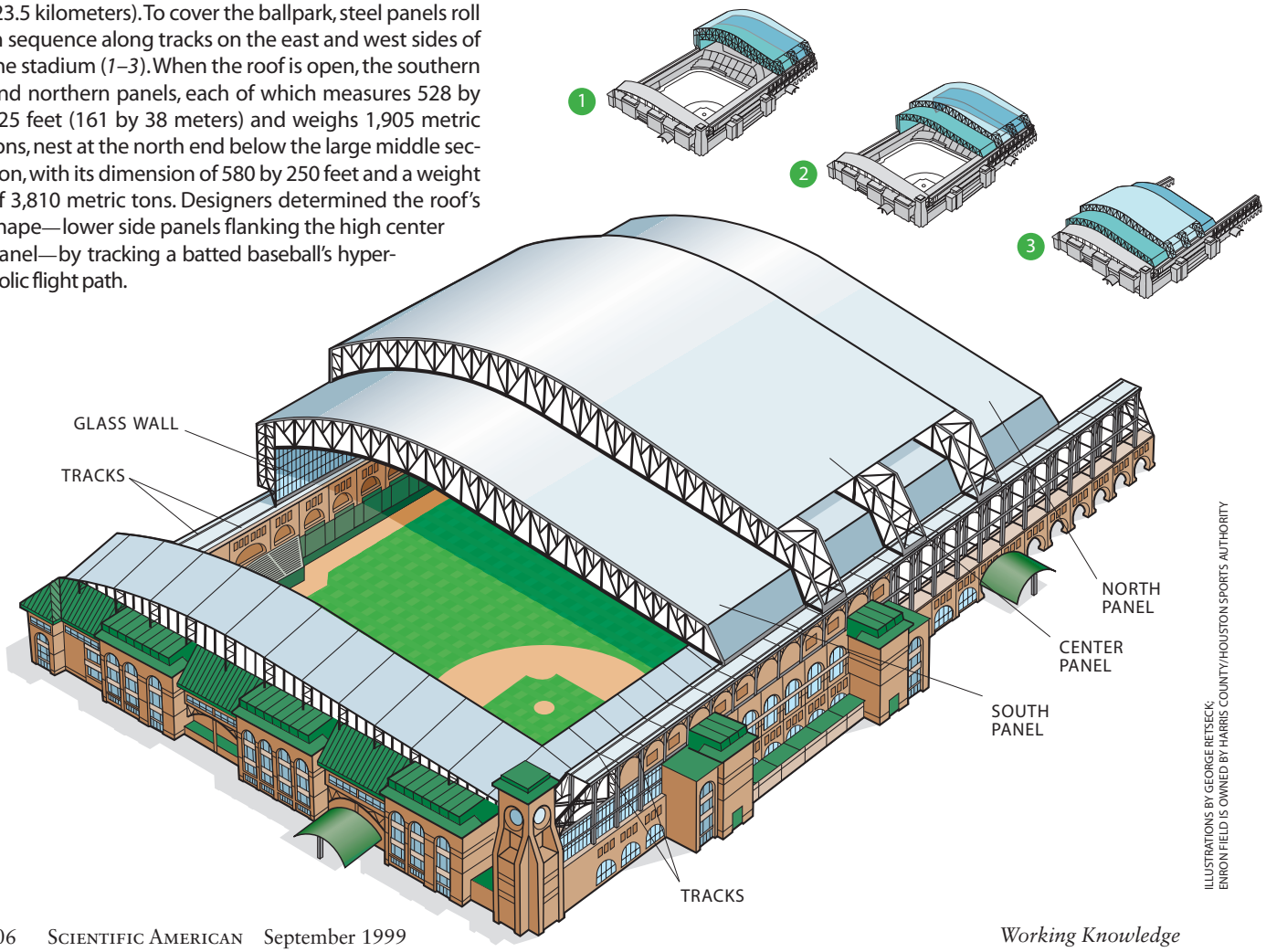
by Cyril Silberman, *Uni-Systems*,
and Earl Santee, *HOK Sports Facilities Group*

Architects design stadium roofs that open and close so that playing fields can be planted with natural grass instead of hard Astroturf. Protecting fans and players from the elements remains a secondary consideration. Since building the first one—the Toronto Skydome in 1989—designers have crafted many types of retractable roofs. Some roofs, for instance, open over only a small central section. The multipaneled movable roof of Enron Field (*shown below*), where the Houston Astros are scheduled to play ball next year, will expose more sky than any other stadium does. The roof will retract completely off the ballpark, uncovering even a glass-walled section of the outfield so that Mark McGwire or another slugger can hit one out of the ballpark.



FORGED STEEL WHEELS measuring 36 inches (91 centimeters) in diameter transport the three roof panels. Each of the 140 wheels has its own braking mechanism, and 60 are equipped with electric motors. If the track were slightly out of alignment, all the weight of a roof panel could come to rest on one wheel, causing severe structural damage. To prevent this, a polyurethane suspension pad that acts as a spring is attached above each wheel to distribute the roof's weight.

MECHANIZED ROOF PANELS on Enron Field will open or close in 12 minutes. They will move back and forth an estimated 160 times a year, a distance of 14.6 miles (23.5 kilometers). To cover the ballpark, steel panels roll in sequence along tracks on the east and west sides of the stadium (*1–3*). When the roof is open, the southern and northern panels, each of which measures 528 by 125 feet (161 by 38 meters) and weighs 1,905 metric tons, nest at the north end below the large middle section, with its dimension of 580 by 250 feet and a weight of 3,810 metric tons. Designers determined the roof's shape—lower side panels flanking the high center panel—by tracking a batted baseball's hyperbolic flight path.



ILLUSTRATIONS BY GEORGE RETSECK; ENRON FIELD IS OWNED BY HARRIS COUNTY/HOUSTON SPORTS AUTHORITY